Title: S-92 Fire Detection System Employment of Optical Fire Detectors

April 6, 2008

Prepared by: Giuseppe Palumbo
Introduction

The S-92 fire detection system employs optical fire detectors in each main engine and APU compartment. The detectors in each S-92 compartment are 4.3 micron optical IR sensors complying with TSO-C79. These detectors respond to IR radiation released during a hydrocarbon fire and use processing electronics to differentiate between a steady light source and the flicker of a flame. Each main engine compartment utilizes 2 of the optical fire detectors strategically placed to detect a fire originating anywhere in the compartment with special emphasis on the areas where temperatures are high enough to ignite flammable fluids and where such fluids are most likely to be present. The small APU compartment utilizes a single detector on the aft wall of the compartment where it can see the APU combustor and turbine areas.

Problem Statement:
Since the first S-92 entered service in December 2005 Sikorsky has seen 70,000 cumulative flying hours successfully with record deliveries for a new aircraft and no fire in the engine or APU compartment. But with any new product roll-out reliability issues have created concerns with the S-92 and one of the top ten drivers is the fire detectors. A total of 130 FRACAS events on False Fire Detection System Annunciations have been recorded requiring pilot to take precautionary measures and unscheduled maintenance for false alarms. The S92 fleet has been plagued by 43 Flame detector events 9 of which have lead to flight aborts. Fire detection in flight sends a cautionary signal to the pilots to abort mission and return to base immediately. Fallout for these false alarms is loss of revenue, increased warrantee cost, AOG, and poor consumer reviews, quality, and safety record.

Figure 1: Top Deck Engine & APU compartment location of Fire Detectors
Objective:

The principal objectives of the project are to determine reliability/availability of the system and to determine the appropriate warranty coverage without exposing the company to significant risk. Since there is minimal historical reliability data available for the fire detector in the field system, the goal is to use the reliability data of component published by the drawing specification and flowed down to the manufacturers of the component. The project will utilize a series of reliability methodologies to analyze the system from different perspectives. We will then analyze the reliability of the system before the project corrective actions have been implemented on the details processes. The results of the project is to develop a management action plan to eliminate all false and spurious fire annunciations Fire Detector Failure, increase reliability, increase flight readiness, and determine required steps to improve maintenance. Resolve intermittent visual and audio Fire Warnings that could make pilots complacent to a real fire condition

Methodologies

This section describes the methodologies used to achieve the objective of the project. The methodologies used are a subset of all the techniques and methodologies covered in the Statistical Methods in Reliability Engineering course.

Reliability Block Diagram

Reliability block diagram is a network of objects describing the function of the system. It shows the logical connections of components needed to perform the specified function of the system. It is a convenient way of breaking down complex systems into simpler components for the purpose of analyzing the system.
In case of the Fire Detectors, all five components must function properly in order for the system to function properly. When all components are necessary the functioning of the system, the components are said to be connected in series in the reliability block diagram. Since the purpose of the system is to detect fire and provide pilots caution on master warning panels and audio tones, the risk and liability associated with any failure of the system is not significant enough to justify any redundancy, added weight, and added costs. Therefore, there are no standby components built in to resume function upon failure of the primary components. It is however, expected that the user of the system will have sufficient supply of spare parts to quickly repair the system in case of any failure of the system.

![Reliability block diagram of the Fire Detector System](image)

**Figure 3: Reliability block diagram of the Fire Detector System**

When a fire is detected by either Fire Detector a ground signal will be outputted to the two Master Warning panels, the Fire Control panel and the two DCUs. DCU will process a signal to the EGPWS (for audio) and MDC (for recording).

**FMECA**

Failure modes, effects, and criticality analysis (FMECA) is a systematic approach to analyze the failure and the effects of the failure of a system. An FMECA of the Fire Detection system is shown in the figure below.
Relevant Reliability Data

As stated earlier, there are no available historical reliability data on the new fire detector system being designed. However, the drawing and specification flown down to the manufacturer of the primary functioning component provides reliability data on the individual component. This data will be used in this analysis to determine the relevant reliability information for the entire system.
The following is the reliability data for the Fire Detector functioning component from the Drawing and requirement specification.

