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Reliability Study of the NiH2 Strain Gage

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INTRODUCTION

This paper summarizes a joint study by Gates Aerospace Batteries [GAB] and the Reliability Analysis Center [RAC]. This study characterizes the reliability and robustness of the temperature compensated strain gages currently specified for sensing of internal pressure of NiH2 cells. These strain gages are characterized as fully encapsulated, metallic foil grids with known resistance that varies with deformation. The measurable deformation, when typically installed on the hemispherical portion of a NiH2 cell, is proportional to the material stresses as generated by internal cell pressures. The internal pressure thus sensed is calibrated to indicate the state-of-charge for the cell. This study analyzes and assesses both robustness and reliability: for the basic design of the strain gage, the installation of the strain gage, and the circuitry involved.

DESCRIPTION OF THE STRAIN GAGE

GAB Part Number 3B84010 defines Micro Measurements' Strain Gage Part Number WK-06-250PD-350. The previous similar part number was 211B2495AB-1. This gage is characterized as (Reference 1.A): dual-element pattern that is fully encapsulated K alloy, equipped with integral, high-endurance beryllium-copper leadwires. The Carrier Matrix [backing] is a high-temperature epoxy-phenolic resin system reinforced with glass fibers. WK-Series gages have the widest temperature range and most extensive environmental capability of any general-purpose strain gage of the self-temperature-compensated type.

Gage length is 0.250 inches, width is 0.240 inches for the grid pair, and resistance is 350 ohms ±0.4%. Operating Range is nominally -269°C to +400°C for Special or Extended Service, and -269°C to +290°C for Normal Service. Backing and adhesive life is projected as $5X10^5$ hours [57 years] at typical Low Earth Orbit [LEO] and Geosynchronous Earth Orbit [GEO] mission environments. Allowable Strain Limit is 1.5%.

GAB Engineering Specification A15B-815 defines Micro Measurements' M-Bond AE-15 Strain Gage Installation Kit. The previous similar part number was 283A6484AE-9. This is characterized as a (Reference 1.B): two-component, 100%-solids epoxy resin system that is recommended for more critical applications. This system is highly resistant to moisture and most chemicals. Typical Elongation Capability is quoted as 10% to 15% at +24°C. A typical set of strain gages as installed is shown in Figure 1.

PURPOSE OF THE STRAIN GAGE

The two strain gage pairs form a typical four-component Whetstone Bridge that is very sensitive to minuscule changes in resistance by forming a null-balance system with two active gages [hard mounted] and two passive gages [soft mounted] for temperature-compensation. Excitation Voltage is generally 6.4±0.005 volts. This excitation voltage is equivalent to 1.6 KW/M^2, and is at the lower side of the optimum range.

The output of the strain gage shows as a resistance change as a function of applied strain level. The strain is directly related to the parent material surface strain, except for the shear -lag of the bonding adhesive. The parent material [i.e., pressure vessel dome] surface stress is a proportional, but indirect, measure of the internal pressure. The internal pressure, created by hydrogen gas, is proportional to the state-of-charge.

Typical expectations for the time dependent GEO mission environment includes: stability and repeatability errors less than 1% over 2000 cycles; and, life expectancy of 15 to 16 years. Different typical expectations for the cycle dependent LEO mission environment includes: repeatability errors less than 1% over life; bridge output voltage drift less than 0.5% per year; and, a life expectancy of approaching forty thousand cycles.

FAILURE MODES, FAILURE CAUSES, and FAILURE EFFECTS

Understanding and defining how a specific failure mechanism produces a discrete failure mode that may effect system operation is important for determining the proper inter-relationship among the events. A proper understanding of this sequence or chain of events is paramount to establishing appropriate corrective actions to prevent recurrence.

In addition, the orientation of the analysis, that is whether to concentrate on system response symptoms or on specific signatures generated by active components, determines both the success of the analysis and the effectiveness of remedial actions. Failure Mode: what aspect, condition, or position is of concern; in what manner does the failure manifest itself. Failure Cause [or Failure Mechanism]: what particular component or part prompts the failure mode to occur and what likelihood of occurrence exists. Failure Effects: what are the effects of the failure, if any, at the interface, on the system, or on the overall mission performance?

