N79-18236

SPACE SHUTTLE LIGHTNING PROTECTION

D. L. SUITER, R. D. GADBOIS, AND R. L. BLOUNT
National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas 77058

BIOGRAPHY

D. L. Suiter is an aerospace engineer, flight systems, in the Engineering Evaluation and Analysis Office of the Program Operations Office at the NASA Lyndon B. Johnson Space Center (JSC). He received his B.A. in mathematics and physics from Texas Christian University in 1960. Before joining NASA in 1963, he worked for 3 years in electrical design with General Dynamics in Fort Worth, Texas, and 3 years as an electronic design project engineer with Brown Engineering and the Hayes International Corporation.

R. D. Gadbois is also an aerospace engineer, flight systems, in the Engineering Evaluation and Analysis Office of the Program Operations Office at the NASA JSC. He received his B.S.E.E. in 1957 from Illinois Institute of Technology and his J.D. in 1974 from South Texas College of Law. Before joining NASA in 1962, he worked for 5 years as a circuit designe General Dynamics-Astronautics in San Diego, California.

Robert L. Blount is the manager of the Engineering Evaluation and Analysis Office at the NASA JSC. He received his B.S.E.E. from the Missouri School of Mines and Metallurgy in 1957. Before joining NASA in 1964, he worked 7 years in electronic design with General Motors and Emerson Electric.

ABSTRACT

The technology for lightning protection of even the most advanced spacecraft is available and can be applied through cost-effective hardware designs and design-verification techniques. In this paper, the evolution of the Space Shuttle Lightning Protection Program is discussed, including the general types of protection, testing, and analyses being performed to assess the lightning-transient-damage susceptibility of solid-state electronics.

INTRODUCTION

In keeping with a national commitment to provide a low-cost space transportation system, the Space Shuttle vehicle (Fig. 1) must accommodate numerous launch and landing operations in an adverse weather environment each year. The advanced solid-state electronics and the unique thermal protection system required for atmospheric entry create particular lightning protection problems.

From past experiences with lightning, the most notable of which was the Apollo 12 lightning strike incident[1] and the resulting Apollo-Soyuz Test Project Overall Simulated Lightning Test[2], NASA Lyndon B. Johnson Space Center engineers recognized that protection for the Space Shuttle would require the application of state-of-the-art technologies. To be cost-effective, protective design measures had to be incorporated into the initial hardware designs.
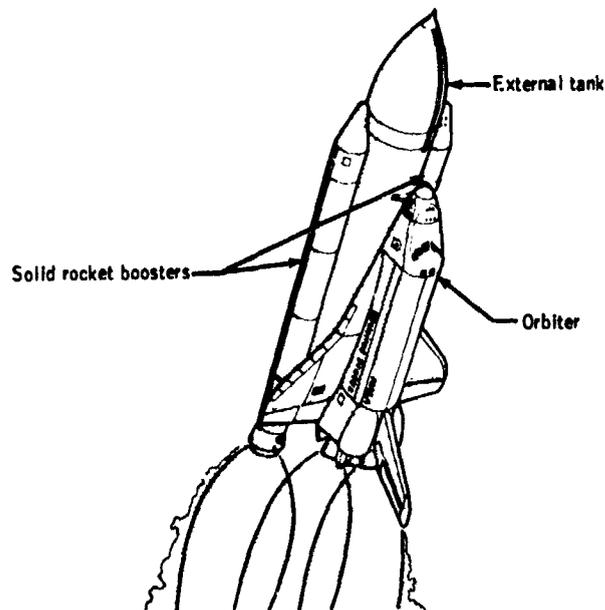

FIGURE 1. SPACE SHUTTLE SYSTEM.

LIGHTNING COMMITTEE

The management approach was to assemble a group of specialists who would provide an early definition of the lightning environment (design model) and who would develop the design requirements. The Space Shuttle Lightning Committee

thus formed consisted of representatives from the Shuttle element contractors, the integrating contractor, the U.S. Air Force, the three NASA centers actively involved with the Space Shuttle Program, and four consultants from the engineering and scientific community.

The product of this committee was the Space Shuttle Lightning Protection Criteria Document[3], a document that is being used in the Shuttle hardware design. The committee continues to function to help resolve particular lightning protection design problems as they arise.

DESIGN REQUIREMENTS

The formulation of the design requirements centered around two basic questions. To what degree or depth should protective measures be applied? What design limits should be imposed?