### 3.2.3.1 Mean Time Between Essential Maintenance Actions (MTBEMA)

The fire detector shall achieve a MTBEMA value of at least 12,600 flight hours per the allocation of the 2000-176-301.

### 3.2.3.2 Mean Time Between Mission Affecting Failures (MTBMAF)

The fire detector shall achieve a MTBMAF value of at least 18,000 flight hours per the allocation of the 2000-176-301.

### 3.2.3.3 Mean Time Between Unscheduled Maintenance Actions (MTBUMA)

The fire detector shall achieve a MTBUMA value of at least 11,800 flight hours per the allocation of the 2000-176-301.

### 3.2.3.4 Useful Life

The fire detector shall have a minimum useful life of 10,000 flight hours while operating within the required limits specified herein and maintained in accordance with maintainability requirements. The useful life is defined as that period of an item's operating life during which failures occur randomly and the failure rate is approximately constant.
### 3.2.4 Maintainability

#### 3.2.4.1 Mean Time to Repair for EMAs (MTTRs)

The fire detector shall achieve a user-level MTTRs of not more than 1.0 hours per the allocation of the 2006-114-314 Table 3.2.1-4.

Where safety retention devices are required, Segments shall use toolless safety retention devices.

The fire detector shall be designed to use only fastener tapes, butters and caulks that are removable without the need for solvents, chemical strippers or scraping devices.

The fire detector shall not include equipment with a shelf life.

---

**Figure 6: Available reliability data from Fire Detector System and Supplier primary functioning component.**

<table>
<thead>
<tr>
<th>MTBMAF</th>
<th>18,000 hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTBEMA</td>
<td>12,600 hrs</td>
</tr>
<tr>
<td>MTBUMA</td>
<td>11,800 hrs</td>
</tr>
<tr>
<td>Useful Life</td>
<td>10,000 hrs</td>
</tr>
<tr>
<td>MTTR</td>
<td>1.0 hrs</td>
</tr>
</tbody>
</table>

Assuming an exponential distribution of failures, which is typical of like systems, the failure and repair rates are derived from the MTBMAF and MTTR data.

**Failure Rate (λ), 1/hrs = 0.000056**

**Repair Rate (µ), 1/hrs = 1.00**

---

**Theoretical Calculations**

The Fire Detector system is a combination of five functioning components arranged in series. For such a situation, the reliability of the system is given by the product of the reliabilities of the individual components. So, the mathematical description of the reliability of the system can be presented as:

$$ RS := R_1 \cdot R_2 \cdot R_3 \cdot R_4 \cdot R_5 $$

where, $R_1$, $R_2$, and $R_3$, ..., are the reliabilities of the five individual components.

The actual derivations of the reliability parameters of the system were performed in Maple 11 and are shown below.
> Restart;

\[ \text{Restart} \]

\[ \lambda_1 := 0.000056; \lambda_2 := 0.000056; \lambda_3 := 0.000056; \lambda_4 := 0.000056; \lambda_5 := 0.000056; \]

\[ \lambda_1 := 0.000056 \]
\[ \lambda_2 := 0.000056 \]
\[ \lambda_3 := 0.000056 \]
\[ \lambda_4 := 0.000056 \]
\[ \lambda_5 := 0.000056 \]

\[ R1 := \exp(-\lambda_1 \cdot t); R2 := \exp(-\lambda_2 \cdot t); \]
\[ R3 := \exp(-\lambda_3 \cdot t); R4 := \exp(-\lambda_4 \cdot t); R5 := \exp(-\lambda_5 \cdot t); RS := R1 \cdot R2 \cdot R3 \cdot R4 \cdot R5; \]

