Evaluation on Wire Covering Degradation (Investigation of ADEOS-II Malfunction)

Electronic, Mechanical Components and Materials Engineering Group
Institute of Aerospace Technology
Japan Aerospace Exploration Agency (JAXA)

Junichiro Ishizawa
Naoko Baba
Midori-II (Originally called the Advanced Earth Observing Satellite-II (ADEOS-II)) stopped supplying observation data due to an electrical power failure.

Fault Tree Analysis (FTA) suggested that a break or short circuit in the power-supply harness between the solar array paddle subsystem and the electrical-power subsystem was the most probable cause.

Each phase of the failure scenario was tested and analyzed, and then material degradation was evaluated for failure verification.
In October 2003, a solar paddle on Midori-II (ADEOS-II) ceased providing electrical power.

FTA determined that the most probable fault locations were the power system and the wiring harness.

Our evaluation determined that the wire insulator had the highest possibility of triggering the failure.
Supposed scenario of malfunction

[Before power supply failure]
1) Multi layer insulation (MLI) charging
   (Ungrounded MLI was charged while in the shadow or aurora zone.)

2) A cut on the wire insulator of the harness

3) Trigger arc between the MLI and the harness
   / Single arc between damaged harnesses

[Break out power supply failure]
4) Continuous discharging between a pair of harnesses

5) Arc spreading to an adjacent harness
   / A pair of harnesses develops a short or open circuit from heat damage caused by continuous discharging, a common occurrence.
Wire insulator

- MLI wrapped harness of 106 cables.

- Raychem Spec 55/ AWG22 (outer diameter: 1.09mm)
  Strand wire (silver-coated copper wire)
  Radiation cross-linked ethylene-tetrafluoroethylene copolymer (ETFE).
  Wall thickness : 0.15mm

Cf. Polyimide or Fluoropolymers (e.g., PTFE) are often used because of their heat resistance.
  ETFE is inferior to PTFE in heat and arc tracking, and greatly superior to PTFE in formability.

Radiation cross linking or cross linking agent are used to increase the mechanical properties of ETFE at elevated temperature, causing the ETFE to become rubbery and preventing it from melting.

Raychem 55/ is cross-linked by an electron beam after the wire is covered.
Raychem 55/ wire has been proven robust in many flights.

→ The main factor in its degradation:
Midori-II’s unique high-temperature cycle,
reaching the crystalline melting point of ETFE
(far beyond the derated temperature).

- Highest temperature (estimation): 230 °C ±10–15 °C
- Thermal endurance (Spec.): 200 °C, 10,000hr
- Crystalline melting point: 236 °C (measured by DSC)
Evaluation of discharge

Single wire
  Discharging test after heat-cycle test
  → No discharging was observed.

Tied harness (Midori-II configuration)
  Discharging was occurred after the heat-cycle test.
  Discharging caused cracking, with charring and blackening of the wire insulator.

Possible scenarios:
  Reduced insulation, damage to covering caused by discharging,
  or
  insulator damage causing discharging.
Thermal cycle tests on tied harness

5,000 thermal cycles, 100 to 250 °C, vacuum condition.

2,400 thermal cycles, 0 to 130 °C, ambient condition.

Discharging was observed.
Cracks were visible on insulator after discharging.
Crack opening:
large, long, smooth
Cracks differed from the fractured surface on normal polymeric materials. The depressed area included abrasions. There seems to be little possibility of such a large heat strain for the heat-cycle conditions based on estimates from Midori-II telemetry data.

- We determined that the crack morphology is peculiar to this material.
Fracture morphology

- Fractured surfaces were similar to those of rubber material in tensile stress. Cross linking was the source of rubber-like elasticity in polymers.

- Radiation cross-linked ETFE:
  Rubbery state near the crystalline melting point. Visible cracks after the discharging test occurred near the crystalline melting point.

- Some radiation cross-linked material:
  Shape recovery phenomenon above the crystalline melting point. Anomalous cracks seems to be related to this phenomenon.
Soldering iron test  
(preliminary experiment)

Heating the covering with a soldering iron

Covering cracked after heating with soldering iron

Crack: Lengthwise or oblique direction, smooth and open.
Wire insulator: Remaining stress or oriented texture in lengthwise direction.

【Stress relaxation】
- Lengthwise direction: Compressive
- Circumferential direction: Tensile

For confirmation
- Tensile tests and thermal expansion measurements in circumferential direction.
Thermal expansion measurements in the circumferential direction

TMA (Non-heated specimen)  TMA: Thermo-mechanical analysis (Tension mode)

Significant expansion during melting of crystals

Significant contraction with crystallization

Total expansion (over 11%)

Processing strain release

*↑#1: 1st rising  ↓#1: 1st descending

Significant expansion was measured at the approximate crystalline melting point.
Thermal expansion measurements in the circumferential direction

TMA (Heated specimen : 245 °C, 169-hr in vacuum)

Thermal expansion : over 11%
Significant expansion was measured at the approximate crystalline melting point.
Thermal expansion measurements in the lengthwise direction

TMA (γ-ray irradiated specimen: 10 months exposure Midori-II)

Opposite behavior (Expansion, Contraction) from the circumferential direction at the approximate crystalline melting point. Inverse strain and ablation probably occurred at the crossing points of the cable of the tied harness in the Midori-II thermal-cycle environment.
Tensile tests in the circumferential direction

Insulator materials reduced in elongation by 169-hr exposure at 260 °C. Maximum stress and strain decreased at 260 °C.
Tensile tests in the circumferential direction

Elastic limit under 10% strain
Elongation: under 0.6mm

Gage length 6mm

Thermal expansion (over 11%) > Elastic limit (under 10%)
Possibility of plastic deformation
(Additional testing is required for more credible assurance.)
Crack-forming mechanism
At cable crossing points in tied harness:
- Cracks with abrasion were observed after thermal-cycle tests.
- Tied harness bonded together at temperatures greater than 230 °C. (Other test results)
- Bonding points prevent stress relief of the harness in the thermal cycle.
- Abrasions could occur that would cause cracks and reduced thickness.

Thermal cycle
↓
Abrasion and thickness reduction of cable-covering material
and
repetitive thermal strain, including significant expansion and contraction
around the crystalline melting point
↓
Crack (Initiation and extension)

In addition, electron-beam exposure and a vacuum environment of high temperatures for an extended time possibly contributed to the damage of the materials.
Temperature conditions for safe use

Thermal strain from 150 to 250 ºC, 3 cycles
DMA (Dynamic Mechanical Analysis) on Raychem spec55/ AWG22 cable covering

Only 2% strain were measured. Modest heat strain from room temperature to 150 ºC.
Verification studies conducted for the cable failure in Midori-II (ADEOS-II) showed that at high temperatures, approximately at the crystalline melting point, significant expansion and contraction occurred in the insulator material.

Due to total heat strain reaching the plastic range, repetitive plastic deformation and abrasion likely damaged the covering materials.

Significant expansion and contraction were not detected for thermal cycles below 150 °C (at maximum temperature).

- Raychem 55/ wire could be used at temperatures up to 150 °C
Standards for satellite design

- Derating standards for satellite harness

- Material degradation test: temperature limit

- Temperature rise test using continuous current

Input power vs. maximum temperature vs. safe temperature

Harness configuration

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