ANALYSIS of FAILURE MODES

Other than a substantial accumulation of fatigue characteristics within Tech Note TN-508-1 (Reference 1.C) to be discussed later, the manufacture has not performed any reliability analyses or assessments. MIL-HDBK-217E does not directly address strain gages for the purpose of reliability prediction. Accordingly, a reliability study was performed by RAC (Reference 2) for a specific contractual obligation. The study included a detailed Failure Modes Effects Analysis [FMEA]; a Worst Case Analysis [WCA]; and, a Circuit Stress Analysis [CSA].

Failure Modes Effects Analysis

Generally, the FMEA contains the largest single source of information on discrete failure events. The FMEA involves the listing of potential failure modes, their causes, and the effects upon the components, subsystems, and subsequent systems. The FMEA is a "bottoms-up" analysis of the product design characteristics relative to the planned fabrication, test, and inspection process. This analysis ensures that the resultant product meets the intended need, expectation, and performance goals. When potential failure modes are identified, corrective action can be initiated to eliminate them or continually reduce their risk [or potential occurrence].

This present FMEA encompasses the design, fabrication, and use of the strain gage installation as applied to the GAB NiH2 cell. This analysis covers the use of the strain gage within specific conditions of environment and use of the host cell as it transits throughout test, integration, and the launch and mission environments. The incorporated Failure Modes Effects Analysis of the strain gage contains substantially more detail than a typical FMEA. The following headings are contained within this analysis [Table 1]:

FMEA No.	Failure Cause
Item Name	Failure Detection and Verification
Part Number	Corrective Action -Short Term
Quantity of Parts	Corrective Action -Long Term
Part Function	Failure Effect on the Mission
Failure Mode	Failure Effect on the System
Failure Causes	Failure Effect at the Interface

A more typical FMEA for a NiH2 cell in similar isolated analysis details only two generic failure modes for the strain gage. Those failure modes are cited as: [1] Loss of signal; and, [2] Inaccurate signal. The present FMEA treats the strain gage and installation in isolation upon the cell. As such, the analysis provides details concerning every component, sub-component, and material used during installation of the strain gage on the cell assembly.

Circuit Stress Analysis

The strain gage and installation do not contain the discrete electrical or electronic piece parts that may be subjected to the typical stress derating and application review. Thus, the CSA portion of the RAC study [Reference 2] analyzed installation and application stresses. These stresses were used to predict the base failure rate for the strain gage installation.

The analysis predicted the base failure rate for the strain gage by two different methods. A thermistor model, utilizing handbook principles, predicted a failure rate of 0.13 failures per million hours. RAC databases indicate a failure rate of 0.128 per million hours for a pair of NiChrome resistors. The handbook failure model for the forty-four hand soldered connections in the strain gage subsystem predicted 0.1144 failures per million hours. The total failure rate for the strain gage installation was predicted at 0.2444 failures per million hours.

Worst Case Analysis

The WCA is used to predict the change in performance parameters if all constituent parts were to operate at their extreme stress value, or at the extreme of design tolerance. The addition of the resultant worst case values will provide an end-of-mission performance extreme. Subsequently, insight is gained then as to which extreme values may be modified to reduce inherent risk.

Thus the WCA portion of the RAC study (Reference 2) analyzed environmental profiles and strain gage attributes to predict resistance changes over the mission life. The analysis showed that the 29.3mW that must be dissipated is only 17% of its maximum allowable for high accuracy and only 2% when mounted on the cell as a heat sink. The analysis further predicted a variation in output readings of 1.04% at 5°F at the end of a potential 16.5 year GEO mission.

ANALYSIS of FATIGUE

Expectations for the time dependent GEO mission environment typically includes 2000 cycles over a life expectancy of 15 to 16 years. Expectations for the cycle dependent LEO mission environment includes 30 to 40 thousand cycles approaching a life expectancy of 5 years. The cycle dependency of the LEO mission environment is one area not previously analyzed for the strain gage installation. Thus, the increased cycle requirement for LEO versus GEO mission environments raises the specter of fatigue. Henceforth, our discussion is centered about two specific areas: [1] Fatigue Analysis of the strain gage proper; and [2] Fatigue Analysis of the strain gage installation. "Strain gage installation" may be more correctly referred to as the strain gage mount and periphery installations including the circuitry.