\[ R1 := \exp(-0.000056t) \]
\[ R2 := \exp(-0.000056t) \]
\[ R3 := \exp(-0.000056t) \]
\[ R4 := \exp(-0.000056t) \]
\[ R5 := \exp(-0.000056t) \]
\[ RS := (\exp(-0.000056t))^5 \]

\[ FS := 1 - RS; fs := \text{diff}(FS, t); zs := \frac{fs}{RS}, \]

\[ FS := 1 - (\exp(-0.000056t))^5 \]
\[ fs := 0.000280 (\exp(-0.000056t))^5 \]
\[ z_s := 0.000280 \]

\[ \text{plot} \left\{ \{RS, FS\}, t = 0 \text{..} 5.000 \right\}; \]

**Figure 7:** Plots of survivor function and failure function.

\[ \text{plot} \left\{ \{fs, zs\}, t = 0 \text{..} 5.000 \right\}; \]

**Figure 8:** Plots of failure probability density function and failure rate function
Mean Time Between Mission Affecting Failures (MTBMAF)
The theoretical mean time between mission affecting failure is given by the inverse of the hazard function (zs). From the information above, the theoretical MTBMAF of the system is 3,751 hours (1/0.000278).

Availability Estimation
The availability of the system at any time t is the probability that the system is functioning at time (t). This is given by the value of the survivor function at time t. For the Fire Detection system, the survivor function is given by:

\[ R_s(t) = e^{-0.000056t}e^{-0.000056t}e^{-0.000056t}e^{-0.000056t}e^{-0.000056t} = e^{-0.000278t} \]

The probability that the system is functioning at t = 3,751 hours is;

\[ R_s(3751) = e^{-0.000278 \times 3751} = 0.35276 \]

A Monte-Carlo simulation is performed to determine the stochastic distribution of availability of the system at (t) = 3751 hours. The procedure and results are presented later in the report.

Monte-Carlo Simulation
Monte-Carlo simulation is a powerful and convenient approach to introducing statistical variation in reliability calculation. The Monte-Carlo simulation uses a random number generator to determine a series of reliability parameters, for example, time between downtime events. An average of a large number of such random events can then be used as a good stochastic representation of the mean time between failures for the system. This procedure can be implemented in Excel. Figure 9 below shows a snapshot of the Excel spreadsheet used in the Monte-Carlo simulation to compute the mean time to failure. The first columns represents the random failure times of the fire detector system. Since the fire detection system consisting of five components arranged in series, the failure of any of the components leads to the failure of the entire system. The random failure times for the system are shown in column titles “System”. These are simply the minimum of the numbers in the first five columns of the corresponding rows.
A large number of such random failure times are then calculated by repeating the procedure. In this case, 5000 such random failure times were generated. The average of these 5000 random failure times is a good representation of the mean time to failure for the system. This is shown in column titled “MTTF”.

To further study the variation of the MTTF calculated as above, a series of such times are calculated and recorded as shown in columns titled “MTTF” on the far right of Figure 9. A histogram of this data was then generated and shown in Figure 10. This figure shows that the mean of the randomly calculated MTTF’s is very close to that obtained using theoretical calculation.

A similar procedure was followed to calculate the random system availability after 3751 hours. A snapshot of the spreadsheet used in the simulation is shown in Figure 11 and the distribution of random system availability after 3751 hours of operation is shown in Figure 12. This figure shows that the mean of the random availabilities calculated using Monte-Carlo simulation is very close to that obtained using theoretical calculations.

