JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 36, No. 4, July–August 1999

Postfire Short Circuit Phenomena of Electroexplosive Initiators

Lien C. Yang*
TRW Systems and Information Technology Group, San Bernardino, California 92408

Recent postfire electrical short circuiting of initiators in two launch vehicles has highlighted a potential problem area for all users of electrically initiated pyrotechnic devices. A high-level firing current continues to flow during the entire firing command (0.045–2 s), long after the initiator has functioned and the bridgewire has burned out. This phenomenon may introduce several undesirable side effects and failure modes. A preliminary assessment has identified a number of parameters that can affect postfire short circuiting: 1) conductivity of the burning propellant and gases; 2) conductive, unburned fuel and residue; 3) the presence of a slurry mix on the bridgewire; 4) the presence of a Viton binder in the propellant; 5) higher voltage levels in firing circuits; and 6) small initial volumes in mechanisms into which initiators are fired. A compilation is presented of the data collected on this phenomenon, and approaches are recommended to accommodate postfire short circuiting and to conduct additional diagnostic testing for possible corrective actions.

Nomenclature

I = firing current or current drawn by the initiator(s), A
t = time from beginning of application of current to the bridgewire(s) of initiator(s), s

Introduction

POSTFIRE short circuiting of direct current, electrically actuated initiators has long been recognized as a potential problem area in launch vehicle and spacecraft applications. Specifications have been generated for both electrical initiators and firing systems to help reduce the occurrence of this phenomenon. However, data collected on past NASA standard initiator (NSI) qualifications, an NSI-derived cartridge, and NSI equivalents on two recent launch vehicles indicate that postfire short circuiting remains an important issue.

Postfire electrical short circuiting occurs in direct-current firing systems, when the level of current remains constant or increases after the propellant within an initiator has ignited and burned. This level of current is sustained throughout the duration of the electronically timed firing pulse, which has been set in launch vehicles from as little as 0.045 s to as much as 2 s. The cross-sectional view of the NSI in Fig. 1 shows the path of the electrical firing signal. The current enters one electrical pin, passes through the bridgewire [a 0.0051-cm- (0.002-in.-) diam stainless-steel wire], and goes out the second electrical pin. A 5-A direct-current input to the NSI typically ignites the propellant adjacent to the bridgewire within 1 ms. The bridgewire burns within that time period, and the current soon decreases to zero. However, postfire short circuiting allows this 5-A current draw to be sustained, which can introduce several deleterious side effects.

1) The time frame for initiating multiple initiators in parallel electrical circuits can be increased. If the current draw remains high in one initiator after functioning, that current cannot be transferred to parallel initiators to accomplish more rapid initiation of the remaining units.

2) The electrical batteries can be depleted more than necessary. The greatest influence occurs with batteries that are shared in a common bus with other subsequent usages.

3) The electrical pins through the initiator body can melt and allow internal hot gases to vent, which could lead to failure of rocket motors and mechanisms.

4) A number of electrical system failure modes can be introduced. High-current draws on electrical circuits can damage resistors and batteries, as well as overload and weld mechanical contacts or stress solid-state relays.

MIL-STD-1512 (Ref. 1), the specification applied in the 1960s, required the initiator to exhibit a postfire open circuit (less than 0.05 A at 28-V dc). However, this standard has been superseded by MIL-STD-1576 (Ref. 2), DoD-E-83578A (Ref. 3), and AFR 127-1 (Ref. 4), which eliminate this requirement and allow relays, fuses, or current-limiting resistors to protect the firing systems. The NSI specification[5] still contains a requirement for a postfire 0.05-A electrical current limitation. Although some manufacturers strictly adhere to NSI manufacturing procedures for NSI equivalents, others have made changes based on customer requests, the relaxation of postfire electrical inspections, and the interest of economy. Also, because drawings and assembly procedures are usually not part of procurement packages, much of this information is considered proprietary.

