Profit-Function of Two- Identical Cold Standby orbital space station System subject to failure due to Potential ammonia leak from S1 radiator due to damaged panel or failure due to Failure in cooling loop A

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Abstract : NASA's space shuttle fleet began setting records with its first launch on April 12, 1981 and continued to set high marks of achievement and endurance through 30 years of missions. Starting with Columbia and continuing with Challenger, Discovery, Atlantis and Endeavour, the spacecraft has carried people into orbit repeatedly, launched, recovered and repaired satellites, conducted cutting-edge research and built the largest structure in space, the International Space Station. The final space shuttle mission, STS-135, ended July 21, 2011 when Atlantis rolled to a stop at its home port, NASA's Kennedy Space Center in Florida.

As humanity's first reusable spacecraft, the space shuttle pushed the bounds of discovery ever farther, requiring not only advanced technologies but the tremendous effort of a vast workforce. Thousands of civil servants and contractors throughout NASA's field centers and across the nation have demonstrated an unwavering commitment to mission success and the greater goal of space exploration. In this paper we have taken failure due to Potential ammonia leak from S1 radiator due to damaged panel or failure due to Failure in cooling loop A. When the main unit fails due to failure due to Potential ammonia leak from S1 radiator due to damaged panel then cold standby system becomes operative. Failure due to collision cannot occur simultaneously in both the units and after failure the unit undergoes very costly repair facility immediately in case of launch failure. Applying the regenerative point technique with renewal process theory the various reliability parameters MTSF, Availability, Busy period, Benefit-Function analysis have been evaluated.

Keywords: Cold Standby, failure due to Potential ammonia leak from S1 radiator due to damaged panel or failure due to Failure in cooling loop A, first come first serve, MTSF, Availability, Busy period, Benefit -Function.

INTRODUCTION

The International Space Station's length and width is about the size of a football field. Credit: NASA

The International Space Station marked its 10th anniversary of continuous human occupation on Nov. 2, 2010. Since Expedition 1, which launched Oct. 31, 2000, and docked Nov. 2, the space station has been visited by 215 individuals.

At the time of the anniversary, the station's odometer read more than 1.5 billion statute miles (the equivalent of eight round trips to the Sun), over the course of 57,361 orbits around the Earth.

The International Space Station is not only an orbiting laboratory, but also a space port for a variety of international spacecraft. As of November 2014, there have been:

- 100 Russian launches
- 37 Space Shuttle launches
- 1 test flight and 3 operational flights by SpaceX's Dragon
- 1 test flight and 2 operational flight by Orbital Science's Cygnus
- 4 Japanese HTVs
- 5 European ATVs

A total of 184 spacewalks have been conducted in support of space station assembly totaling over 1,152 hours, or approximately 48 days.

The space station, including its large solar arrays, spans the area of a U.S. football field, including the end zones, and weighs 924,739 pounds. The complex now has more livable room than a conventional six-bedroom house, and has two bathrooms, a gymnasium and a 360-degree bay window.

Additional launches will continue to augment these facts and figures, so check back here for the latest.

International Space Station Size & Mass

- Module Length: 167.3 feet (51 meters)
- Truss Length: 357.5 feet (109 meters)
- Solar Array Length: 239.4 feet (73 meters)

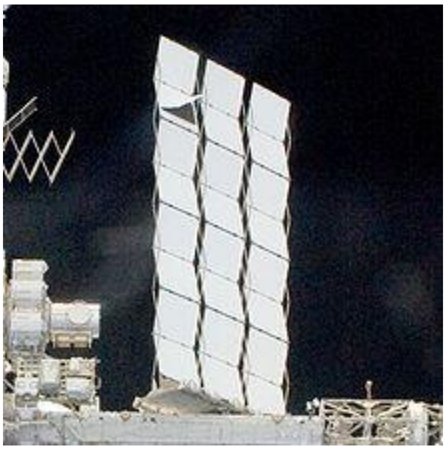
- Mass: 924,739 pounds (419,455 kilograms)
- Habitable Volume: 13,696 cubic feet (388 cubic meters)
- Pressurized Volume: 32,333 cubic feet (916 cubic meters)
- Power Generation: 8 solar arrays = 84 kilowatts
- Lines of Computer Code: approximately 2.3 million

Since construction started, the International Space Station (ISS) programme has had to deal with several maintenance issues, unexpected problems and failures. These incidents have affected the assembly timeline, led to periods of reduced capabilities of the station and in some cases could have forced the crew to abandon the space station for safety reasons, had these problems not been resolved.

