Failure Analysis of Nonvolatile Residue (NVR) Analyzer Model SP-1000

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National Aeronautics and Space Administration (NASA) subcontractor Wiltech contacted the NASA Electrical Lab (NE-L) and requested a failure analysis of a Solvent Purity Meter; model SP-1000 produced by the VerTis Instrument Company. The meter, used to measure the contaminate in a solvent to determine the relative contamination on spacecraft flight hardware and ground servicing equipment, had been inoperable and in storage for an unknown amount of time. NE-L was asked to troubleshoot the unit and make a determination on what may be required to make the unit operational. Through the use of general troubleshooting processes and the review of a unit in service at the time of analysis, the unit was found to be repairable but would need the replacement of multiple components.

I. Introduction

In January of 2011, National Aeronautics and Space Administration (NASA) subcontractor Wiltech contacted the NASA Electrical Lab (NE-L) and requested a failure analysis of a Solvent Purity Meter; model SP-1000 produced by the VerTis Instrument Company. In the failure analysis of a complex unit such as the SP-1000 it is imperative to understand the unit's intended operation, the functional principals, and manner in which it has failed. Due to the closing of VerTis and subsequent modifications that were made, the amount of technical literature and technical support for this instrument was limited. With the extended storage time after the instrument was taken out of service, and no record of what had failed on the instrument prior to storage, it was difficult to differentiate between original failures and failures that manifested during storage. Fortunately there was one SP-1000 left in service that was available for comparison. However; because the instrument in service was the only operational instrument of its kind, access and the amount of disassembly allowed was limited.

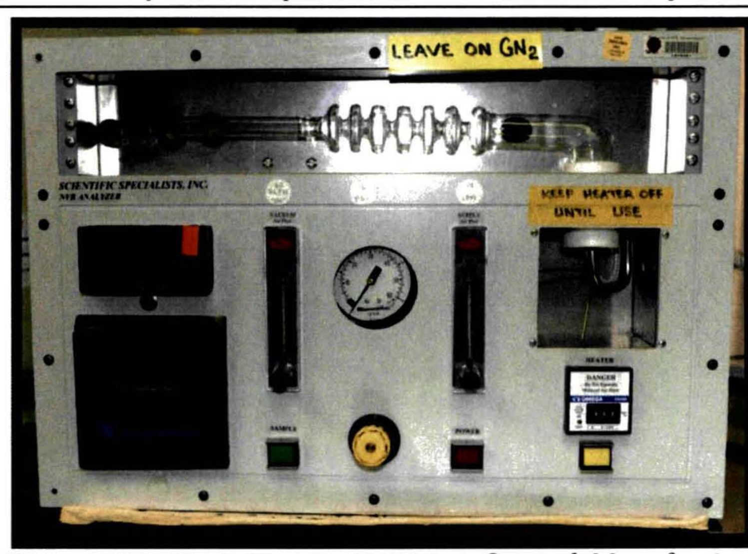

Figure 1. SP-1000 Solvent Purity Meter. *Original Magnification: 0.25X*

Spacecraft flight hardware and ground servicing equipment must be free of contamination, particularly contamination that is not compatible with the various fluids used to launch and operate the spacecraft. A particular class of contamination that is not compatible with liquid oxygen systems is called nonvolatile residue (NVR). A previous practice to determine cleanliness levels had been to flush parts with precision cleaning solvents until NVR

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concentrations in the solvent are acceptable and no further NVR can be removed from the components. The standard measurement of NVR content in the wash solvent is achieved by a gravimetric method (KSC-C-123). This method requires at least 30 minutes of analysis time. The SP-1000 Solvent Purity Meter (Virtis Instrument Company, Figure 1) was designed to provide real-time instantaneous measurement of NVR in 1,1,2-trichloro-1, 2,2-trifluoroethane (CFC 113) solutions. This provides significant time and cost savings. The SP-1000 accomplishes this measurement by using an aspirator to atomize the CFC 113 along with any NVR into a drying tube that utilizes a closely controlled air flow to evaporate the solvent and to carry suspended contaminate particles to the optical system of the SP-1000. The SP-1000 optical system utilizes the principle of forward-scattered light to provide extremely accurate and sensitive measurements of minute particles suspended in a gaseous medium. Due to the production and sale of CFC 113 being banned in 1995, the SP-1000 units were later modified to allow for the use of alternate solvents such as isopropyl alcohol (IPA) and/or trichloroethylene (TCE).

