In-orbit Failure Analysis and Verification for Thermistors outside Satellites

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Abstract: Satellite thermistor is used to measure the in-orbit temperature to support thermal control so that the on-board equipment can work in the appropriate temperature to get higher reliability and more life-time. In recent years, there have been several in-orbit failure events of thermistors outside the satellite, which have brought troubles to the thermal control of the whole satellite. In this paper, failure modes of in-orbit thermal resistors outside cabin are analyzed by fault tree, and ground simulation experiment is carried out by high-low temperature impact test. Fault cause is given according to test result and analysis.

Keywords: Thermistor, failure analysis, in-orbit, satellite

1. Introduction
As we know, all the satellites work in the dark cold space environment. If thermal control measures are not taken, when the satellite is facing the sun, the surface temperature will rise sharply under the sun's illumination. At the same time, the temperature on the side against the sun will be very low. The instruments on the satellite can not endure the wide range of cold and hot alternating environment. This may harm even damage the instrument inside the satellite [1]. Therefore, thermal control design and manufacturing should be carried out in the stage of satellite development in order to keep the in-orbit temperature in proper range to get good working and storing performance for on-board instruments, so as to help us improve the overall performance and prolong the life-time of the whole satellite. Accurate acquisition of on-board temperature is the first step in thermal control [2,3].

Thermal resistor, which is short for thermistor, is used to measure the temperature of satellite during the in-orbit work in order to get the working temperature of the instruments or panels.

But in recent years, some thermistors outside the satellite lost their functions during the in-orbit work. It brought troubles for thermal control of the satellites. So it is very necessary to analyze the failures of the satellite thermistors to find the reasons to help us to improve the design and assembly of the thermistor circuit.

2. Composition of the thermistor circuit
Thermistor circuit is composed by thermistor and conductive wires, as shown in Figure 1. The thermistor pin is Dumet wire. The conductive wire is copper wire. The Dumet wire and the conductive wire are well together before installed on the satellite.
For insulation considerations, the Dumet wire of thermistor is covered by single heat-shrinkable sleeve before welt, and the welding point between Dumet wire and Copper wire is covered by double layers of heat-shrinkable sleeve, as shown in Figure 2. After the thermistor is fixed on the surface of the satellite, it is covered by silicone rubber glue. One case of the installation state of thermistor outside the satellite is shown by Figure 3.

### Table 1. In-orbit failure statistic of thermistors outside satellite

| No. | Working time (month) | Installation state | In-orbit temperature range(℃) |
|-----|----------------------|--------------------|--------------------------------|
| 1   | T0+0                 | Uncovered          | -140→+110                     |
| 2   | T0+2                 | Uncovered          | -100→+100                     |
| 3   | T0+2                 | Uncovered          | -140→110                      |
| 4   | T0+6                 | Uncovered          | -45~ +13                      |
| 5   | T0+8                 | Uncovered          | -80→95                        |
| 7   | T0+8                 | Uncovered          | -130→+120                     |
| 8   | T0+8                 | Uncovered          | -40→+10                       |
| 9   | T0+11                | Uncovered          | -140→+110                     |
| 10  | T0+12                | Uncovered          | -150→50                       |
| No. | Working time (month) | Installation state | In-orbit temperature range(℃) |
|-----|---------------------|-------------------|--------------------------------|
| 11  | T0+12               | Uncovered         | -150~+100                     |
| 12  | T0+18               | Uncovered         | -140~+110                     |
| 13  | T0+19               | Uncovered         | -80~++95                      |
| 14  | T0+19               | Uncovered         | -80~++95                      |
| 15  | T0+28               | Uncovered         | -140~+110                     |

"T0 means the launching time"

Though the analysis of the in-orbit failure statistics, the features are summarized as follow:

- Signal jump-normal-jump before failed
  1 case is invalid right after launch, and there is no signal for it. The others are working until the signal jumps and at last there is no signal reserved.
- Less working hours
  Compared with 6-10 years life time of the whole satellites, most of the failure occurred within 1 year after launch.
- Wide and alternated working temperature rang
  Most of the failure thermistors have been working in the alternating temperature changing from the temperature below -80℃ to the temperature above +90℃. In some worse cases, the working temperature is alternated from -150℃ to +100℃, or from -140℃ to +110℃.
  According to the in-orbit temperature measuring data statistics, most of the working temperature of thermistors inside the satellite is in the range of -60℃ to +60℃, and the thermistors can be working stably in that situation.