2009 – Potential ammonia leak from S1 radiator due to damaged panel

2010 – Failure in cooling loop A

2009 – Potential ammonia leak from S1 radiator due to damaged panel



The damaged S1 radiator on the ISS starboard truss.

The S1-3 radiator has a damaged cooling panel that may require on-orbit repair or replacement, as the damage may have the potential to create a leak in the External Thermal Control System (ETCS) of the station, possibly leading to unacceptable loss of the ammonia coolant.

There are six such radiators, three on the starboard truss, and three on the port truss, each consisting of 8 panels. They appear as the large white pleated objects extending in the aft direction from the trusses, between the central habitable modules and the large solar panel arrays at the ends of the truss structure, and control the temperature of the ISS by dumping excess heat to space. The panels are double-sided, and radiate from both sides, with ammonia circulating between the top and bottom surfaces.

The problem was first noticed in Soyuz imagery in September 2008, but was not thought to be serious. The imagery showed that the surface of one sub-panel has peeled back from the underlying central structure, possibly due to micro-meteoroid or debris impact. It is also known that a Service Module thruster cover, jettisoned during a spacewalk in 2008, had struck the S1 radiator, but its effect, if any, has not been determined. Further imagery during the fly-around from STS-119 raised concerns that structural fatigue, due to thermal cycling stress, could cause a serious leak to develop in the ammonia cooling loop, although there is as yet no evidence of a leak or of degradation in the thermal performance of the panel. Various options for repair are under consideration, including replacement of the entire S1 radiator in a future flight, possibly with return of the damaged unit to ground for detailed study.

On 15 May 2009, the damaged radiator panel's ammonia tubing was mechanically shut off from the ETCS, by the computer-controlled closure of a valve. The same valve was used immediately afterwards to vent the ammonia from the damaged panel. This eliminates the possibility of an ammonia leak from the cooling system via the damaged panel.

2010 – Failure in cooling loop A

Early on 1 August 2010, a failure in cooling Loop A (starboard side), one of two external cooling loops, left the station with only half of its normal cooling capacity and zero redundancy in some systems. The problem appeared to be in the ammonia pump module that circulates the ammonia cooling fluid. Several subsystems, including two of the four CMGs, were shut down. The failed ammonia pump was returned to Earth during STS-135 to undergo root cause failure analysis.

Planned operations on the ISS were interrupted through a series of EVAs to address the cooling system issue. A first EVA on Saturday, 7 August 2010, to replace the failed pump module, was not fully completed due to an ammonia leak in one of four quick-disconnects. A second EVA on Wednesday, 11 August, successfully removed the failed pump module. A third EVA was required to restore Loop A to normal functionality.

Stochastic behavior of systems operating under changing environments has widely been studied. Dhillon , B.S. and Natesan, J. (1983) studied an outdoor power systems in fluctuating environment . Kan Cheng (1985) has studied reliability analysis of a system in a randomly changing environment. Jinhua Cao (1989) has studied a man machine system operating under changing environment subject to a Markov process with two states. The change in operating conditions viz. fluctuations of voltage, corrosive atmosphere, very low gravity etc. may make a system completely inoperative. Severe environmental conditions can make the actual mission duration longer than the ideal mission duration. In this paper we have taken **failure due to Potential ammonia leak from S1 radiator due to damaged panel or failure due to Failure in cooling loop A.** When the main operative unit fails then cold standby system becomes operative. Failure due to Failure in cooling loop A cannot occur simultaneously in both the units and after failure the unit undergoes repair facility of very high cost in case of failure due to Potential ammonia leak from S1 radiator due to damaged panel immediately. The repair is done on the basis of first fail first repaired.