II. Operation and Construction

The SP-1000 measures a relative aerosol concentration by detecting the intensity of light scattered by particles sampled through the scattering chamber of the instrument. The optical arrangement of the light scattering chamber had been designed such that light not be incident on the photomultiplier tube unless a particle enters the sensitive region on the chamber. When an aerosol is drawn through the chamber, it will pass through the sensitive region and will cause light to be scattered forward to the light sensitive photomultiplier tube. Intensity of the scattered light is proportional to the parts per million of the suspended particulates. The signal from the photomultiplier tube is transmitted through the photometer amplification circuitry where a relative concentration (Parts Per Million, PPM) reading is displayed on a digital panel meter. The meter reading is a function of the magnitude of small-angle forward-scattering of light by particles of contaminate dispersed in the solvent continuously drawn through a dark-field illumination chamber. The equipment comprising the instrument consists of three functionally distinct units, A. optical system, B. electronic system, C. air sampling system.

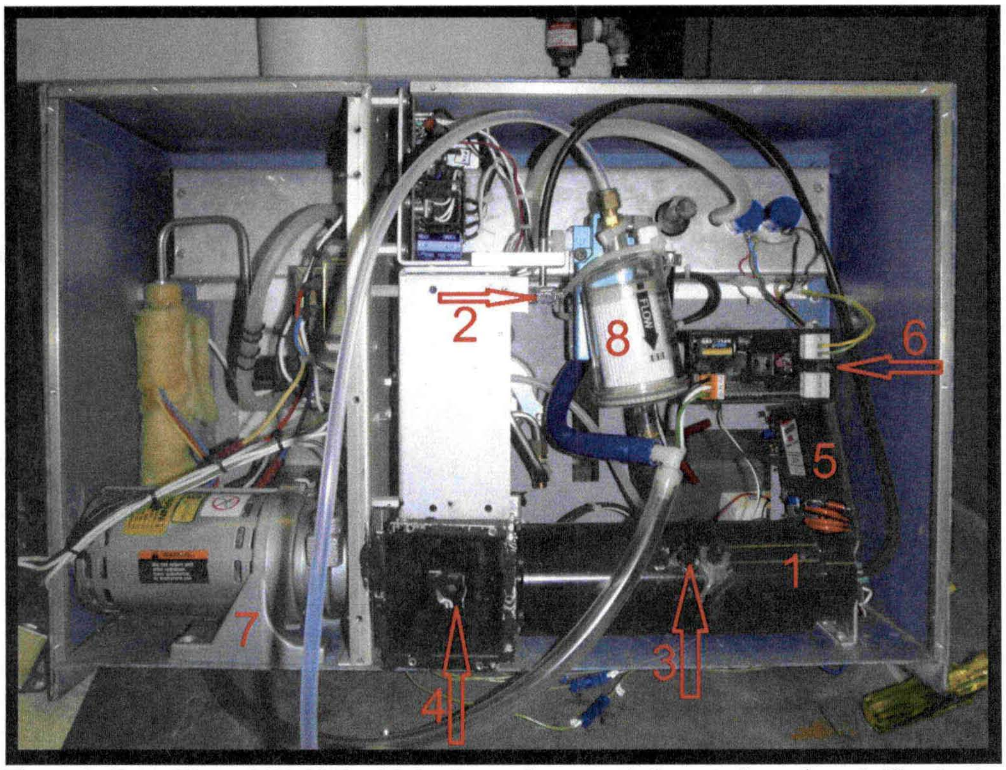

Figure 2. Rear View of SP-1000 with back panel removed. *Items indicated are 1. Illumination Chamber, 2. Light Source, 3. Smoke Tube, 4. Photomultiplier Tube, 5. Amplifier circuit Board, 6. Digital Panel Meter, 7. Vacuum Pump, 8. HEPA Filter.*

A. Optical System

The optical system utilizes a controlled stream of a test aerosol or particulate, flowing across an intense beam of light. The sample small-angle forward scattered light is then focused upon the cathode of a photomultiplier tube. The measurement of small-angle forward-scattering light with a highly sensitive photomultiplier tube provides extreme resolution. Depending on the nature of the particulate matter, forward scattering is 100 to 10,000 times greater than the scattering in all directions. The cylindrical smoke illumination chamber (Fig. 2, Item 1) houses the light source, optical system and smoke tube. The light source (Fig. 2, Item 2) is a 12 volt, 3 amp lamp, and is energized through a voltage regulated power supply. The light is transferred to the illumination chamber through a fiber optic cable. The optical system consists of two condensing lenses and suitable stops and diaphragms for producing dark field illumination and minimizing stray light. The collecting lens focuses the scattered light on the photomultiplier tube. The smoke tube (Fig. 2, Item 3), through which the sampled aerosol passes, has two openings in opposing faces at the intersection with the optic axis, so that light is incident directly upon the air stream. The photomultiplier tube (PMT; Fig. 2, Item 4) is mounted in a shroud with a removable cover with its aperture facing the image of the illuminated particles formed by the collecting lens.

B. Electronic System

The signal from the photomultiplier tube is transmitted though the amplifier circuit board (Fig. 2, Item 5) which amplifies the signal into a reading displayed on a digital panel meter (Fig. 2, Item 6).