4. Cause analysis

In view of in-orbit failure problem mentioned above, a failure mode fault tree is established for failure reason analysis[4-6], as shown in Figure 4.

![Fault tree of thermistor in-orbit failure](image)

Figure 4. Fault tree of thermistor in-orbit failure

The specific analysis is as follows:
1) Reason 11: Thermistor failure by electronic component failed
Thermistors used outside the cabin are processed and manufactured according to relevant standards, and have been tested for electrical performance, mechanics and adaptability of in-orbit environment. They are selected according to the in-orbit working range of the satellite, and their performance can satisfy various requirements of the satellite on the ground testing. But the satellite will experience a bad and complex space environment during its in orbit work. The thermistor exposed outside the cabin without the protection of Multi-layer Insulation materials, which is used to control the temperature in suitable range in order to protect the instruments and the temperature sensitive components, may cause performance degradation or failure. The influence degree has not been tested and verified. Therefore, reason 11 cannot be exclude.

2) Reason 12: Thermistor failure by external damage
The technical design and process requirements for the final assembly and distribution of thermistor is implemented. The conformance of the operation and implementation state has been examined by professional inspection, electric test, vibration test and thermal test. The failure caused by external force can be completely avoided by means of standardized operation and strengthened management. Reason 12 can be excluded.

3) Reason 21: Welding failure by performance degradation and failure caused by space environment
For weld exposed to space environment, it is analyzed that their performance is subject to extreme cold-hot alternating environment, which will cause degradation and failure of welding performance. Especially under the environment of in-orbit high-low temperature cycle, certain internal stress is generated both in Dumet wire and Copper wires because of the different expansion coefficient of different materials (thermal expansion coefficient of thermistor dumet wire is about 10\(^{-6}\), and copper wire is10\(^{-5}\)). The stress could further aggravate the displacement of each other, causes welding alloy layer lattice moved, reduces the adhesion strength of the alloy layer and substrate, eventually makes the welding joint cracking. That caused the failure. Reason21 can not be excluded.

4) Reason 22: Welding failure caused by insulated sleeves failure
If the heat-shrinkable sleeves coated on the welding points and the wires closed to them cannot withstand cold-hot alternating environment, it expands when heated and shrinks when cooled. Frequent thermal expansion and contraction produces stress acting on the welding points , which leads to the cracking of the welding points. That caused the failure. Reason 22 can not be excluded.

5) Reason 23: Welding failure caused by incorrect welding parameters
Because of the neglect of the cold-hot alternating environment outside the satellite, there is no special validation welding experiment for thermistors outside the cabin The welding parameters are the same as those inside the satellite. This makes the welding points cannot withstand the space environment of alternating heat and cold outside cabin, resulting in cracking and failure of welding point. That caused the failure. Reason 23 can not be excluded.

6) Reason 31: Wire failure caused by insulated sleeves failure
Just like the reason 22, frequent thermal expansion and contraction of the insulated sleeves which cover the wirers and welding points produces stress acting on the Copper wires, which leads to the borked of the wires. That caused the failure. Reason 31 can not be excluded.

7) Reason 32: Wire failure caused by fixed material failure
If the wire fixing materials cannot bear the cold-hot alternating environments, the fixed materials fail and cannot play a fixed role on the wire. It results swings of the wire in-orbit work. Multiple bending of the wire under stress will break the wire, resulting in failure of the thermistor circuit. Reason 32 can not be excluded.

