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Reliability Consideration of Thin-Film Temperature Sensors in Future Space Shuttle Propulsion Systems

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The paper investigates the failure modes of the thin-film thermocouple high-temperature sensors being newly developed and analyzes theoretically the probabilistic risks of flying the Space Shuttle equipped with such new sensors with and without fuel turbine discharge temperature "redline" protection. Newly observed facts include a new failure mode not associated with the existing thermistor-type sensors and a probability risk math model with three sensors per turbopump. The probability of erroneous engine shutdown is significantly reduced from the existing 37.94$E-5$ to 1.85$E-5$; thus, a better Shuttle engine reliability may be achieved.

Nomenclature

a	= one parameter of Weibull distribution in seconds to the power of $-b$
b	= another parameter of Weibull distribution, a constant
D	= event that a failing sensor is disqualified
E	= event that a failing sensor erroneously votes to cut
FD	= failure rate or probability for event D
FE	= failure rate or probability for event E
FT	$= FD + FE + FU$
FU	= failure rate or probability for event U
H	= event of fuel/oxygen turbopump overtemperature
PE	= probability of an erroneous engine shutdown for one Space Shuttle main engine
PU	= probability of an undetected turbine overtemperature for one Space Shuttle main engine
Pxx	= probability for state xx
_U_E_D_H_	= state figure that means that after the launch firing starts, ___ seconds later a failing sensor underreports, some time ___ later a second sensor erroneously votes to cut, then a third one is ___ later disqualified, and then ___ later a fuel turbine overtemperature event occurs until the duration of a typical launch firing ($T = 520$ s)
U	= event that a failing sensor underreports a real overtemperature as an operable one
xi	= some arbitrary time, s, $i = 1, \ldots, 4$
t	= time interval, s

Introduction

THE Space Shuttle main engine (SSME) turbopumps—the high-pressure fuel turbopump (HPFT) and the high-pressure oxygen pump (HPOT)—are subjected to rapid and extreme thermal transients.[1] They are critical to liftoff and all of the way through nominal main engine cutoff (MECO). During the shuttle's ascent, a premature main engine shutdown can cause a mission abort that is unsafe. On the other hand, launch without protection against a turbine overtemperature event, which is symptomatic of impending catastrophe, is not a safe condition either.

Operation of the SSME in the presence of possible overtemperature events and temperature sensor failures entails a measurable risk. Such risk must be analyzed and has been analyzed[2] for the existing SSME HPFT using the present thermistor-type temperature sensors, models 71 and 81, called resistance temperature devices (RTDs), two for each HPFT or HPOT.[3,4] Unfortunately, these sensors have a history of unreliability during both ground test and flight.[2] For a more reliable and safer space propulsion system in the future, NASA and the Department of Energy (DOE) have been developing a new technology related to thin-film thermocouple (TFTC)[5-7] to replace the existing RTD. Initial results with coupons of MAR-246 and PWA 1480 have been followed by fabrication of TFTCs on SSME turbine blades. Preparations are being made for testing in the turbine blade tester at the NASA George C. Marshall Space Flight Center.[8]

Estimation of the risks requires consideration of the reliability of the temperature sensors, the HPFT/HPOT relative to overheating, and the computer voting logic in the presence of all possible failure scenarios of the sensors and the turbines. This paper investigates the failure modes of the new TFTC sensors and theoretically analyzes the probabilistic risk of flying a Space Shuttle with and without turbine discharge temperature "redline" protection when the new sensors are used. (Redline is the space engine protection shutdown logic to deactivate the main engine when measured temperature rises above a preset level during launch or does not reach a preset level during startup. The two RTD sensors used in one HPFT are used within the SSME control and monitoring system by this logic to shut down the engine in trouble. For the engine protection shutdown logic to be tripped, an event referred to as "vote to cut," the temperature must remain in the critical region for at least 40 ms.) Since such a TFTC temperature sensor is still in the development phase, no probabilistic risk analysis (PRA) has appeared yet in the literature for the SSME with HPFT/HPOT using TFTC temperature sensors, except some preliminary study by the author in 1988.

The paper first describes the degradation mechanism of these new TFTC sensors. Then a system modeling application for the aforementioned PRA is proposed. As a byproduct, a new failure mode U has been discovered for the system. This failure mode has been incorporated into the reliability modeling. Field data for SSME tests with the existing RTD sensors[2,9] upon modification along with an assumed failure rate for the new failure mode, "underreport," of the new sensor are used for numerical calculation for illustration purposes only.