Assumptions

1. $\lambda_{1,}\ \lambda_2$ are constant failure rates for failure due to Potential ammonia leak from S1 radiator due to damaged panel, failure due to Failure in cooling loop A respectively. The CDF of repair time distribution of Type I and Type II are $G_1(t)$ and $G_2(t)$.
2. The failure due to Failure in cooling loop A is non-instantaneous and it cannot come simultaneously in both the units.
3. The repair starts immediately after failure due to Potential ammonia leak from S1 radiator due to damaged panel or the failure due to collision and works on the principle of first fail first repaired basis.
4. The repair facility does no damage to the units and after repair units are as good as new.
5. The switches are perfect and instantaneous.
6. All random variables are mutually independent.
7. When both the units fail, we give priority to operative unit for repair.
8. Repairs are perfect and failure of a unit is detected immediately and perfectly.
9. The system is down when both the units are non-operative.

Notations

$\lambda_{1\,,}\ \lambda_2$ - failure rates for failure due to Potential ammonia leak from S1 radiator due to damaged panel, failure due to Failure in cooling loop A respectively.

$G_1(t)$, $G_2(t)$ – repair time distribution Type –I or Type-II due to Potential ammonia leak from S1 radiator due to damaged panel, due to Failure in cooling loop A respectively.

p, q - probability of failure due to Potential ammonia leak from S1 radiator due to damaged panel, failure due to Failure in cooling loop A respectively such that p+ q=1

$M_i(t)$ System having started from state i is up at time t without visiting any other regenerative state

$A_i(t)$ state is up state at instant t

R_i (t) System having started from state i is busy for repair at time t without visiting any other regenerative state.

$B_i(t)$ the server is busy for repair at time t.

$H_i(t)$ Expected number of visits by the server for repairing given that the system initially starts from regenerative state i

Symbols for states of the System

Superscripts O, CS, PALF, CLF,

Operative, Cold Standby, failure due to Potential ammonia leak from S1 radiator due to damaged panel or failure due to Failure in cooling loop A respectively

Subscripts npalf, palf, clf, ur, wr, uR

No failure due to Potential ammonia leak from S1 radiator due to damaged panel, failure due to Potential ammonia leak from S1 radiator due to damaged panel, failure due to Failure in cooling loop A, under repair, waiting for repair, under repair continued from previous state respectively

Up states – 0, 1, 2, 7, 8;

Down states – 3, 4, 5, 6

regeneration point – 0,1,2, 7, 8

States of the System

0(O_{npalf}, CS_{npalf})

One unit is operative and the other unit is cold standby and there is no failure due to Potential ammonia leak from S1 radiator due to damaged panel in both the units.

1($PALF_{palf,\,ur}$, O_{npalf})

The operating unit fails due to failure due to Potential ammonia leak from S1 radiator due to damaged panel and is under repair immediately of very costly Type- II and standby unit starts operating with no launch failure

2($CLF_{clf,\,ur}$, O_{npalf})

The operative unit fails due to Collision and undergoes repair of type I and the standby unit becomes operative with no failure due to Potential ammonia leak from S1 radiator due to damaged panel

3($CLF_{clf,\,uR}$, $PALF_{palf,\,wr}$)

The first unit fails due to Failure in cooling loop A and under very costly Type-I repair is continued from state 1 and the other unit fails due to PALF resulting from Failure due to Potential ammonia leak from S1 radiator due to damaged panel and is waiting for repair of Type - II.

4($PALF_{palf,uR}$, $PALF_{palf,wr}$)

The repair of the unit is failed due to PALF resulting from Failure due to Potential ammonia leak from S1 radiator due to damaged panel is continued from state 1and the other unit failed due to PALF resulting from Failure due to Potential ammonia leak from S1 radiator due to damaged panel is waiting for repair of Type-II.