From a practical approach, circuit upsets would be acceptable, if adverse actions were unlikely to occur. Some damage would be acceptable only if such damage did not result in loss of the vehicle. Several factors, such as vehicle safety, weight, simplicity, cost, and existing technology for protective designs influenced the design requirements. The Shuttle specification thus imposed specific protection requirements in some areas while criteria and guidelines for protection were provided in other areas.

The design requirements were divided into two categories - direct lightning effects and indirect lightning effects. The direct effects were defined as burning, blasting, direct coupling of voltages and currents, and structural deformation caused by lightning-arc attachment. Also included in this definition were the high-pressure shock waves and magnetic forces caused by the high lightning currents. The indirect effects were defined as the damage or malfunctions (circuit upsets) caused by induced currents and voltages that are produced by the electromagnetic fields that occur with lightning.

Lightning protection measures are divided into four groups: the control of lightning paths, isolation of sensitive circuits, unique circuit design, and design verification. These measures fundamentally entail the application of low-resistance electrical bonding and grounding, circuit isolation, aperture closeouts, wire and cable shielding, filtering, and special circuit designs to negate the effects of lightning-induced voltage and current transients.

DESIGN VERIFICATION

The capability of the hardware to withstand both the direct and indirect effects of lightning can be verified through analysis or test; but, in some cases, a combination of both is required. For the Space Shuttle, a full-threat-level direct effects test has been specified for antennas, pitot tubes, thermal protection coverings, vents, doors, and other

external hardware that must be located in main current paths or arc-attachment zones.

To determine the arc-attachment zones, a test was conducted on a 0.03-scale model of the Space Shuttle vehicle (Fig. 2). The results of this test are contained in Reference 4. Of particular concern to the designers was the extent of damage to the Orbiter thermal protection coverings. Hence, two further tests were conducted. The purpose of the first test was to perform a preliminary evaluation to determine the vulnerability of the various protective materials to lightning and to determine the feasibility of incorporating lightning diverter strips. The results[5] led to the conclusion that diverter strips that could withstand entry heating were too heavy. Therefore, the second test was conducted to establish the extent of damage caused by a full-threat swept-stroke lightning strike. An analysis of the results[6] showed that the area of damage produced in the latter test was thermally acceptable with no special protection required.

FIGURE 2. LIGHTNING ARC-ATTACHMENT TEST.

Another area of primary concern was the pyrotechnics, which could be ignited or damaged with direct lightning arc attachment. Two worst-case candidates, the Orbiter outer panel severance system (for crew inflight escape) and the solid rocket booster frustrum separation system, were tested. The results of these tests are given in References 7 and 8, respectively. The tests indicated that both ordnance systems could withstand a full-threat (200 000 A) lightning strike without any adverse effects.

Many other direct effects tests were conducted on Shuttle hardware. For the interested reader, results of the more important tests may be obtained from References 9 to 21.

-84-

Various indirect effects tests were also conducted, and of special note was the testing on the solid rocket booster nozzle severance (ordnance) system cable that is detailed in Reference 22. In this test, a 40 000-A lightning current was driven through the ordnance cable outer shield (triple shielded) without firing or dudding the explosives. In addition, the pyrotechnic initiator controller that provides the electrical signal to fire the ordnance was not adversely affected.

A method for terminating cable shields using diodes was tested for possible Shuttle application and the results are discussed in Reference 23. This scheme can be used when a conflict exists in electromagnetic interference and lightning-shielding requirements.

Verification that hardware is immune to the indirect effects of lightning, however, proved to be more difficult than originally envisioned.

ANALYSIS VERSUS TEST

The original plan to assess the indirect effects of lightning on Shuttle hardware was twofold. First, the electromagnetic field levels inside the vehicle were calculated based on a full-threat-level (200 000-A design model) lightning strike to the vehicle. (The details of the analytical procedure used will be discussed in another paper presented at this conference.) Various unshielded circuit runs, using worst-case loop areas routed through these magnetic fields, were postulated and analyzed. From these analyses, open-circuit voltages and short-circuit currents were calculated. The results were then discussed with the Lightning Committee. Based on experience with indirect lightning effects on similar types of equipment, the committee concluded that the off-the-shelf avionics equipment being proposed for the Shuttle should withstand a 50-V and 10-A (2-μsec) lightning transient without damage. Thus, this requirement was imposed on all flight-critical electrical and electronic hardware. The electromagnetic environment inside the vehicle would be controlled, with at least a 6-dB margin, to levels below the equipment design levels. This lightning design control would be exercised through the use of shielding, aperture closeouts, judicious equipment location, and other design techniques.