NSIs and NSI equivalents were created to provide the electrical ignition interface for a wide variety of pyrotechnic applications. Prior to the Apollo program, NASA, recognizing the myriad problems being encountered with initiators, decided to create and utilize an NSI. The NSI was derived from the dual bridgewire Apollo standard initiator (ASI) and the single bridgewire Apollo standard initiator (SBASI). NASA Johnson Space Center (JSC) has the management responsibility for production and distribution of the NSI to all government agencies and their contractors. Each manufacturing lot of NSIs is certified to meet a −251°C (−420°F) functional requirement; without this certification and rigorous quality assurance documentation, no other initiator can be an NSI. NASA policy restricts the sale or transfer of Government property for private use or exposure of the Government to a shared liability for the success of a commercial project. Therefore, commercial launch vehicle managers requested NSI equivalents, which were subsequently accepted for U.S. Air Force sponsored programs. The intent was that the NSI equivalents met the same form, fit, and function, including the same output charge, as the NSI, and were thus interchangeable. However, a number of postfire short circuits have occurred with the use of NSI equivalents in several recent launches. Because the initiator firing circuits in these vehicles were designed with current-limiting resistors or could accommodate heavy current loads, the phenomenon did not cause electrical system failures. The phenomenon was rarely observed in ground-test firings because the complete electrical system and explosive devices were not used in these tests.

The purpose of the effort described in this paper is to provide information on experiences of postfire and electrical short circuit anomalies, to consider the causes, and to recommend corrective actions to reduce the opportunity of such occurrences. The approach for the effort was to compile and analyze the direct-current firing data for the

Received 21 August 1998; revision received 23 November 1998; accepted for publication 7 December 1998.

*Senior Staff Engineer, Propulsion, Structures and Fluid Mechanics Center, Strategic Systems Business Unit, 1475 E. Harry Sheppard Boulevard. Member AIAA.

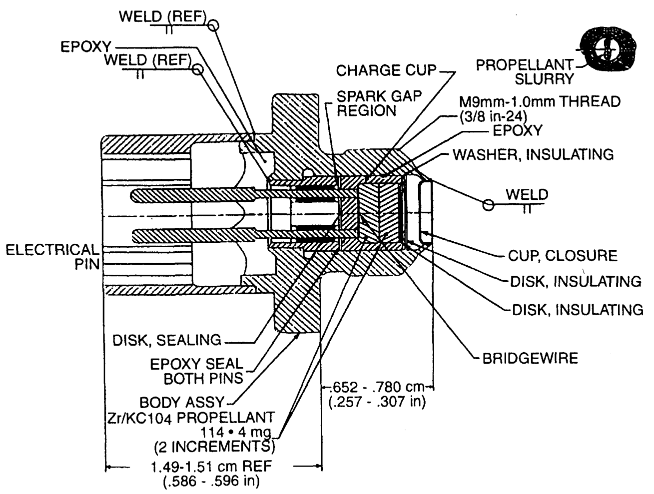

Fig. 1 Cross-sectional view of NSI.

NSI, the NSI-derived gas-generating cartridge (NGGC) (a cartridge with the NSI electrical interface), and NSI equivalents, which are used on the U.S. Air Force sponsored Multi-Service Launch System (MSLS) and Atlas Centaur launch vehicles.

Description of Initiators and Applications

This section describes the initiators evaluated in this study: the NSI, the NGGC, and the NSI equivalents with their applications.

Common to all these initiators/cartridges is the closed-bomb test used for lot acceptance. The initiator is fired into a 10-cm^3, cylindrical, closed volume (approximately 1.9 cm in diameter and 3.2 cm long). This volume is at least an order of magnitude larger than those normally found in pyrotechnically actuated devices. Prior to the 1980s, a second closed bomb with a 0.5-cm^3 volume test was required for the NSI. As given in Sec. 1.3.3, Output Pressure/Function, of Ref. 5, the initiator shall be designed to produce the following pressures and/or function time under the following conditions.