5($CLF_{clf, uR}$, $CLF_{clf, wr}$)

The operating unit fails due to Failure in cooling loop A and under repair of Type – I continue from the state 2 and the other unit fails also due to Failure in cooling loop A is waiting for repair of Type- I.

6($CLF_{clf, uR}$, $PALF_{palf ,wr}$)

The operative unit fails due to Failure in cooling loop A and under repair continues from state 2 of Type –I and the other unit is failed due to PALF resulting from Failure due to Potential ammonia leak from S1 radiator due to damaged panel and under very costly Type-II

7(O_{npalf} , $PALF_{palf,ur}$)

The one unit is operative with no Failure due to Potential ammonia leak from S1 radiator due to damaged panel and the other unit failed due to PALF resulting from Failure due to Potential ammonia leak from S1 radiator due to damaged panel is under repair of Type-II

8(O_{npalf} , $CLF_{clf, ur}$)

The one unit is operative with no Failure due to Potential ammonia leak from S1 radiator due to damaged panel and the other unit is failed due to collision is under very costly repair of Type-I.

Transition Probabilities

Simple probabilistic considerations yield the following expressions:

$p_{01} = p$, $p_{02} = q$,

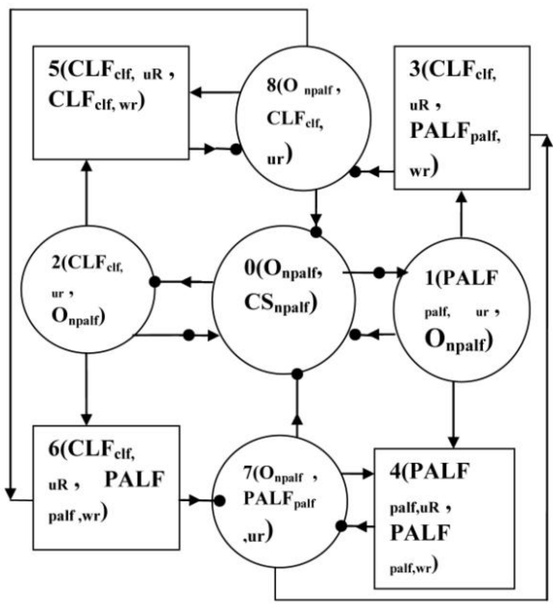


Fig. The State Space Diagram

up state down state

regeneration point

$p_{10} = pG_1^*(\lambda_1)+q\, G_1^*(\lambda_2) = p_{70}$,

$p_{20} = pG_2^*(\lambda_1)+q\, G_2^*(\lambda_2) = p_{80}$,

$p_{11}^{(3)} = p(1- G_1^*(\lambda_1)) = p_{14} = p_{71}^{(4)}$, $p_{28}^{(5)} = q(1- G_2^*(\lambda_2)) = p_{25} = p_{82}^{(5)}$ (1)

We can easily verify that

$p_{01} + p_{02} = 1$,

$p_{10} + p_{17}^{(4)} (= p_{14}) + p_{18}^{(3)} (= p_{13}) = 1$,

$p_{80} + p_{82}^{(5)} + p_{87}^{(6)} = 1$ (2)

And mean sojourn time is

$\mu_0 = E(T) = \int_0^\infty P[T > t]dt$

Mean Time To System Failure

$Ø_0(t) = Q_{01}(t)[s]\, Ø_1(t) + Q_{02}(t)[s]\, Ø_2(t)$

$Ø_1(t) = Q_{10}(t)[s]\, Ø_0(t) + Q_{13}(t) + Q_{14}(t)$

$Ø_2(t) = Q_{20}(t)[s]\, Ø_0(t) + Q_{25}(t) + Q_{26}(t)$ (3-5)