Secondly, the calculated electromagnetic field environment would be verified by actual measurement in an overall vehicle (Orbiter only) simulated lightning test. Prediction of the electromagnetic fields inside symmetrical vehicles, such as the solid rocket booster and the external tank, is well established from first principles of physics; therefore, testing at the vehicle level to verify internal fields was not planned. Avionics and other critical electrical equipment would be verified at the unit, subsystem, and vehicle levels using transient analysis tests similar to those described in Chapter 17 of Reference 24.

Lightning transient testing at the unit and subsystem levels was a new experience for most equipment vendors. Costs quoted for such testing were prohibitive and serious weight penalties (up to 600 lb) for shielding were necessary to maintain the induced-voltage levels below design limits. Also, during the Apollo-Soyuz lightning test, induced voltages as high as 350 V were measured with no resulting component damage. In addition, studies performed for the U.S. Air Force[25] indicated that component pulse failure powers could vary by 1 or 2 orders of magnitude among components with the same part number. Thus, qualification testing to determine failure levels for electrical and electronic hardware proved to be impractical. At this point, the lightning protection program for the Shuttle vehicle was redirected.

Space Shuttle critical avionics systems have been designed to be failure tolerant; that is, sufficient redundancy has been used so that the vehicle can still perform a mission after one failure in a critical system. A second failure in that system, at worst, will still allow a successful return of the Orbiter. The vehicle is, therefore, designed to be fail-operational/fail-safe. Lightning-induced failures in critical avionics equipment can be tolerated, as long as the fail-safe design requirement is not violated.

LIGHTNING TRANSIENT DAMAGE ANALYSIS

The lightning transient survivability of electrical components and equipment can be determined by analysis. Theoretical and experimental work by D. C. Wunsch and R. R. Bell[26] has shown that the power level required to damage a semiconductor junction is proportional to the minus one-half power of the pulse width of the applied power for pulse widths between 0.1 and 100 μsec.

$$P_F = Kt^{-1/2}$$

where P_F = failure power, K = proportionality constant, and t = pulse width.

The proportionality constant has been named the "Wunsch" or "damage" constant. In general, the pulse widths of lightning-induced voltage fall within the cited range, and the Wunsch damage equation can be used directly to predict whether avionics semiconductors will survive lightning-induced voltages. Based on the Apollo-Soyuz Test Project lightning test, a 5-μsec pulse width was chosen for Shuttle systems analysis. Damage constants of semiconductor devices were calculated using the junction capacitances C_j and breakdown voltages V_{bd}, and the thermal impedances from junction-to-ambient θ_{ja} or from junction-to-case θ_{jc}, using the equations given in Reference 27. The damage constants can also be determined by testing, but a statistically significant number of components (six to nine) must be tested to failure. A wide dispersion (plus or minus 1 to 2 orders of magnitude) exists in damage constants for like components

with the same part number. The significance of this fact cannot be overlooked when contemplating lightning transient damage susceptibility testing at the unit or subsystem level. Damage levels can, however, be calculated to within plus or minus 1 to 2 orders of magnitude; and, through the use of derating techniques, a damage constant can be calculated to ensure that at least 95 percent of the components will actually have a higher damage constant. This fact, along with the multiple redundancies used in critical systems, allows an analytic approach to be taken to assure that, from a component damage standpoint, the vehicle will be able to return safely after being struck by lightning. The analytic techniques described in this paper are quite similar to those that are currently in use for electromagnetic pulse survivability analysis.

Damage constants have been determined for more than 18 000 components by the U.S. Air Force. These data, stored in a computer program called SUPERSAP, were made available for the Shuttle analysis effort. References 25, 27, and 28 have been used for Shuttle analysis.

The analytic approach used by the Space Shuttle Program is divided into three steps, the first two of which are performed in parallel. First, for each criticality I (failure of which causes loss of life or vehicle) black box or component, the internal circuits that are connected in flight were identified and detailed to the external connector and pin numbers. Using electromagnetic pulse analysis techniques, the damage levels, failure voltage, and failure current are established for each connector contact. In the analysis, all damage constants are derated by a factor of 0.1, unless other data indicate that the damage constant corresponds to the lower 95-percentile failure level. A pulse width of 5 μsec is used for all circuits except those that cross the Orbiter/external tank, solid rocket booster/external tank, or the Shuttle vehicle/ground checkout interfaces. For those interface circuits, a pulse width of 50 to 100 μsec is used because lightning currents can flow directly in the overall shields of the interconnecting cables. Simplifying assumptions are used whenever possible to shorten the analysis. Such assumptions, however, are always selected to provide a more conservative answer.