Analysis of Strain Gage Proper

GAB has adopted and applied the manufacturer's recommendations as stated in Tech Note TN 505 (Reference 1.D) for both the strain gage and the installation. In addition, the manufacture has performed substantial testing of strain gages to determine their fatigue characteristics. The following information is paraphrased from their Tech-Note [Reference 1. C].

The metal foils used in strain gages are prone, as are all metals, to fatigue damage when cyclically strained at sufficiently high amplitude. In general, larger grid areas result in higher fatigue life, while higher resistance result in lower fatigue life. Micro Measurements monitors three parameters on strain gages during fatigue testing: "super-sensitivity," gage factor change, and zero-shift. Super-sensitivity results from cracks that are just forming, and that are open only during the tension portion of the loading cycle. Super-sensitivity can only be detected and monitored by using an oscilloscope. Fatigue cracks can also cause increases in the tension gage factor; however, they are easily detected since the compression value will be much lower. For purely dynamic strain measurements, zero-shift is relatively incidental, and strain gages can be considered functionally adequate until fatigue damage has progressed almost to the stage of super-sensitivity. Generally, Nominal Fatigue Life is based upon a zero-shift of 100$\mu\varepsilon$.

Figure 2 illustrates those fatigue stress test results. Numerically, Micro Measurements cites a Fatigue Life of 10^6 cycles for a Strain Level of $\pm 2400\mu\varepsilon$, and 10^7 cycles for a Strain Level of $\pm 2200\mu\varepsilon$. This fatigue life data is based on fully reversed strain levels. As a generalized approximation, this data can be used for unidirectional strains, or various mean-strains by taking the indicated peak amplitude and derating by 10 percent. As an example, $\pm 1500\mu\varepsilon$ would be approximately equivalent in gage fatigue damage to strain levels of +2700 to 0$\mu\varepsilon$, or 0 to -2700$\mu\varepsilon$, or +2500/-200$\mu\varepsilon$. However, a mean-strain that increases in a tensile direction during cycling will lead to a much earlier failure.

A typical GAB design destined for a LEO mission environment yielded the following characteristics. Internal cell pressure varies according to MCP[1-DOD], where MCP is the maximum cell pressure and DOD is the depth-of-discharge. For a typical LEO mission:

MCP = 950 PSIG @ BOL [beginning of life];

MCP = 1000 PSIG @ EOL [end of life]; and,

DOD = 30% for a nominal 89 A-H.

The Worst Case pressure varies between 700 to 1000 PSIG [850±150 PSIG]. Therefore, for a minimum thickness of 0.019 inches the strain varies from 1595 to 2277$\mu\varepsilon$ [or, 1936±341$\mu\varepsilon$]. Thus, $5X10^4$ cycles at 1595 to 2277$\mu\varepsilon$ appear well below the manufacturer's point of concern.

Analysis of Strain Gage Mount and Periphery Installations

Appendix A of Tech-Note TN-508-1 provides numerous installation recommendations for Maximum Strain Gage Fatigue Life. This appendix refers to an additional series of both Tech Notes and Tech Tips for hands-on installation techniques and tips. These tips and hints include:

1. Avoiding excess adhesive films;
2. Soft solders with low melt points;
3. Using auxiliary bondable terminals;
4. Leadwire attachment techniques; and,
5. Use of overcoatings.

GAB has adapted all the installation techniques into their current MCD's. The installation process is controlled and basic instruction techniques were provided by Micro Measurements. The soldering process is certified to NHBB 5300.5[3A-1].

CONCLUSIONS and RECOMMENDATIONS

1. The expanded Failure Modes & Effects Analysis, the Circuit Stress Analysis, and the Worst Case Analysis each show the design, fabrication and installation of the strain gage to be conservative in view of the manufacture's available equipment list and installation recommendations.