C. Air Sampling System

The vacuum pump (Fig. 2, Item 7) is connected by means of Teflon tubing to the optical system. The sample aerosol is first drawn through the drying tube, then through the optical system. A solenoid valve switch is provided on the front panel for opening and closing the sample intake. Intake of room air, cleaned by a High Efficiency Particulate Air (HEPA) filter (Fig. 2, Item 8) introduces clean air into the optical system to provide a rapid purge of air when going from contaminated sample to clean room air.

III. Procedure and Results

Upon initial inspection the unit was found to have multiple issues. Some issues may have been from the extended storage time and others due to an original malfunction. NE-L was not given any information on the reason for the unit being put into storage. With the possibility of the unit being taken out of service only due to it no longer being needed, NE-L powered up the machine during initial inspection to identify any functional issues other than the ones found by visual inspection. The items found during the initial inspection included the vacuum pump not producing vacuum. It was noted that pressure gauge located on the front panel appeared to be inoperable due to the position of the needle; however this was not verified until later. The digital panel meter located on the front of the instrument would power up and the solenoid valve could be heard when the sample button pressed; however, without an operating vacuum pump a sample could not be tested to verify the digital panel meter and solenoid was functional. The air pressure regulator had become brittle and seized with time. The printer located under the digital panel meter was missing the cover. Multiple spare components were supplied with the unit. In the collection of spare components was the missing cover.

With the printer, air gauge, and pump being defective, a sample could not be taken and thus the integrity of the electronic system could not be verified. Before any more diagnostics could be performed, the air sampling system had to be repaired. The pump was removed from the unit and inspected. It was found that the pump was seized and would need to be rebuilt or replaced. NE-L contacted the manufacture of the pump and was informed no rebuild kit was available for the pump and it must be replaced. NE-L contacted Wiltech and informed them of the status. Without knowing if the electronic system was functional, investment in a new pump at this point was not practical. In an effort to get the air sampling system operational long enough to complete the troubleshooting of the system a general service vacuum pump was loaned to NE-L by another lab. With an operational vacuum pump the rest of the air sampling system was verified to be operational and the instrument ready to test a sample. When running the sample the instrument was non-responsive pointing towards a failure in the optical or electronic systems.

To verify the integrity of the optical system the illumination chamber and fiber optic cable were removed for inspection. A visual inspection of the fiber optic cable indicated that there was not physical damage to the exterior and that light passed through it with no noticeable reduction in light intensity. The illumination chamber was placed in the IRT Real Time X-ray machine to look for any debris that could obstruct the light. While in the X-ray machine it was also noted how the illumination chamber could be disassembled. Upon disassembly of the illumination chamber the condensing lenses, stops and diaphragms were inspected and determined to be clean and in good working order. Once reassembled the illumination chamber and fiber optic cable was placed back into the instrument and the instrument was turned on. An $1/8^{th}$ inch zip-tie was inserted into the smoke tube to verify the light was reaching the photomultiplier tube.

After verifying the optical system to be in good working order the troubleshooting of the electronic system was required. Because no circuit or wire diagrams for the unit were available one was produced to aid in the troubleshooting. This schematic is shown in the appendix.

Photomultiplier tubes (PMT) require a high potential difference on the order of kilovolts. Because of this high voltage a standard digital multimeter (DMM) must be fitted with a high-voltage circuit probe that allows the measurement of such voltages. With a high-voltage probe, approximately 1000 volts was measured at the PMT connector. This indicated that the amplifier circuit board was supplying a voltage reasonable for the application. The next step was to test the output from the PMT. The PMT was placed back into the instrument and powered up. To make sure light was incident on the PMT, the $1/8^{th}$ inch zip-tie was reinserted into the smoke tube. An ammeter was placed in between PMT pins 9 and 10 as shown in figure 3. When powered up no current was measured from the PMT indicating a possible defective PMT. Without a working PMT no further diagnostics to the electronic system were possible. With a known good PMT, further analysis of the electronic system may provide useful diagnostics. However, with the fact that the amplifier circuit board is producing the needed high voltage, it is assumed that amplifier circuit board is operating as designed.

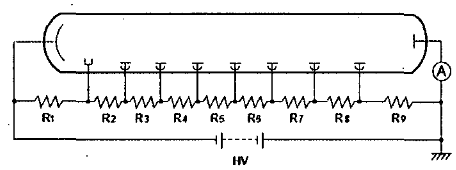

Figure 3. Placement of Ammeter for PMT Test.