Second, the induced open-circuit voltage and short-circuit current for each interconnecting wire are calculated using the method established in Appendix F of Reference 3. If the calculated induced-voltage and short-circuit current exceed the calculated failure voltage and current, step 3 is undertaken.

Third, the analysis is expanded to include total end-to-end circuit impedances, and the simplifying assumptions are removed. An analysis of the total circuit then yields the voltage that appears at each end of the circuit and a current that is limited by the total circuit impedance. If these values exceed the failure voltage and current, corrective action is

taken. This action consists of adding shields to wires, relocating equipment and wiring to areas of lower magnetic field intensity, adding transient suppression devices, or redesigning the affected equipment. A sensitive circuit is shown in Figure 3. The equivalent circuit and sample analysis are shown in Figures 4 and 5. It is interesting to note that the most susceptible components in the circuit shown in Figure 3 are zener diodes that were added to protect the rest of the circuit from transients. If the diodes are removed, the circuit failure
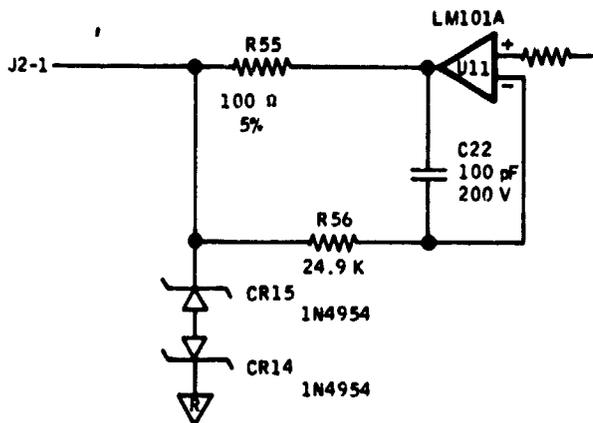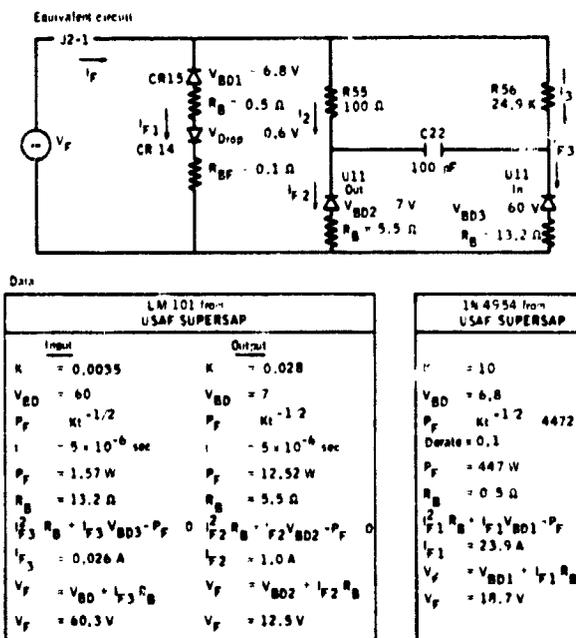

FIGURE 3. TYPICAL CIRCUIT FOR LIGHTNING TRANSIENT ANALYSIS.

FIGURE 4. SAMPLE EQUIVALENT CIRCUIT AND FAILURE DATA.