2. The Root Cause of numerous Failure Modes identified within the FMEA could be traced to potential fatigue damage. The Fatigue Analysis of the strain gage shows the gage usage and environment to be well below even the manufacturer's points of minimum concern. Significant test data exists for the prediction of fatigue life of the strain gage. However, this gage installation and periphery, while following all possible recommendations, have not been tested for fatigue life.

3. The end result of this analysis is the recommendation for two life test regimes for the strain gage and installation. A LEO test of 2000 cycles at Room Temperature has already been scheduled for completion by year end. A GEO test is being devised with expected completion by Mid-1993. Success and failure criteria are being determined, and test results will be reported in a later paper.

TABLE 1: Expanded Strain Gage FMEA

No.	Item Name	Part Number	Qty	Function	Failure Mode	Failure Causes
STR-1	Strain gage	211B2495AB1	2	Strain gage	Open	Corrosion; Mishandling; Shipping damage; Cracked die; Lifted or broken solder joint
STR-2					Intermittent open	Cracked die (gage); Cracked solder joint
STR-3					Short (hard)	Extraneous particles; Solder whiskering
STR-4					Intermittent or soft short	Extraneous particles; Solder whiskering; Ionic contam.; Cracked or voided epoxy
STR-5	Soldereze wire	283A6484WA	10	Soldereze wire connections	Open	Mishandling; Shipping damage; Broken wire; Lifted or broken solder joint
STR-6					Intermittent open	Cracked wire; Cracked solder joint; Cold solder joint
STR-7	Balco wire	283A6484WC	1	Balco wire temperature compensation	Open	Mishandling; Shipping damage; Broken wire; Lifted or broken solder joint
STR-8					Intermittent open	Cracked wire; Cracked solder joint; Cold solder joint
STR-9					Improper length	Wire cut too long; Wire cut too short
STR-10	Strain gage wires [cupron]	283A6484WD	1	Cupron wire balance	Open	Mishandling; Shipping damage; Broken wire; Lifted or broken solder joint
STR-11					Intermittent open	Cracked wire; Cracked solder joint; Cold solder joint

No.	Item Name	Part Number	Qty	Function	Failure Mode	Failure Causes
STR-12					Improper length	Wire cut too short; Wire cut too long
STR-13	Terminal strip	2B72001	1	External connections	De-bonding of copper foil & backing	High g-field [shock]
					Cracked solder joint	High strain field
STR-14	Terminal strip	2B72002	2	Bridge intra-connect	De-bonding of copper foil & backing	High g-field [shock]
					Cracked solder joint	High strain field
STR-15	Polyimide Tape	A23C-801	A/R	Electrical insulation	Intermittent or soft short	Mishandling; Shipping damage
STR-16	Control shim	2B74008	1	Installation support	De-bonding of installation	Mishandling, improper mix or handling of epoxy
STR-17	Adhesive	A15B-815	A/R	Structural bonding	De-bonding of gage or terminal strips	Improper mix or application
STR-18	Adhesive	A15F-801	A/R	Structrural bonding	De-bonding of control shim installation	Improper mix or application
STR-19	Solder	2C93001	A/R	Electrical connections	De-bonding or corrosion	Improper solder flux
STR-19	Polyurethane	A8B-801	A/R	Installation overcoat	De-bonding	Improper mix or application

No.	Failure Detect/Verf	C/A Short Term	C/A Long Term	Failure Effect [Mission]
STR-1	Electrical and visual tests	Electrical tests	Certified soldering process, epoxy control requirements	Loss of pressure reading from cell
STR-2	Electrical/thermal, material, final vibr./integration testing	Electrical tests	Certified soldering process, epoxy control requirements	Intermittent pressure readings from cell
STR-3	Electrical measurements	Electrical tests	Certified soldering process, epoxy control requirements	Lowered pressure reading from cell (discharge indication)
STR-4	Electrical measurements & calibration cycle	Electrical tests, stabilization bake	Certified soldering process, epoxy control requirements	Intermittent low pressure reading from cell (discharge indication)
STR-5	Electrical and visual measurements	Electrical tests	Certified soldering process	Loss of pressure reading from cell
STR-6	Electrical/thermal measurements	Electrical tests	Certified soldering process	Intermittent (loss of) pressure reading from cell
STR-7	Electrical and visual measurements	Electrical tests	Certified soldering process	Incorrect pressure reading from cell
STR-8	Electrical/thermal measurements	Electrical tests	Certified soldering process	Fluctuation in pressure reading from cell
STR-9	Electrical and visual measurements	Electrical tests	Control cutting process	Incorrect pressure reading from cell
STR-10	Electrical and visual measurements	Electrical tests	Certified soldering process	Incorrect pressure reading from cell
STR-11	Electrical/thermal measurements	Electrical tests	Certified soldering process	Fluctuation in pressure reading from cell