<table>
<thead>
<tr>
<th>FD1</th>
<th>FD2</th>
<th>FD3</th>
<th>FD4</th>
<th>FD5</th>
<th>System</th>
<th>MTTF</th>
<th>Trial #</th>
<th>MTTF</th>
</tr>
</thead>
<tbody>
<tr>
<td>15193</td>
<td>33630</td>
<td>1685</td>
<td>7849</td>
<td>21722</td>
<td>1586</td>
<td>3620</td>
<td>1</td>
<td>3568</td>
</tr>
<tr>
<td>29595</td>
<td>6240</td>
<td>10106</td>
<td>22704</td>
<td>17096</td>
<td>6240</td>
<td>2</td>
<td>3</td>
<td>3608</td>
</tr>
<tr>
<td>15525</td>
<td>1067</td>
<td>6888</td>
<td>4806</td>
<td>10600</td>
<td>4806</td>
<td>3</td>
<td>3</td>
<td>3578</td>
</tr>
<tr>
<td>27548</td>
<td>17160</td>
<td>31964</td>
<td>24195</td>
<td>19514</td>
<td>17160</td>
<td>4</td>
<td>3</td>
<td>3509</td>
</tr>
<tr>
<td>54932</td>
<td>5223</td>
<td>4175</td>
<td>96277</td>
<td>25</td>
<td>25</td>
<td>5</td>
<td>3</td>
<td>3577</td>
</tr>
<tr>
<td>40737</td>
<td>1941</td>
<td>6736</td>
<td>19836</td>
<td>2486</td>
<td>1941</td>
<td>6</td>
<td>3</td>
<td>3568</td>
</tr>
<tr>
<td>48846</td>
<td>35212</td>
<td>4025</td>
<td>7482</td>
<td>442</td>
<td>442</td>
<td>7</td>
<td>3</td>
<td>3516</td>
</tr>
<tr>
<td>29378</td>
<td>29087</td>
<td>520</td>
<td>2317</td>
<td>54368</td>
<td>520</td>
<td>6</td>
<td>3</td>
<td>3573</td>
</tr>
<tr>
<td>18693</td>
<td>3992</td>
<td>32818</td>
<td>43032</td>
<td>39610</td>
<td>3992</td>
<td>9</td>
<td>3</td>
<td>3496</td>
</tr>
<tr>
<td>11434</td>
<td>15017</td>
<td>22754</td>
<td>8222</td>
<td>2399</td>
<td>2399</td>
<td>10</td>
<td>3</td>
<td>3552</td>
</tr>
<tr>
<td>30258</td>
<td>32729</td>
<td>24587</td>
<td>2134</td>
<td>35704</td>
<td>2134</td>
<td>11</td>
<td>3</td>
<td>3606</td>
</tr>
<tr>
<td>5043</td>
<td>58304</td>
<td>6624</td>
<td>14577</td>
<td>43869</td>
<td>5043</td>
<td>12</td>
<td>3</td>
<td>3544</td>
</tr>
<tr>
<td>42537</td>
<td>3075</td>
<td>9755</td>
<td>16231</td>
<td>7190</td>
<td>3075</td>
<td>13</td>
<td>3</td>
<td>3628</td>
</tr>
<tr>
<td>5017</td>
<td>5638</td>
<td>7995</td>
<td>3250</td>
<td>20548</td>
<td>3250</td>
<td>14</td>
<td>3</td>
<td>3702</td>
</tr>
<tr>
<td>30251</td>
<td>15703</td>
<td>20000</td>
<td>1536</td>
<td>22524</td>
<td>1536</td>
<td>15</td>
<td>3</td>
<td>3552</td>
</tr>
<tr>
<td>2176</td>
<td>12249</td>
<td>6821</td>
<td>45127</td>
<td>13077</td>
<td>2176</td>
<td>16</td>
<td>3</td>
<td>3503</td>
</tr>
<tr>
<td>41575</td>
<td>12182</td>
<td>9339</td>
<td>34114</td>
<td>723</td>
<td>723</td>
<td>17</td>
<td>3</td>
<td>3554</td>
</tr>
<tr>
<td>11299</td>
<td>20588</td>
<td>3654</td>
<td>28820</td>
<td>12806</td>
<td>3554</td>
<td>18</td>
<td>3</td>
<td>3562</td>
</tr>
<tr>
<td>8076</td>
<td>15713</td>
<td>20312</td>
<td>786</td>
<td>4286</td>
<td>786</td>
<td>19</td>
<td>3</td>
<td>3590</td>
</tr>
<tr>
<td>37996</td>
<td>4320</td>
<td>2832</td>
<td>3624</td>
<td>3919</td>
<td>2832</td>
<td>20</td>
<td>3</td>
<td>3570</td>
</tr>
<tr>
<td>2626</td>
<td>813</td>
<td>15603</td>
<td>17163</td>
<td>415</td>
<td>415</td>
<td>21</td>
<td>3</td>
<td>3545</td>
</tr>
<tr>
<td>46521</td>
<td>4173</td>
<td>2227</td>
<td>12376</td>
<td>13472</td>
<td>2227</td>
<td>22</td>
<td>3</td>
<td>3564</td>
</tr>
<tr>
<td>3613</td>
<td>10209</td>
<td>20232</td>
<td>6143</td>
<td>10517</td>
<td>3613</td>
<td>23</td>
<td>3</td>
<td>3548</td>
</tr>
<tr>
<td>4158</td>
<td>21840</td>
<td>21260</td>
<td>21006</td>
<td>6694</td>
<td>4158</td>
<td>24</td>
<td>3</td>
<td>3527</td>
</tr>
<tr>
<td>5514</td>
<td>36349</td>
<td>19156</td>
<td>3226</td>
<td>21823</td>
<td>3326</td>
<td>25</td>
<td>3</td>
<td>3574</td>
</tr>
<tr>
<td>9963</td>
<td>2773</td>
<td>19916</td>
<td>40307</td>
<td>4650</td>
<td>2773</td>
<td>26</td>
<td>3</td>
<td>3506</td>
</tr>
<tr>
<td>61026</td>
<td>27405</td>
<td>12954</td>
<td>74525</td>
<td>27216</td>
<td>12954</td>
<td>27</td>
<td>3</td>
<td>3578</td>
</tr>
<tr>
<td>21006</td>
<td>4775</td>
<td>59724</td>
<td>10840</td>
<td>19805</td>
<td>4776</td>
<td>28</td>
<td>3</td>
<td>3595</td>
</tr>
<tr>
<td>25096</td>
<td>7703</td>
<td>4424</td>
<td>2571</td>
<td>61667</td>
<td>2571</td>
<td>29</td>
<td>3</td>
<td>3564</td>
</tr>
<tr>
<td>911</td>
<td>53771</td>
<td>17709</td>
<td>25966</td>
<td>35638</td>
<td>911</td>
<td>30</td>
<td>3</td>
<td>3579</td>
</tr>
</tbody>
</table>