We can regard the failed state as absorbing

Taking Laplace-Stiljes transform of eq. (3-5) and solving for

$ø_0^*(s) = N_1(s) / D_1(s)$ (6)

where

$N_1(s) = Q_{01}^*[Q_{13}^*(s) + Q_{14}^*(s)] +$

$Q_{02}^*[Q_{25}^*(s) + Q_{26}^*(s)]$

$D_1(s) = 1 - Q_{01}^*\, Q_{10}^* - Q_{02}^*\, Q_{20}^*$

Making use of relations (1) & (2) it can be shown that $ø_0^*(0) = 1$, which implies that $ø_0(t)$ is a proper distribution.

$$MTSF = E[T] = \left. \frac{d}{ds}\, ø_0^*(s) \right|_{s=0}$$

$= (D_1'(0) - N_1'(0)) / D_1(0)$

$= (\mu_0 + p_{01}\, \mu_1 + p_{02}\, \mu_2) / (1 - p_{01}\, p_{10} - p_{02}\, p_{20})$

where

$\mu_0 = \mu_{01} + \mu_{02}$,

$\mu_1 = \mu_{01} + \mu_{17}^{(4)} + \mu_{18}^{(3)}$,

$\mu_2 = \mu_{02} + \mu_{27}^{(6)} + \mu_{28}^{(5)}$

Availability analysis

Let $M_i(t)$ be the probability of the system having started from state i is up at time t without making any other regenerative state. By probabilistic arguments, we have

$M_0(t) = e^{-\lambda_1 t} e^{-\lambda_2 t}$, $M_1(t) = p\, G_1(t)\, e^{-(\lambda_1+\lambda_2)} = M_7(t)$

$M_2(t) = q\, \overline{G_2(t)}\, e^{-(\lambda_1+\lambda_2)} = M_8(t)$

The point wise availability $A_i(t)$ have the following recursive relations

$A_0(t) = M_0(t) + q_{01}(t)[c]A_1(t) + q_{02}(t)[c]A_2(t)$

$A_1(t) = M_1(t) + q_{10}(t)[c]A_0(t) + q_{18}^{(3)}(t)[c]A_8(t) + q_{17}^{(4)}(t)[c]A_7(t)$,

$A_2(t) = M_2(t) + q_{20}(t)[c]A_0(t) + [q_{28}^{(5)}(t)[c]\ A_8(t) + q_{27}^{(6)}(t)]\ [c]A_7(t)$

$A_7(t) = M_7(t) + q_{70}(t)[c]A_0(t) + [q_{71}^{(4)}(t)[c]\ A_1(t) + q_{78}^{(3)}(t)]\ [c]A_8(t)$ $A_8(t) = M_8(t) + q_{80}(t)[c]A_0(t) + [q_{82}^{(5)}(t)[c]\ A_2(t) + q_{87}^{(6)}(t)]\ [c]A_7(t)$ (7-11)

Taking Laplace Transform of eq. (7-11) and solving for $\hat{A}_0(s)$

$\hat{A}_0(s) = N_2(s) / D_2(s)$ (12)

where

$N_2(s) = \hat{M}_0 (1 - \hat{q}_{78}^{(3)} - \hat{q}_{87}^{(6)})-$

$\hat{q}_{82}^{(5)}(\hat{q}_{27}^{(6)} \hat{q}_{78}^{(3)} + \hat{q}_{28}^{(5)} - \hat{q}_{71}^{(4)}$

$(\hat{q}_{17}^{(4)} + \hat{q}_{87}^{(6)} \hat{q}_{18}^{(3)}) + \hat{q}_{71}^{(4)} \hat{q}_{82}^{(5)} (\hat{q}_{17}^{(4)} - \hat{q}_{27}^{(6)} \hat{q}_{18}^{(3)})] + \hat{q}_{01}[\hat{M}_1(1 -$

$\hat{q}_{78}^{(3)} \hat{q}_{87}^{(6)}) + \hat{q}_{71}^{(4)}(\hat{M}_7 + \hat{q}_{78}^{(3)}$