-86-

For CR15, $I_{F1} = 23.9$ A

$V_F = V_{BD1} + I_{F1}(R_B + R_{BF}) + V_{Drop} = 21.74$ V

For U11 Out, $I_{F2} = 1.0$ A

$V_F = I_{F2}(R_{55} + R_B) + V_{BD2}$

$V_F = 118.7$ V

For U11 In, $I_{F3} = 0.026$ A

$R_{55}C_{22} = 0.01$ μsec

0.01 μsec $\ll 5$ μsec

Legend	
V_F = Failure voltage	
I_F = Failure current	
R_B = Reverse bulk resistance	
R_{BF} = Forward bulk resistance	
V_{BD} = Reverse breakdown voltage	

Therefore, C_{22} can be considered open

$V_F = I_{F3}R_{56} + V_{BD3} = 707$ V

V_F for CR15 is less than V_F for U11

input and output; therefore, CR15 is the

ORIGINAL PAGE IS
OF POOR QUALITY

most susceptible component, and

$V_F = 21.7$ V

$I_F = I_{F1} + I_2 + I_3, I_3 = 0$ because U11 input $V_{BD} < V_F$

$$I_F = I_{F1} + \frac{V_F - V_{BD2}}{R_{55} + R_B}$$

$I_F = 24$ A

FIGURE 5. SAMPLE CALCULATIONS.

voltage would increase from 22 V to 119 V, a greater than fivefold increase. However, the failure current would decrease from 24 A to 1 A. The diode suppression, therefore, would be adequate only if impedance in series with the induction generator (at the other end of the wire run) is high enough to limit the short-circuit current to less than 24 A.

ORBITER SIMULATED LIGHTNING TEST

The present plan is to conduct a simulated lightning test on the Shuttle Orbiter vehicle. The primary objectives will be to identify the critical circuit upsets (i.e., those that could cause loss of the vehicle) and to verify the predicted lightning-induced magnetic fields within the vehicle. It should be noted that, although upset levels can be analytically determined, the analysis would be extremely complicated. Also, upset levels should not vary significantly from vehicle to vehicle, so results obtained from testing one vehicle should apply to all vehicles. For the first phase, the Orbiter will be isolated from ground, powered up, and systems configured for flight operations below 50 000 ft. The output of a high-voltage generator, fed through a pulse-forming network, will be connected to the vehicle and a series of voltage waveforms (Fig. 6) will be applied to excite the vehicle as an open-ended transmission line. Figure 7 shows a rudimentary test configuration. The system will be monitored
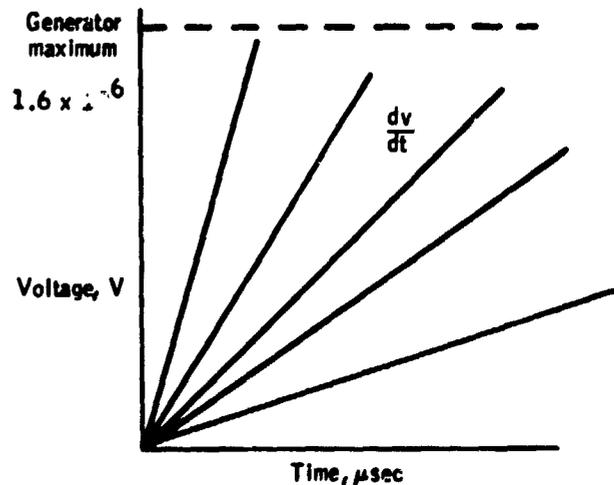

FIGURE 6. PHASE I TEST VOLTAGE WAVEFORMS.

through the existing radiofrequency link to the launch processing system and by onboard visual observation (manned). A number of circuits, particularly sensitive to lightning-induced effects, will be monitored by a special fiber optics system.

For the second phase, the vehicle systems and test configuration will be the same as for the first phase except that a test current (Fig. 8) will be passed through the vehicle and returned through a number of wires placed symmetrically around the vehicle.

The results of these tests and the results of the aforementioned analyses will then be used to evaluate the lightning protection designs of the vehicle.

CONCLUDING REMARKS

Adequate lightning protection can be provided efficiently and effectually in a spacecraft by incorporating well established and relatively simple practices into system designs. Proper analyses are required to determine where and how to apply these practices in the design.

The costs (i.e., weight and effects on systems) to implement a lightning protection program must be closely balanced against the gains in the utility of the vehicle to perform its mission.

The indirect effects analyses and the planned vehicle level lightning test are perhaps "breaking new ground"; however, they are practical and economical ways to ensure that the design will protect critical circuits.