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Degradation Mechanism of Thin-Film Thermocouple Temperature Sensors

Based on the information available about TFTC high-temperature sensors in the SSME environment, the failure modes or states of this new device may be conjectured as follows.

A platinum (Pt) vs Pt plus 13% rhodium (Rh) TFTC sensor was designed and tested in the harsh, high-temperature environment of a ceramic-insulated, low-heat-rejection diesel engine.[6] The thin-film sensor performed reliably during 6–10 h of repeated engine runs at indicated mean surface temperatures as high as 950 K. However, the sensor exhibited partial loss of adhesion in the TFTC junction area following maximum cyclic temperature excursions to greater than 1150 K. The sputtered thin film of Pt apparently blistered, whereas the film of Pt plus 13% Rh showed no visible anomaly, a result of Pt film separated from the underlying aluminum oxide layer. (The underlying aluminum oxide layer adhered well to the zirconia substrate. Efforts to improve adhesion of Pt film are under way. The TFTC so fabricated survived the thermal shock cycling test.[8])

In addition, continual use of types R and S thermocouples at high temperatures will cause excessive grain growth that can result in mechanical failure of the Pt element.[7,10-13] It also renders the Pt susceptible to contamination, which causes negative drift in calibration; that is, a reduction in the emf output of the thermocouple. Calibration changes also may be caused by diffusion of Rh from alloy into the Pt or by volatilization of Rh from the alloy. Furthermore, positive thermal elements in types S and R are unstable to radiation transmutation because of the rapid depletion of Rh. Essentially, all of the Rh will be converted to palladium in a 10-yr period. Besides these elements, the use of dissimilar metals for external connections also can increase the possibility of electrochemical attack of the thin films and thereby can increase the interconnection contact resistance.[13]

All of these previously mentioned failure mechanisms will introduce a false temperature indication that will either overreport an operable temperature as an overtemperature, causing erroneous engine shutdown, or underreport a real overtemperature as an operable temperature, causing engine overheating. This failure mechanism never existed in the existing RTD sensors. Fortunately, overreporting temperature beyond the redline upper limit may be treated in the same way as one of the failure modes of the existing RTD sensors, erroneous vote to cut E.[2] However, underreporting temperature is an additional case that needs to be studied and analyzed. As a result, a new failure mode is introduced in the failure analysis of TFTC high-temperature sensors to be used in the SSME environment that may be called underreport U. The two other failure modes of the existing RTD temperature sensors,[2] i.e., disqualified D, and erroneous vote to cut E, will also be inherited by this new type of thin-film sensor. A failing sensor with a reading recognized as being impossible (i.e., greater than 2900°R; refer to p. 16 of Ref. 12 for broken thermocouple safety devices) is immediately recognized as being bad by the computer and is disqualified, a state that is henceforth ignored by the computer. A failing sensor can also read an erroneous temperature that drifts into the redline region for more than 40 ms and, thus, trips the redline logic that produces a vote to cut. During this time, the sensor is still classified as good, and its reading is thus falsely interpreted as warning of an overtemperature event and, if the other sensors have already been disqualified or failed, would result in an erroneous engine shutdown. Therefore, in total, three failure modes (U, E, and D) exist with thin-film sensors.

Since the three or more redundant thin-film temperature sensors on turbine blades can be provided for a single turbine and thin-film devices on the turbine blades revolve with the turbine blades in the exhaust gas of the HPFT or the HPOT to provide more accurate and uniform gas temperature readings, the overall risk for undetected SSME overtemperature or erroneous SSME shutdown may quite possibly be reduced. Therefore, the overall SSME reliability may be enhanced. For easy demonstration in this paper, three TFTC sensors are assumed to be used per one HPFT.

As in the PRA for SSMEs with two thermistor-type RTD sensors,[2] the computer voting logic considers the sequence in which failures occur, and the time required by the computer to classify a failing sensor as being either good or bad is crucial; therefore, the analysis must include the chronological variable time as well. The reliability model for a single SSME with three sensors of three failure modes each in the HPFT will be developed. This result will then be used to compute the reliability of the Space Shuttle three-engine configuration. Since