$\hat{M}_8) + \hat{q}_{18}^{(3)}(\hat{M}_7 \hat{q}_{87}^{(6)} - \hat{M}_8)-$

$\hat{q}_{82}^{(5)}(\hat{M}_1(\hat{q}_{27}^{(6)} \hat{q}_{78}^{(3)} + \hat{q}_{28}^{(5)})+$

$\hat{q}_{17}^{(4)} (-\hat{M}_2(\hat{q}_{78}^{(3)} + \hat{M}_7 \hat{q}_{28}^{(5)})-$

$\hat{q}_{18}^{(3)}(\hat{M}_2 + \hat{M}_7 \hat{q}_{27}^{(6)})\}] \hat{q}_{02}[\hat{M}_2(1 - \hat{q}_{78}^{(3)} \hat{q}_{87}^{(6)}) + \hat{q}_{27}^{(6)}($

$\hat{M}_7 + \hat{q}_{78}^{(3)} \hat{M}_8) + \hat{q}_{28}^{(5)}(\hat{M}_7$

$\hat{q}_{87}^{(6)} + \hat{M}_8) - \hat{q}_{71}^{(4)}(\hat{M}_1(- \hat{q}_{27}^{(6)} -$

$\hat{q}_{28}^{(5)} + \hat{q}_{87}^{(6)}) + \hat{q}_{17}^{(4)} (\hat{M}_2 + \hat{q}_{28}^{(5)}$

$\hat{M}_8) - \hat{q}_{18}^{(3)} (- \hat{M}_2 \hat{q}_{87}^{(6)} + \hat{M}_8$

$\hat{q}_{27}^{(6)})\}] \hat{q}_{18}^{(3)}(\hat{M}_2 + \hat{M}_7 \hat{q}_{27}^{(6)})\}]$

$D_2(s) = (1 - \hat{q}_{78}^{(3)} - \hat{q}_{87}^{(6)}) - \hat{q}_{82}^{(5)}($

$\hat{q}_{27}^{(6)} \hat{q}_{78}^{(3)} + \hat{q}_{28}^{(5)}) - \hat{q}_{71}^{(4)}$

$(\hat{q}_{17}^{(4)} + \hat{q}_{87}^{(6)} \hat{q}_{18}^{(3)}) + \hat{q}_{71}^{(4)} \hat{q}_{82}^{(5)} (\hat{q}_{17}^{(4)} \hat{q}_{28}^{(5)} - \hat{q}_{18}^{(3)})] + \hat{q}_{01}[- \hat{q}_{10} (1 -$

$\hat{q}_{78}^{(3)} \hat{q}_{87}^{(6)}) - \hat{q}_{71}^{(4)}(\hat{q}_{70} + \hat{q}_{78}^{(3)}$

$\hat{q}_{80}) - \hat{q}_{18}^{(3)}(\hat{q}_{70} \hat{q}_{87}^{(6)} - \hat{q}_{80})-$

$\hat{q}_{82}^{(5)}(- \hat{q}_{10}(\hat{q}_{27}^{(6)} \hat{q}_{78}^{(3)} + \hat{q}_{28}^{(5)})+$

$\hat{q}_{17}^{(4)} (\hat{q}_{20} (\hat{q}_{78}^{(3)} - \hat{q}_{70} \hat{q}_{28}^{(5)})+$

$\hat{q}_{18}^{(3)}(\hat{q}_{20} + \hat{q}_{70} \hat{q}_{27}^{(6)})\}] \hat{q}_{02}[- \hat{q}_{20}(1 - \hat{q}_{78}^{(3)} \hat{q}_{87}^{(6)}) - \hat{q}_{27}^{(6)}(\hat{q}_{70} + \hat{q}_{78}^{(3)}$