The damage analyses for all critical circuits are expected to be completed before the vehicle-level test of Orbiter vehicle 102, which should occur in early 1980. For this test, the goal will be to identify critical circuit upsets and
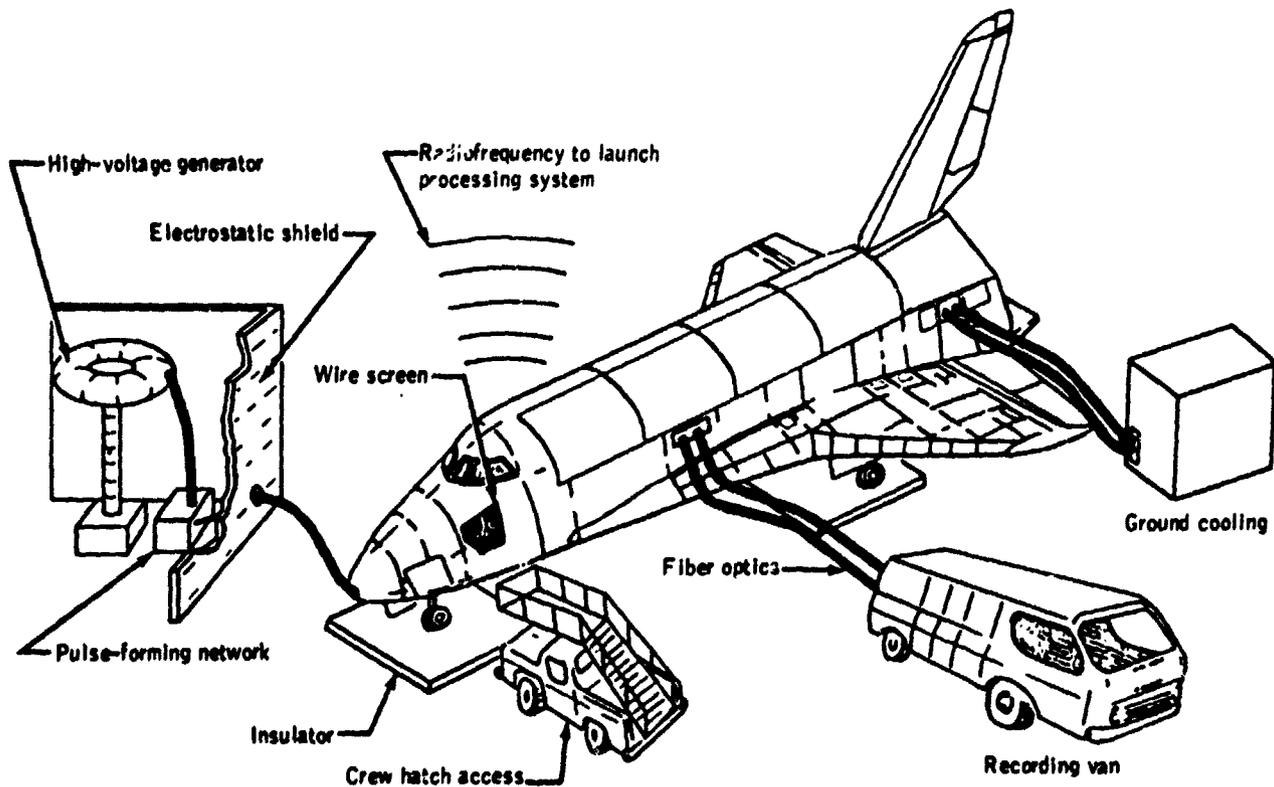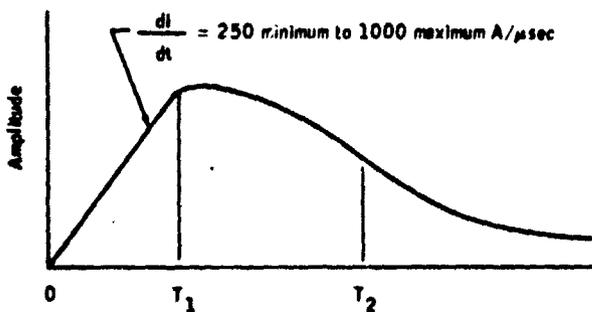
FIGURE 7. PHASE I TEST CONFIGURATION.

$\frac{di}{dt} = 250$ minimum to 1000 maximum A/μsec

T_1 (time to peak value) = 2 μsec

T_2 (time to half value) = 50 μsec

FIGURE 8. PHASE II TEST WAVEFORM.

to verify the induced-voltage predictions with the least possible risk of damaging equipment and with the least effect on program schedules. The voltage test waveforms that will be applied to the vehicle as an open-ended transmission line need further understanding in terms of their similarity to the actual voltage rise experienced by a vehicle when struck by lightning in flight. Perhaps additional data are presently available or will become available before the testing is performed. Your knowledge in this area is solicited.