1) A pressure of $4.48 \times 10^6 \pm 0.85 \times 10^6$ Pa (650 ± 125 psig) in a 10-cm^3 volume within a temperature range from -162.2 to $+148.9$°C (-260 to $+300$°F) should be produced.

2) Time to reach 3.62×10^6 Pa (525 psig) in a 10-cm^3 volume shall not exceed 0.01 s from -162.2 to $+148.9$°C (-260 to $+300$°F) as measured from application of the current (5–22 A dc from -162.2 to -54.4°C, 3.5–22 A from -54.4 to $+148.9$°C, or with capacitor ignition circuits).

3) Prior to 1992, a minimum pressure of 3.45×10^7 Pa (5000 psi) is required in a 0.5-cm^3 volume at a pressure of 10^{-6} torr from -162.2 to $+148.9$°C (-260 to $+300$°F). (This requirement has been deleted.)

Unfortunately, as described in Ref. 6, closed-bomb tests do not represent the conditions encountered in pyrotechnically actuated mechanical devices, such as small initial free volume and piston stroke. The combination of small and changing free volume, decreasing pressure and expanding surface area to increase heat sinks has a dramatic effect[7] on the combustion process of the propellant.

Three additional differences in the application of NSIs and NSI equivalents should be highlighted: 1) NSIs on the Space Shuttle use capacitor firing circuits, in which postfire electrical short circuiting would not occur due to the short-duration pulse. 2) The NASA JSC managers of the NSI recommend that the NSI not be used as the sole energy source for pyrotechnic mechanisms, as are NSI equivalents. Thus, in the Space Shuttle, NSIs are fired into large (0.5–10 cm^3 or larger) volumes or into booster charges, whereas the NSI equivalents are applied directly to mechanisms that contain volumes that are much less than 0.5 cm^3. 3) In most NASA applications, parallel firing of multiple initiators is prohibited.

NSI

The NSI, as shown in Fig. 1, is the unit of choice for NASA and some Department of Defense programs, required for the Space Shuttle vehicle, and the recommended unit for Shuttle payloads. A 0.0051-cm- (0.002-in.-) diam, 304 stainless-steel bridgewire provides a highly controlled 1-Ω resistance for the heat source to initiate the zirconium/potassium perchlorate propellant. This propellant, which contains 5% Viton B binder and 1% carbon, is highly stable and has a fast reaction rate. Intimate contact between the bridgewire and propellant is assured through a slurry preparation process, painted and cured on the bridgewire. The left end of the housing is a standard electrical connector with a number of keyway configurations to reduce the opportunity for mismatching connections.

To date, approximately 200,000 units have functioned successfully. Special manufacturing procedures provide several advantages. The size of the production lots are usually large, 1500 units minimum. The numbers of sample units tested for lot acceptance are also large, 154 units, resulting in more thorough testing. These production lots allow dedicated engineering and quality personnel more time for detailed monitoring of production.

NGGC

The NGGC[8] was developed to deliver a greater output than the NSI. It utilizes the same housing and bridgewire interface as the NSI, including the slurry mix. However, the output charge consists of 0.04 g of zirconium/potassium perchlorate and 0.09 g of a gas-generating propellant. The NGGC is initiated with a direct-current, 200-V power supply; the voltage and current-limiting resistors can be set to provide constant-current inputs at preset levels. The NGGC as yet has no applications.

NSI Equivalents

Two major launch vehicle programs use standard initiators that are based primarily on the NSI. The two NSI equivalents in this study were manufactured by Hi-Shear Technologies. Hi-Shear uses a company-standard housing, the PC23, which is modified to meet customer requirements and given a dash number for each configuration. For example, the unit that most closely matches the NSI (without the NASA certification process) is the PC23-23. The Hi-Shear part numbers for each unit, along with the differences from the NSI, are described as follows.