No.	Failure Detect/Verf	C/A Short Term	C/A Long Term	Failure Effect [Mission]
STR-12	Electrical/thermal measurements	Electrical tests	Control cutting process	Fluctuation in pressure reading from cell
STR-13	Electrical/thermal, material, final vibr./integration testing	Care and handling, protective cap	Shock indicators in shipping containers	Intermittent pressure readings from cell
	Electrical/thermal, material, final vibr./integration testing	Electrical tests	Use 'half-terminal' technique [see Note 2]	Intermittent pressure readings from cell
STR-14	Electrical/thermal, material, final vibr./integration testing	Care and handling, protective cap	Shock indicators in shipping containers	Intermittent pressure readings from cell
	Electrical/thermal, material, final vibr./integration testing	Electrical tests	Use 'half-terminal' technique [see Note 2]	Intermittent pressure readings from cell
STR-15	Electrical/thermal, material, final vibr./integration testing	Protective cap	Protective cap	Intermittent low pressure reading from cell (discharge indication)
STR-16	Electrical/thermal, material, final vibr./integration testing	Protective cap, epoxy control requirements	No futher action required	Intermittent pressure readings from cell
STR-17	Electrical/thermal, material, final vibr./integration testing	Electrical tests	Epoxy control requirements	Intermittent pressure readings from cell
STR-18	Electrical/thermal, material, final vibr./integration testing	Electrical tests	Epoxy control requirements	Intermittent pressure readings from cell
STR-19	Electrical/thermal, material, final vibr./integration testing	Electrical tests	Certified soldering process	Intermittent pressure readings from cell
STR-19	Visual inspection	Visual inspection	Epoxy control requirements	Minimal-to-no effect

No.	Failure Effect [System]	Failure Effect [Interfaces]
STR-1	Loss of strain gage reading	Loss of strain gage voltage
STR-2	Intermittent strain gage reading	Intermittent strain gage voltage
STR-3	Lowered strain gage reading	Lowered strain gage voltage
STR-4	Intermittent low strain gage reading	Intermittent loss of strain gage resistance (see note 1)
STR-5	Loss of strain gage reading	Loss of strain gage voltage
STR-6	Intermittent strain gage reading	Intermittent strain gage voltage
STR-7	Inaccurate strain gage reading when temperature changes	Improper reading due to loss of temperature compensation
STR-8	Voltage fluctuation	Improper pressure indication, intermittent temperature compensation
STR-9	Inaccurate strain gage reading when temperature changes	Improper reading due to incorrect temperature compensation
STR-10	Loss of differential voltage zeroing	Intermittent pressure loss from loss of voltage compensation
STR-11	Voltage fluctuation	Intermittent pressure indication due to voltage compensation

NOTES:
1. During shock, vibration, and thermal vacuum environment
2. Alternate Technique when using bondable terminals

No.	Failure Effect [System]	Failure Effect [Interfaces]
STR-12	Voltage fluctuation	Incorrect voltage compensation
STR-13	Intermittent strain gage reading	Intermittent strain gage voltage
	Intermittent strain gage reading	Intermittent strain gage voltage
STR-14	Intermittent strain gage reading	Intermittent strain gage voltage
	Intermittent strain gage reading	Intermittent strain gage voltage
STR-15	Intermittent low strain gage reading	Intermittent loss of strain gage resistance (see note 1)
STR-16	Intermittent strain gage reading	Intermittent strain gage voltage
STR-17	Intermittent strain gage reading	Intermittent strain gage voltage
STR-18	Intermittent strain gage reading	Intermittent strain gage voltage
STR-19	Intermittent strain gage reading	Intermittent strain gage voltage
STR-19	Minimal-to-no effect	Minimal-to-no effect [@ ground environment only]