Figure 9: Spreadsheet for Monte-Carlo simulation to compute mean time to failure (MTTF)
Figure 10: Distribution of random system failure times calculated using Monte-Carlo simulation

Figure 11: Spreadsheet for calculating availability using Monte-Carlo simulation
Analysis as a Maintained System

A maintained system behaves differently from an un-maintained system in that whenever it goes into a state of failure, it is repaired and brought back into the functioning state. In the case of the fire detector, the manufacturers of the detector provided data on the mean time to failure and mean time to repair, the time it would typically take to bring the component back into the functioning state.

Theoretical Calculations

For a system consisting of 5 independent fire detector components arranged in series, the availability of the system is given by:

\[ A_{sys} = \frac{\mu_1 \cdot \mu_2 \cdot \mu_3 \cdot \mu_4 \cdot \mu_5}{(\lambda + \mu)^5} \]

Where, \( \lambda_i \) is the failure rate of component \( i \) and \( \mu_i \) is the repair rate of component \( i \).
Substituting the data for the failure rates and repair rates of the five components, the availability of the fire detection system becomes:

\[ A_s = \frac{(1)^5}{(0.000056 + 1.0)} = 0.999944 \]

The frequency of system failure is given by:

\[ \omega_F = A_s \cdot (\lambda_1 + \lambda_2 + \ldots + \lambda_5) = 0.999944 \cdot (0.000056 \times 5) = 0.00028 \]

This compares with the failure rate of the un-maintained system, which is 0.00028. The mean time between downtime events for a system with a failure rate of 0.00028 is 3751 hours.