REFERENCES

1. Analysis of Apollo 12 Lightning Incident, NASA Report No. MSC-01540, Feb. 1970.

2. ASTP Simulated Lightning Test Report, NASA Report No. JSC-09221, Nov. 1974.

3. Space Shuttle Lightning Protection Criteria Document, NASA Report No. JSC-07636, Nov. 4, 1975.

4. Simulated Lightning Test Shuttle .03 Scale Model, McDonnell Douglas Report No. MDC A3155, Dec. 1974.

5. Preliminary Evaluation of Space Shuttle Thermal Protection System (TPS) Response to Lightning Strikes, McDonnell Douglas Report, May 1973.

6. Swept Stroke Simulated Lightning Tests Space Shuttle Thermal Protection System, Lightning and Transients (L&T) Report No. 595, Dec. 197..

7. Lightning Test of Space Shuttle Orbiter Outer Panel Severance System Phase I, McDonnell Douglas Report No. MDC E1568, Sept. 1976.

8. Lightning Tests of Space Shuttle Pyrotechnics Phase II Rocket Booster Frustrum Separation Ring, McDonnell Douglas Report No. MDC A4864, June 1977.

9. Lightning Current Effects on the Space Shuttle External Tank Thermal Protection Systems, Martin Marietta Report No. 826-2058, Sept. 1974 (L&T Report No. 591).

10. Artificial Lightning Tests of Space Shuttle External Tank Gaseous Oxygen Line, Martin Marietta Report No. 826-2097, March 1975 (L&T Report No. 597).

11. High Current Lightning Test of Space Shuttle External Tank Lightning Protection System, Martin Marietta Report No. 826-2019, Feb. 1976.

12. TPS Covered GO_2 Line Lightning T (External Tank), Martin Marietta Report No. 826-2163, Aug. 1976 (McDonnell Douglas Report No. A4308).

13. External Tank Gaseous Oxygen Line Simulated Lightning Tests, NASA TM X-73322, 1972.

14. Simulated Lightning Discharge Current Effects on Space Shuttle Exhaust Nozzle Coolant Tubing, L&T Report No. 563, May 1973.

15. Lightning Current Distribution Tests on a Scale Model, Space Shuttle Rocket Engine, General Electric Report No. SRD-73-117, Sept. 1973.

16. Space Shuttle SRB/ET Forward Attach Point Lightning Test, George C. Marshall Space Flight Center, Nov. 1977.

17. Lightning Tests of the Shuttle SRB Nozzle Severance System, L&T Report No. 629, Feb. 1977.

18. Direct Effects Tests Space Shuttle SRB Thermal Protection System (TPS), L&T Report No. 652, Dec. 1977.

19. Static Charge Measurement and Lightning Tests of Shuttle ET Skin Welds, TPS, and Lightning Protection System, Martin Marietta Report No. 826-2171, Sept. 1977.

20. An Experimental Study of Electromagnetic Coupling Into the Shuttle SRB Cable T··· From Lightning Passage Through the Shuttl Vehicle, prepared for Mission Research Corporation by LTRI, Aug. 1975.

21. Shielding Effectiveness of a Cable Tray to be Used on the Space Shuttle External Fuel Tank, prepared by General Electric for Martin Marietta Report No. 826-2099.

22. Lightning Tests on the Shuttle SRB Nozzle Severance System Cable, L&T Report No. 629, Feb. 1977.

23. Lightning Activated Electrical Cable Shield Ground, presented by K. D. Castle of NASA at the AIAA Second Annual Technical Mini-Symposium at the Johnson Space Center, Houston, Texas, March 1977.

24. Fisher, F. A., and Plumer, J. Anderson. Lightning Protection of Aircraft. NASA Reference Publication 1008, Oct. 1977.

25. EMP Susceptibility of Semiconductor Components, Defense Department Report No. D224-13042-1, Sept. 1974.

26. Wunsch, D. C., and Bell, R. R. Determination of Threshold Failure Levels of Semiconductor Diodes, and Transistors Due to Pulse Voltages. IEEE Transactions on Nuclear Science, Vol. NS-15, No. 6, Dec. 1968.

27. EMP Electronic Analysis Handbook, Defense Department Report No. D224-10022-1, May 1973.

28. EMP Electronic Design Handbook, Defense Department Report No. D2'4-10019-1, April 1973.