$\hat{q}_{80}) - \hat{q}_{28}^{(5)}(\hat{q}_{70} \hat{q}_{87}^{(6)} + \hat{q}_{80}) - \hat{q}_{71}^{(4)}(\hat{q}_{10} (\hat{q}_{27}^{(6)} + \hat{q}_{28}^{(5)} \hat{q}_{87}^{(6)}) - \hat{q}_{17}^{(4)} (\hat{q}_{20} - \hat{q}_{28}^{(5)} \hat{q}_{80}) - \hat{q}_{18}^{(3)} (\hat{q}_{20} \hat{q}_{87}^{(6)} +$

$\hat{q}_{80} \hat{q}_{27}^{(6)})\}]$

(Omitting the arguments s for brevity)

The steady state availability

$A_0 = \lim_{t\to\infty}[A_0(t)]$

$= \lim_{s\to 0}[s\,\hat{A}_0(s)] = \lim_{s\to 0}\frac{s\,N_2(s)}{D_2(s)}$

Using L' Hospitals rule, we get

$$A_0 = \lim_{s\to 0}\frac{N_2(s)+s\ N_2'(s)}{D_2'(s)} = \frac{N_2(0)}{D_2'(0)} \quad (13)$$

The expected up time of the system in (0,t] is

$\lambda_u(t) = \int_0^{\infty} A_0(z)dz$

\So that $\bar{\lambda}_u(s) = \frac{\hat{A}_0(s)}{s} = \frac{N_2(S)}{SD_2(S)}$ (14)

The expected down time of the system in (0,t] is

$\lambda_d(t) = t - \lambda_u(t)$

So that $\bar{\lambda}_d(s) = \frac{1}{s^2} - \bar{\lambda}_u(s)$ (15)

The expected busy period of the server when there is failure due to Failure in cooling loop A or failure due to Potential ammonia leak from S1 radiator due to damaged panel in (0,t]

$R_0(t) = q_{01}(t)[c]R_1(t) + q_{02}(t)[c]R_2(t)$

$R_1(t) = S_1(t) + q_{10}(t)[c]R_0(t) + q_{18}^{(3)}(t)[c]\ R_8(t) + q_{17}^{(4)}(t)[c]R_7(t)$

$R_2(t) = S_2(t) + q_{20}(t)[c]R_0(t) + q_{28}^{(5)}(t)\ R_8(t) + q_{27}^{(6)}(t)][c]R_7(t)$

$R_7(t) = S_7(t) + q_{70}(t)[c]R_0(t) + Q_{71}^{(4)}(t)\ R_1(t) + q_{78}^{(3)}(t)][c]R_8(t)$

$R_8(t) = S_8(t) + q_{80}(t)[c]R_0(t) + Q_{82}^{(5)}(t)\ R_2(t) + q_{87}^{(6)}(t)][c]R_7(t)$ (16-20)

Taking Laplace Transform of eq. (16-20) and solving for $\bar{R}_0(s)$

$\bar{R}_0(s) = N_3(s) / D_2(s)$ (21)

where

$N_3(s) = \hat{q}_{01}[\hat{S}_1(1 - \hat{q}_{78}^{(3)} \hat{q}_{87}^{(6)}) + \hat{q}_{71}^{(4)}(\hat{S}_7 + \hat{q}_{78}^{(3)} \hat{S}_8) + \hat{q}_{18}^{(3)}(\hat{S}_7$

$\hat{q}_{87}^{(6)} - \hat{S}_8)] - \hat{q}_{01} \hat{q}_{82}^{(5)}(\hat{S}_1 \hat{q}_{27}^{(6)} \hat{q}_{78}^{(3)} + \hat{q}_{28}^{(5)}) + \hat{q}_{17}^{(4)} (\hat{S}_2 \hat{q}_{78}^{(3)} + \hat{S}_7 \hat{q}_{28}^{(5)})-$