PC23 Used on MSLS

This initiator was procured as PC23. No detailed requirements were made on the electrical initiation interface or the zirconium/potassium perchlorate propellant formulation. Therefore, because any PC23 type was acceptable, four or five different available lots, including different dash numbers, were provided. Two PC23 initiators are used in each of four 0.95-cm ($\frac{3}{8}$-in.) and eight 1.27-cm ($\frac{1}{2}$-in.) separation nuts and one isolation valve for the MSLS. Also used were separation thrusters that employ PC178-1 cartridges, containing dual, 1-Ω bridgewires. The applications in the mission require 3, 4, and 6 initiators to be fired in parallel. The working volume within the 1.27-cm ($\frac{1}{2}$-in.) nut is 70% greater than that of the 0.95-cm ($\frac{3}{8}$-in.) nut. Each electrical firing circuit employs a 28 ± 4 V battery with current limiting resistors to provide 5.5-A, 0.045-s gated pulse for each bridgewire. The currents drawn in each of the redundant firing systems on the MSLS were measured during flight and transmitted to ground recorders.

General Dynamics Standard Initiator Used on the Atlas Centaur Vehicle

The General Dynamics standard initiator (GDSI), part number 55-07261-1 (Hi Shear PC23-34), is identical to the NSI, except there is no slurry on the bridgewire, the first increment of propellant against the bridgewire contains no Viton binder, and the pin configuration in the connector is slightly different. The devices used on this vehicle are similar to those on the MSLS. Again, a 28-V, 5.5-A, current-limited pulse is provided. However, the gated firing pulse duration is 2 s. Firing currents were measured in flight and transmitted to ground recorders.

Study Procedure

Functional data on the available postfire short circuit phenomena for the NSI, the NGGC, and each of the NSI equivalents in each respective application were collected and reviewed. The potential causes for the observed short circuit phenomena then were analyzed, based on each particular configuration.

Results

The results of this effort are presented in the order: the NSI, the NGGC, and the NSI equivalents.

NSI

Direct current, closed-bomb, lot acceptance data on over 1000 firings of ASI and SBASI (predecessors to the NSI),[9,10] indicated a difference in postfunctioning decay of current between firings in 10 and 0.5-cm^3 closed bombs. It should be noted that the firing system used in these tests was a solid-state system, which maintained the preset current level, as the resistance at the bridgewire interface changed, until the 50-V limit voltage was exceeded. As shown in Fig. 2, for the 10-cm^3 bomb firings, the current at 3.5 A decreased exponentially to zero in 0.002 s after bridgewire burnout. The current in the 22-A firings dropped to zero in 0.0003 s after bridgewire burnout. However, in the 0.5-cm^3 bomb firings (Fig. 3), the current decays were 0.0077 s for 3.5 A and 0.0097 s for 5 A; the 22-A firing trace indicated an 8-A current draw at 0.00043 s, at which time it exceeded the recorder's time limit.

Electrical conductivity between the electrical pins occurs during the combustion of the zirconium/potassium perchlorate propellant. The following observations have been made. The burning of the zirconium/potassium perchlorate produces a highly conductive plasma and creates a temporary short circuit between the pins and between the pins and the initiator body. The level of voltage available in the firing system has a significant effect; when the bridgewire burns away, the full voltage of the firing source appears across the pins to drive an electrical current through the plasma. Conductivity is further enhanced when two cartridges are fired simultaneously in redundant devices. As long as the gases remain hot, conductivity continues. Firing into smaller volumes, as described in the preceding paragraph, produces higher pressures and requires longer times for the gases to cool. The products of combustion of a stoichiometric zirconium/potassium perchlorate (ZPP) composition are nonconductive solids, ZrO_2 and KCl, and gaseous CO_2 (due to the 5% Viton and 1% graphite additives). The ZrO_2 and KCl can only be gases in the vapor state at thousands of degrees in temperature; they quickly condense on the cool walls of the containment volume. However, because the composition is formulated to be fuel (zirconium) rich, the unburned zirconium is highly conductive.