Table 1 All possible states and the computer voting logic

State figures[a]				Computer decision	Comments
1, _				CTF	Nominal state
2, H ; 15, E D H ;	4, D H ; 72, D E H ;	6, E H ; 73, E E H ;	10, D D H ;	SD	Correct decision
43, E D E ;	53, D D E ;	65, D E E ;	70, E E E ;	SD	Erroneous shutdown
3, D ; 11, D E ; 17, E U ;	5, E ; 12, D U ; 19, U D ;	7, U ; 14, E D ; 21, U E ;	9, D D ; 16, E E ; 23, U U ;	CTF	Loss of redundancy
8, U H ; 22, U E H ; 31, U E D H ; 40, U U U H ; 50, E U U H ; 60, D U U H ; 69, E E U H ; 76, D U E H ;	13, D U H ; 24, U U H ; 34, U E U H ; 42, E D D H ; 52, D D D H ; 62, D E D H ; 71, U D E H ;	18, E U H ; 26, U D D H ; 36, U U D H ; 45, E D U H ; 55, D D U H ; 64, D E U H ; 74, U E E H ;	20, U D H ; 29, U D U H ; 38, U D E H ; 47, E U D H ; 57, D U D H ; 67, E E D H ; 75, E U E H ;	CTF	Undetected hot fuel turbine
25, U D D ; 32, U E E ; 39, U U U ; 48, E U E ; 56, D U D ; 63, D E U ;	27, U D E ; 33, U E U ; 41, E D D ; 49, E U U ; 58, D U E ; 66, E E D ;	28, U D U ; 35, U U D ; 44, E D U ; 51, D D D ; 59, D U U ; 68, E E U ;	30, U E D ; 37, U U E ; 46, E U D ; 54, D D U ; 61, D E D ;	CTF	Flying without protection

[a]For the meaning of the state figures, see the explanation of the state figure of state no. 31 given in the Nomenclature and the section titled Mathematical Model. The remaining figures can be described in a similar way.

Table 2 Construction of $P31(T)$ using the compound-event approach

1) Time interval in seconds for compound event of state no. 31 with $T = 520$ s

No failure	First failure (underreport) U	No failure	Second failure (erroneous vote to cut) E	No failure	Third failure (disqualified) D	No failure	Fourth failure (overtemperature) H	
$t=0$	x_1	x_1+dx_1	x_2	x_2+dx_2	x_3	x_3+dx_3	x_4	x_4+dx_4 T

2) Construction of $P31(T)$

Let $FT = FU + FE + FD$

$$P31(T) = \int_0^T \int_0^{x_2} \int_0^{x_3} \int_0^{x_4} [e^{-3(FT)x_1}]\,(3FU\,dx_1)\,[e^{-2(FT)(x_2-x_1)}]\,(2FE\,dx_2)\,[e^{-(FT)(x_3-x_2)}]\,(FD\,dx_3)\,[e^{-a(x_4)^b}]\,\{[ab(x_4)^{(b-1)}\,dx_4]\}$$

$[e^{-3(FT)x_1}]$	Probability of no sensor failure to x_1
$(3FU\,dx_1)$	Probability of an underreport in dx_1
$[e^{-2(FT)(x_2-x_1)}]$	Probability of no sensor failure from x_1 to x_2
$(2FE\,dx_2)$	Probability of an erroneous vote to cut in dx_2
$[e^{-(FT)(x_3-x_2)}]$	Probability of no sensor failure from x_2 to x_3
$(FD\,dx_3)$	Probability of a sensor being disqualified in dx_3
$[e^{-a(x_4)^b}]$	Probability of no over-temperature event to x_4
$\{[ab(x_4)^{(b-1)}\,dx_4]\}$	Probability of HPFT/HPOT overtemperature event in dx_4

in the proposed new system three or more thin-film sensors may be used to provide redundancy, the new requirements for computer decision as shown in Table 1 will be upgraded as follows.

Each revolving thin-film sensor will provide more uniform and accurate measurement. If all three sensors are considered good by the computer, then the vote of three sensors to cut will be required to shut down the engine. Furthermore, if two sensors are considered good by the computer, then the vote of two sensors to cut will be required to shut down the engine. Finally, if only one sensor is considered good by the computer, of course, one vote to cut is needed to shut down the engine. In the proposed new TFTC sensor system, after a sensor underreports a temperature, the real overtemperature is undetected. This sensor failure cannot be recognized by the computer. Therefore, when a sensor is in this failure mode, it is not disqualified and is still considered good by the computer, which reads the actual overtemperature as being wthin redline limits. Using *D, E, U,* and *H* to represent, respectively, three failure modes of a sensor and a fuel turbine overtemperature event, we can see that there is a total of 76 possible system states. These states are depicted in column 1 of Table 1. The horizontal dash lines denote time in seconds and their sum T corresponds to the duration of a typical launch firing (which is about 520 s based on NASA field data for SSMEs). Column 2 of Table 1 gives the computer's decision for that state. This decision is either continue to fire (CTF) or shut down (SD). Column 3 contains comments relevant to the study; e.g., undetected hot HPFT. Note that for an HPFT turbine with 2 RTD sensors with only 2 failure modes each (disqualified and erroneous vote to cut) there are only 12 possible system states.[2]