The mean duration of system down time or MDT can be calculated from the system availability and system failure rate information as follows:

\[ \theta_F = \frac{1 - A_s}{\omega_F} = \frac{1 - 0.999944}{0.00028} = 0.200 \]

This shows that every time the system goes into a state of failure, it is expected to take 0.20 hours to bring it to the functioning state.

**Raptor Simulation**

The calculations shown above for the behavior of the maintained system are the theoretically exact solutions. Another approach to determining the reliability parameters of a maintained system is to use Raptor simulation. The figure below shows a typical raptor simulation screen. The input to the simulation are the system structure including the reliability parameters such as failure rate and repair rate of individual components as well as a set of simulation parameters depending upon the objective of the simulation. In order to calculate the availability and mean down time of a system, one could run the simulation through a number of failures.
For the Fire Detector System, a series of simulations were performed, each simulation consisted of 10 system failures and each data point is the average of 10 different runs. The Raptor simulation shows that the average availability of the system is (Ao) 99.9698%, the mean time between downtime events (MTBDE) is 3,599.94 hours and the mean downtime duration is 1.033467 hours. These compare with 99.994%, 3,751 hours, and 0.99994 hours obtained using the exact solution.
System Uptime and Preventive Maintenance Plan

The analyses presented above provide useful information in understanding the overall system capability of Aircraft Fire Detector System. The Fire Detector System if correctly working to the requirement specification would be 99% uptime based on the calculated availability. The company may use the mean time between failures data to recommend a preventive maintenance schedule. Recommend that the Fire Detector System be maintained after every 3,700 hours of operation to prevent unscheduled downtime. The results also show that once the system fails, it is expected to be unavailable for about 0.20 hours. Unfortunately the system uptime is unacceptable and below the specification requirements for S-92 with total in-fleet aircraft of 48, service hours of 70,000 hours and 123 FRACAS events. Therefore, corrective action steps such as field surveys, product improvements, root cause corrective action, and FMECA are required to be performed and re-analysis the overall system once implemented. Below is a summary of the major findings and corrective immediate actions taken to improve system overall reliability.

Field surveys conducted

Fire Detector Improvement
1 - Water intrusion, loose connector body
Moisture was discovered behind the lens of optical eye end of the flame detector. It was discovered that the flame detector was not designed/manufactured with a means to prevent water ingress on the electrical connector end of the detector. It was determined that moisture could potentially cause an internal electrical ground causing a false fire warning. According to the DOT TSO-C79, the instrument shall not be adversely affected by exposure to rain, fuel, salt spray, oil, or sand. The Drawing states the same under contamination, when 100% of the viewing window is covered by a mixture of these there is no scheduled service, maintenance nor inspection required. Removal and replacement shall be based on an on-condition, rather than a scheduled basis.

Action: Manufacturer Walter Kidde has agreed to redesign the flame detector housing which includes a welded electrical connector to housing configuration eliminating potential for moisture ingestion.

Action: Sealed unit prevents connector movement and moisture intrusion
2- Engine V-Band Clamp Reorientation

Engine exhaust gas in Detector field of view can cause false fire indications. Rotated Engine V-Band clamps to minimize exhaust gas exposure.
False Fire indication rate decreasing since rotating V-Band Clamp

3- Fire Detector Harness
Issues: Insulation deterioration in high temp environment. Action: Replace #2 Fire Detector braided harness in the exhaust cowling with new unbraided high temperature insulation harness and retrofit to the field.
Reliability of other components involved can include and are subject to additional investigation to improve reliability of the Air Vehicle System;

- Data Concentrator Units (2) (DCU’s)
- Fire Control Panel
- Master Warning Panel
- EGPWS (Audio Warning)