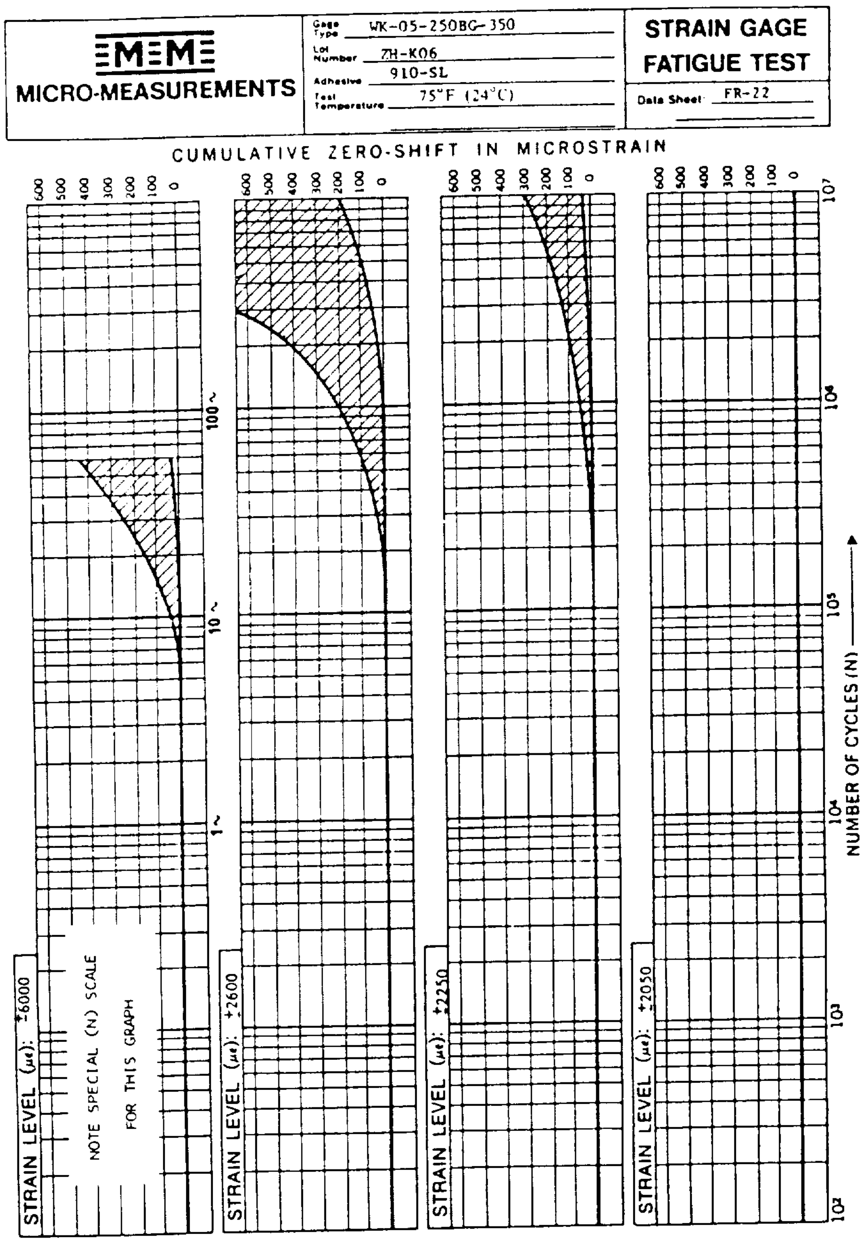

Figure 2 --Strain Gage Fatigue Test Results

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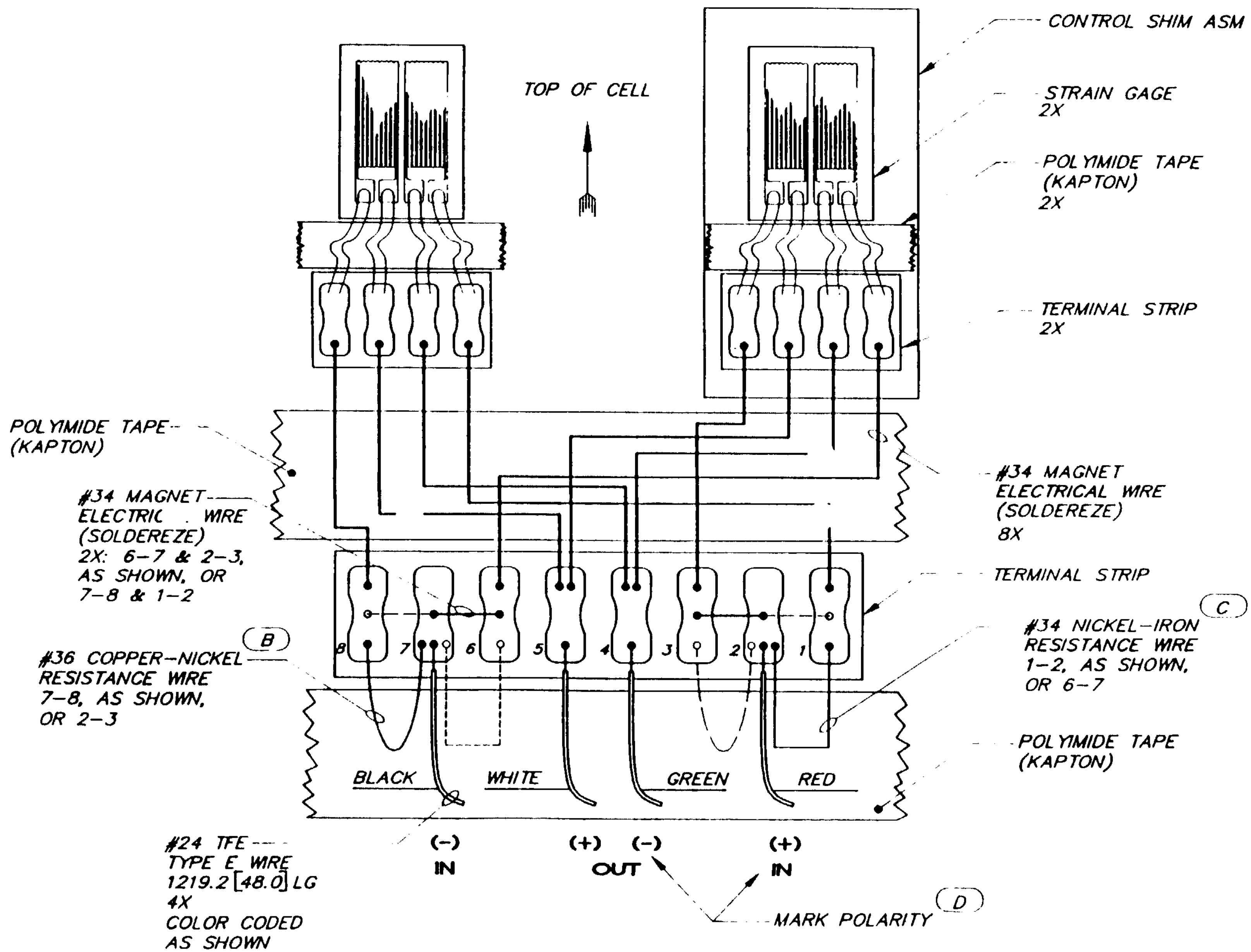

Figure 1 --Typical Strain Gage and Installation

REFERENCES

1. Strain Gage Technology Manual; Measurements Group -*Vishay*, Raleigh, NC; 1991:
    - A. Catalog 500, Parts A & B.
    - B. Catalog A-110-5.
    - C. Tech Note TN-508-1, "Fatigue Characteristics of Micro-Measurements Strain Gages."
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2. Reliability Study of the NiH2 Strain Gage; Reliability Analysis Center, Rome, NY; 1992.