$\hat{q}_{18}^{(3)}(\hat{S}_2+\hat{S}_7\hat{q}_{27}^{(6)})]+\hat{q}_{02}[\hat{S}_2(1-\hat{q}_{78}^{(3)}\ \hat{q}_{87}^{(6)})+\hat{q}_{27}^{(6)}(\hat{S}_7+\hat{q}_{78}^{(3)}\hat{S}_8)+\hat{q}_{28}^{(5)}(\hat{S}_7\ \hat{q}_{87}^{(6)}+\hat{S}_8)-\hat{q}_{02}\hat{q}_{71}^{(4)}(\hat{S}_1(-\hat{q}_{27}^{(6)}-\hat{q}_{28}^{(5)}\ \hat{q}_{87}^{(6)}\ \hat{q}_{17}^{(4)}(\hat{S}_2+\hat{q}_{28}^{(5)}\hat{S}_8)-\hat{q}_{18}^{(3)}(-\hat{S}_2\ \hat{q}_{87}^{(6)}+\hat{S}_8\ \hat{q}_{27}^{(6)})]$

and

$D_2(s)$ is already defined.

(Omitting the arguments s for brevity)

In the long run, $R_0 = \dfrac{N_3(0)}{D_2'(0)}$ (22)

The expected period of the system under failure due to Failure in cooling loop A or failure due to Potential ammonia leak from S1 radiator due to damaged panel is

$\lambda_{rv}(t) = \int_0^\infty R_0(z)dz$ So that $\bar{\lambda}_{rv}(s) = \dfrac{\hat{R}_0(s)}{s}$

The expected number of visits by the repairman for repairing the identical units in (0,t]

$H_0(t) = Q_{01}(t)[s][1+H_1(t)] +$

$Q_{02}(t)[s][1+H_2(t)]$

$H_1(t) = Q_{10}(t)[s]H_0(t)] + Q_{18}^{(3)}(t)[s]$

$H_8(t) + Q_{17}^{(4)}(t)]\ [s]H_7(t)$,

$H_2(t) = Q_{20}(t)[s]H_0(t) + Q_{28}^{(5)}(t)\ [s]$

$H_8(t) + Q_{27}^{(6)}(t)]\ [c]H_7(t)$

$H_7(t) = Q_{70}(t)[s]H_0(t) + Q_{71}^{(4)}(t)\ [s]$

$H_1(t) + Q_{78}^{(3)}(t)]\ [c]H_8(t)$

$H_8(t) = Q_{80}(t)[s]H_0(t) + Q_{82}^{(5)}(t)\ [s]$

$H_2(t) + Q_{87}^{(6)}(t)]\ [c]H_7(t)$ (23-27)

Taking Laplace Transform of eq. (23-27) and solving for $H_0^*(s)$

$H_0^*(s) = N_4(s) / D_3(s)$ (28)

In the long run,

$H_0 = N_4(0) / D_3'(0)$ (29)

Benefit- Function Analysis

The Benefit-Function analysis of the system considering mean up-time, expected busy period of the system under failure due to Failure in cooling loop A or failure due to Potential ammonia leak from S1 radiator due to damaged panel, expected number of visits by the repairman for unit failure.

The expected total Benefit-Function incurred in (0,t] is

C(t) = Expected total revenue in (0,t]

- expected busy period of the system under failure due to Failure in cooling loop A or failure due to Potential ammonia leak from S1 radiator due to damaged panel for repairing the units in (0,t]

- expected number of visits by the repairman for repairing of identical the units in (0,t]

The expected total cost per unit time in steady state is

$C = \lim_{t\to\infty}(C(t)/t)$

$= \lim_{s\to 0}(s^2C(s))$

$= K_1A_0 - K_2R_0 - K_3H_0$

where

K_1 - revenue per unit up-time,

K_2 - cost per unit time for which the system is under repair of type- I or type- II

K_3 - cost per visit by the repairman for units repair.

CONCLUSION

After studying the system, we have analyzed graphically that when the failure rate failure due to Failure in cooling loop A or failure due to Potential ammonia leak from S1 radiator due to damaged panel increases, the MTSF, steady state availability decreases and the Profit-function decreased as the failure increases.

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