Assumptions

To derive a set of equations that mathematically models the 76 states as depicted in Table 1, one must make the following assumptions about the probabilities associated with these failures. (See usage demonstrated in Table 2.)

1) For the three failure modes of the sensor (*D, E,* and *U*), the probability that a particular sensor is disqualified, or giving erroneous vote to cut, or providing underreport in time Δt is $FD\ \Delta t$, $FE\ \Delta t$, and $FU\ \Delta t$, respectively. Assuming an exponential distribution for the time to failure for such sensors implies a constant failure rate *FD,* or *FE,* or *FU.*

2) Sensor failures and turbine overtemperature events are statistically independent.

3) The time to failure probability distribution for an HPFT overtemperature event follows a Weibull distribution. The reason for choosing this two-parameter distribution is that it provides the flexibility to model the possibility that the hazard of an overtemperature is not necessarily constant; e.g., an overtemperature might be more likely to occur at the beginning of a mission rather than the end or vice versa.[2]

4) As for the existing system, a sensor that fails does not later recover and become operational again.

Mathematical Model

The compound-event approach,[14] which leads directly to multiple integral expressions for the state probabilities in terms of the system hazard, will be used for modeling. For the state no. 31 with symbol *UEDH*, the probability is derived such that a failing sensor underreports U first; sometime later, the second sensor erroneously votes to cut E; the third sensor is later disqualified D; and then sometime later, there is a fuel turbine overtemperature event H. This represents one of the 29 state probabilities that contribute to the probability of an overtemperature event going undetected. Assume that the first event (underreport U) occurs at some arbitrary time $= x_1$, the second sensor erroneously votes to cut E at time $t = x_2$, the third sensor is disqualified D at time $t = x_3$, and then there is an overtemperature event H at $t = x_4$, where $x_1 < x_2 < x_3 < x_4 <= 520$ s. Construction of the probability for state no. 31, $P31(T)$, is formalized in Table 2. The solution by first integrating with respect to x_1, then x_2, then x_3, and then x_4 is given in Table 3. The other 75 state probabilities can be derived in a similar way. When the appropriate estimated parameters are substituted into these equations, the desired probabilities may then be computed. The probability of an undetected HPFT turbine overtemperature event for one SSME engine is given by summing up the probabilities of 29 states as follows:

$$P8 + P13 + P18 + P20 + P22 + P24 + P26 + P29 + P31 + P34 + P36 + P38 + P40 + P42 + P45 + P47 + P50 + P52 + P55 + P57 + P60 + P62 + P64 + P67 + P69 + P71 + P74 + P75 + P76 = PU \quad (1)$$

Similarly, the probability of an erroneous engine shutdown event for one SSME engine is given by summing up the probabilities of four states as follows:

$$P43 + P53 + P65 + P70 = PE \quad (2)$$

One can see that $P43$, $P53$, $P65$, or $P70$ or the combined probability of each of the remaining 36 pairs is equal to a linear combination of 3 unique integrals, namely,

$$\int_0^T \exp(-ax^b)\exp(-FTx)\,\mathrm{d}x$$

$$\int_0^T \exp(-ax^b)\exp(-2FTx)\,\mathrm{d}x$$

$$\int_0^T \exp(-ax^b)\exp(-3FTx)\,\mathrm{d}x$$

except the combined probability of the pair $P1$ and $P2$, or $P1+P2$, which is

$$1-3FT\int_0^T \exp(-ax^b)\exp(-3FTx)\,\mathrm{d}x$$

Therefore, PU is equal to $[3+6(FE/FD)+3(FU/FD)+(FD/FU)+2(FE/FU)+3(FE/FD)(FU/FD)+(FE/FD)(FE/FU)+3(FE/FD)^2+(FU/FD)^2]$ times $P26$. And $P26$ is

$$(FU)(FD/FT)^2\Bigg(-\exp(aT^b)\{1-\exp[-(FT)T]\}^3/(FT) + \bigg\{\int_0^T \exp(-ax^b)\exp[-(FT)x]\,\mathrm{d}x - 2\int_0^T \exp(-ax^b)\exp[-2(FT)x]\,\mathrm{d}x + \int_0^T \exp(-ax^b)\exp[-3(FT)x]\,\mathrm{d}x\bigg\}\Bigg)$$