IV. Conclusion

Based on the findings from the analysis performed on the SP-1000 to date, NE-L believes that the unit is repairable. At a minimum the unit will need a new Photomultiplier Tube, Vacuum Pump, Low Pressure Air Gauge, Air Regulator Valve, and various miscellaneous parts including wire and vacuum hose. Assuming that the amplifier circuit board is operational the instrument should be able to be repaired for less than $1500. If the photomultiplier tube is replaced and the unit continues to be inoperable then further diagnostics of the electronic system will be required. Due to the lack of information on the amplifier circuit board the electronic system may need to be redesigned. This could be done using newer PMT technologies while utilizing much of the existing circuitry of the instrument. If this is required to get the instrument operational it may cost $1500 to $3000, with an additional amount of engineering time to redesign a new electronic system. If Wiltech decides that the cost is too great to repair the unit it still may be valuable for the spare parts that can be used for the instrument still in service.

Appendix

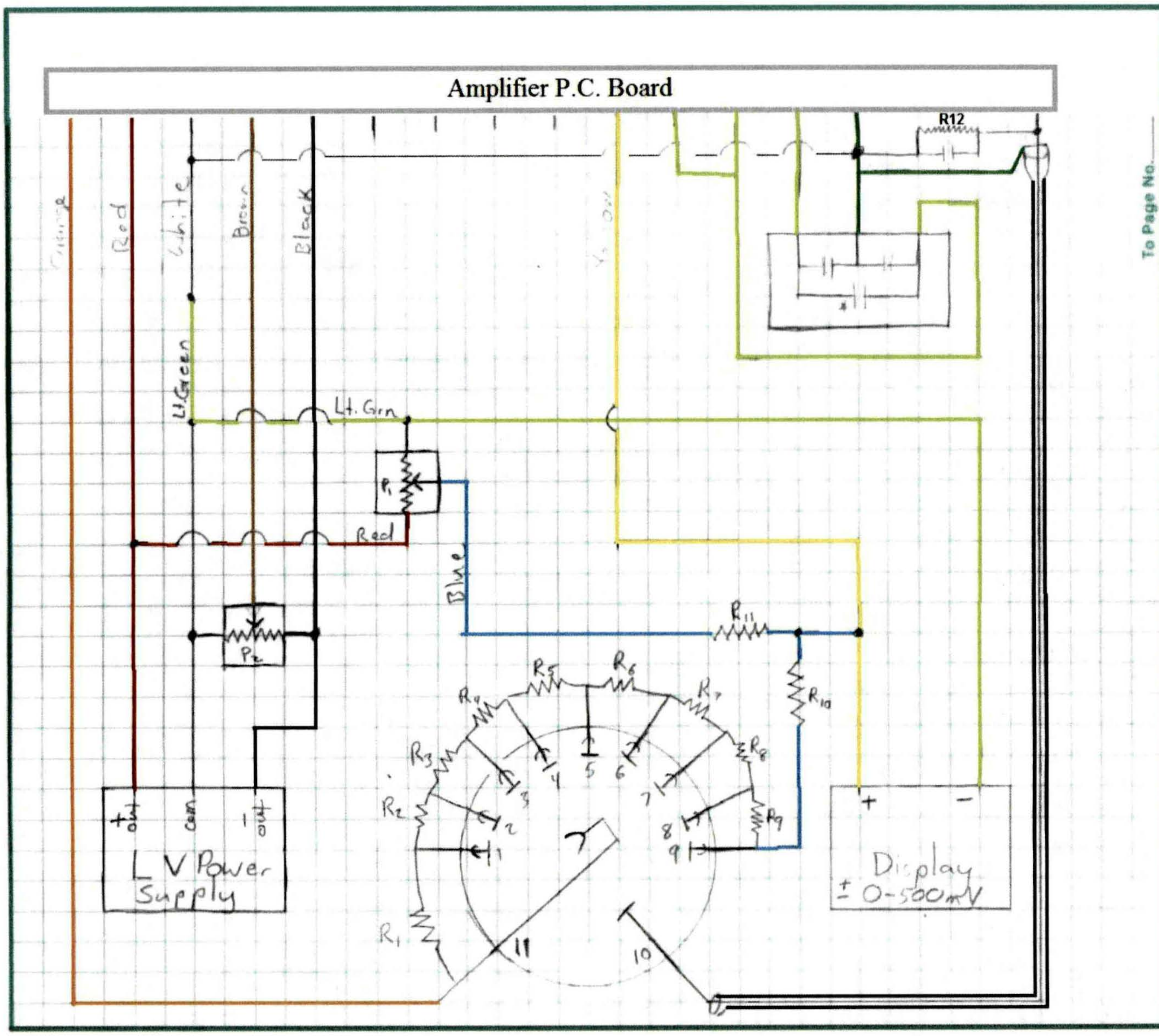

Figure 3. Electrical Schematic for SP-1000. *R_1-R_9 = 478kΩ, R_{10} = 563kΩ, R_{11} = 28kΩ, R_{12} = 24.5MΩ, LV Power = ±15VDC, P_1-P_2 = 10kΩ potentiometer.*