5. Verification
In order to verify which is the real reason among the courses that analyzed above, a simulated experiment was taken. In the experiment, two kinds of thermistors, six of each, were employed. They were installed on an aluminium board with GD414 silicone rubber the same installation method as the thermistors installed on satellite.
The temperature impact tests were carried out and the temperature was cycling as +20°C to -196°C to +125°C to +20°C, which is wider than the in-orbit failed themistsors’ working temperature range. Electrical performance tests and appearance inspections were done before impact test, after 50 period cycling, after 500 period cycling, and after 1500 period cycling to see if there is something wrong during the temperature impact tests. The result is shown in Table 2.

**Table 2.** Resistance value at room temperature during the experiment

| Resistance value at room temperature (kΩ) | before impact test | after 50 period | after 500 period | after 1500 period |
|-----------------------------------------|------------------|----------------|----------------|-----------------|
| A1                                      | 27.86            | 29.08          | 23.59          | open            |
| A2                                      | 26.04            | 27.12          | 22.10          | 26.85           |
| A3                                      | 24.73            | 25.77          | 21.02          | 25.38           |
| A4                                      | 26.31            | 27.43          | 22.30          | 27.21           |
| A5                                      | 27.11            | 28.28          | 22.98          | open            |
| A6                                      | 26.96            | 28.07          | 22.92          | 27.63           |
| B1                                      | 30.57            | 31.42          | 28.23          | 31.24           |
| B2                                      | 28.14            | 28.85          | 25.94          | 28.68           |
| B3                                      | 24.89            | 25.57          | 23.05          | 25.52           |
| B4                                      | 26.58            | 27.33          | 25.51          | open            |
| B5                                      | 24.87            | 25.56          | open           | open            |
| B6                                      | 25.89            | 26.61          | 24.01          | open            |

After 50 times temperature impact test, all the 12 themistor circuits can measure the room temperature, and there is no significantly deformation for each themistor. After 500 times of temperature impact test, one test circuit of thermistor appeared to be open. After 1500 times of temperature impact test, five test circuits of thermistor appeared to be open. There is no obvious deformation on the head of the thermistor. It means reason 1 can be excluded. One case was shown by Figure 5. But there is obvious deformation of both the Dumet wire and the Copper wire, especially the copper wire where is close to the welding point. One case was shown by Figure 6. Figure 6 also shows there is deformation of insulated sleeves during the temperature experiment. That means reason 22 and reason 31 can not be excluded. In the experiment, there is no fixing material failed, so that the reason 32 can be excluded.

**Figure 5.** Photo of thermistor of one failed case after 1500 times temperature impact test

**Figure 6.** Photo of welding point and wire after 1500 times temperature impact test
Using test pins, the thermistor resistance values of all 5 open thermistor circuits were measured correctly. It means that the components are normal. The reason 1 can be excluded.

For the further inspection, X-ray detection was employed. In the X-ray film, fractures can be seen clearly between the Copper wires and welding points in all 5 open thermistor circuit cases, and there is no damage on the welding points and the thermistors, as shown by Figure 7 and Figure 8. That means the reason 21, reason 22, and reason 23 can be excluded. The reason 31 is the course of the in-orbit failure of thermistor outside the satellite.

6. Conclusion
In this paper, the failure causes of in-orbit thermistors are analyzed. Through fault tree analysis, 7 possible causes of in-orbit failure of thermistor outside satellites are analyzed. Through cold - hot temperature impact test, the causes are further analyzed and verified, and with the help of X-ray detection, the causes of the problems are finally determined. It was caused by the fractures between the Copper wires and Welding points due to the expansion and contraction stress of insulated heat-shrinkable sleeves in the cold-hot alternating environment in space.

However, due to the limitations of the samples and the inadequate fidelity of the in-orbit environment model, there may be other reasons that cannot be exposed, and further analysis and verification can be carried out in the follow-up.

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