And PE is

$$[6(FE)(FD)(FE)/(FT)^2+3(FD)(FD)(FE)/(FT)^2+3(FE)^3/(FT)^2]$$
$$\times\bigg\{\int_0^T \exp(-ax^b)\exp[-(FT)x]\,\mathrm{d}x - 2\int_0^T \exp(-ax^b)\exp[-2(FT)x]\,\mathrm{d}x + \int_0^T \exp(-ax^b)\exp[-3(FT)x]\,\mathrm{d}x\bigg\}$$

Summing up the coefficients for each of the three unique integrals, one finds that the total coefficient for each integral is exactly zero. Therefore, the sum of the probabilities for all of the 76 states for one SSME equals 1 as it should.

Table 3 State probabilities[a]

State no.	Probability
31 $P31(T) = P_{UEDH}(T)$	

$$= -\frac{(FU)(FE)(FD)}{(FT)^2}\{[1-e^{(FT)T}]^3 e^{-a(T)^b}\} + \frac{3(FU)(FE)(FD)}{(FT)^3}\int_0^T [1-e^{-(FT)x}]^2 e^{-(FT)x} e^{-ax^b}\,\mathrm{d}x \quad (1)$$

$$= -(FU)(FE)(FD)\{1-\exp[-(FT)T]\}^3\exp(-aT^b)/(FT)^3] + [3(FU)(FE)(FD)/(FT)^3] \quad (2)$$

where[2] FE is estimated by the number of erroneous votes to cut originated by failing sensors in the HPFT divided by the cumulative time on both failed and unfailed HPFT sensors; FD and FU may be estimated similarly for disqualified and underreported failure modes, respectively.

Constants a and b are determined from the numerical solution of the two simultaneous equations in terms of a and b[2]:

$$a - R\Big/\left(\sum_{i=1}^{R} t_i^b + \sum_{j=1}^{S} t_j^b\right) = 0 \quad (3)$$

and

$$(R/b) + \left(\sum_{i=1}^{R} \ln t_i\right) - \left[R\Big/\left(\sum_{i=1}^{R} t_i^b + \sum_{j=1}^{S} t_j^b\right)\right]\left(\sum_{i=1}^{R} t_i^b \ln t_i + \sum_{j=1}^{S} t_j^b \ln t_j\right) = 0 \quad (4)$$

where S is the number of successful engine firings without HPFT overtemperature; R is the number of HPFT overtemperature occurrences that have the potential to occur during flight; t_i is the time of the ith HPFT overtemperature occurrence, $i = 1, 2, \ldots, R$; and t_j is the duration of the jth successful firing without HPFT overtemperature occurrences, $j = 1, 2, \ldots, S$.

[a]The probabilities for the remaining 75 states can be obtained in a similar way.

Numerical Examples

We use the failure rates FD and FE of one of the existing RTDs of model 71[2] and assume that the new TFTC sensors have the same failure rates, FD and FE. Furthermore, we assume that FU for the new sensors is equal to FE and that the Weibull parameters a and b are the same as those for the HPFT.

Then

FD = 8.293859 $E-5$ disqualified per second
FE = 1.5079744 $E-5$ erroneous cut per second
FU = 1.5079744 $E-5$ underreport per second
a = 3.25 $E-4$
b = 0.566

for the failure rate of HPFT overtemperature expressed in the Weibull form

$$z(t) = (ab)\,t^{(b-1)} \quad (3)$$

For a typical launch firing duration of 520 s, we have from the previous results derived from the equations in Table 3,

$$PU = 8.9987525E-5$$
$$PE = 1.8542084E-5$$

Comparing the previous results with the values of PU and PE calculated for the existing RTD sensors[2] of $0.5232E-5$ and $37.94E-5$, we see a significant improvement in reducing the probability of erroneous engine shutdown. The probability of not detecting an HPFT turbine overtemperature does not worsen much.

Conclusion

A promising more reliable future Space Shuttle with new thin-film thermocouple high-temperature sensors for HPFT/HPOT turbines is forthcoming. Further study in this field is needed, and the results of such development should be quickly updated as new sensors and fuel turbine life statistics become available.

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