Fuel-rich mixtures were selected to achieve a fast burn rate. The dissimilarity in particle size (zirconium 1–8 μm vs potassium perchlorate 15–20 μm) increases the opportunity for heterogeneity, reduces physical fuel-to-oxidizer contact, and ultimately yields fuel-rich residue. Heterogeneity is further exacerbated by the differences in material density (zirconium is 6.5 g/cm^3 and potassium perchlorate is 2.52 g/cm^3). The presence of unreacted zirconium is virtually inevitable. The addition of 5% Viton and 1% carbon slows the burn rate and enhances the opportunity for more complete combustion.

Ignition, burn rate, and combustion efficiency are dramatically affected[7] by the size and shape of the volume into which the NSI is fired. The ZPP formulation is very sensitive to ambient pressure and the thermal conductivity of the housing materials. The higher the pressure and the lower the thermal losses (as provided by small initial free volumes), the faster and more completely it burns, an avalanching effect. Large volumes induce lower ignition and combustion efficiencies, but do allow the burning material to be expelled from the NSI to reduce the opportunity of zirconium deposits on its electrical pins.

The presence of a bridgewire slurry mix could have an affect on postfire short circuiting. The slurry, being the first to ignite, could assist in the expulsion of the main portion of the propellant load and the reduction of combustion residue from the electrical pins, particularly in large initial free volumes.

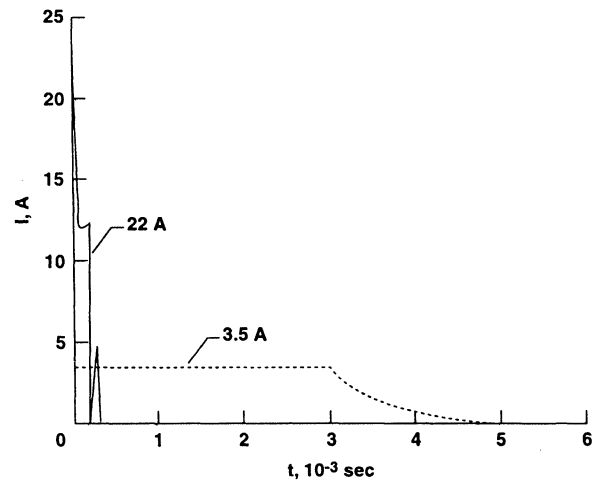

Fig. 2 Single ASI/SBASI firing current traces in 10-cm^3 bomb tests.

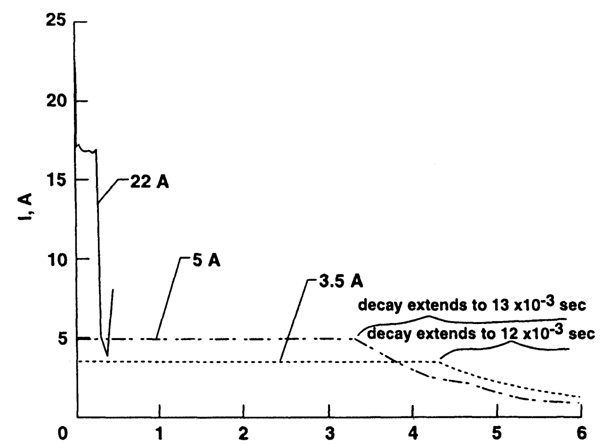

Fig. 3 Single ASI/SBASI firing current traces in 0.5-cm^3 bomb tests.

NGGC

As described in Ref. 8, the NGGC exactly duplicated the electrical ignition characteristics of the NSI. At higher current levels (15 and 20 A), however, a number of postfire short circuits were observed. These short circuits can be attributed to the high voltages applied (up to 200 V) and to firing into devices with small initial free volumes.

PC23 in the MSLS

Although the electrical initiation characteristics of the PC23 were normal (comparable to Fig. 2) during 10-cm^3 bomb firings for lot acceptance testing, actual flight data showed otherwise. In the first flight of the MSLS, firing circuit A was free of postfire short circuiting, whereas the identical redundant circuit B had severe shorting. A current trace for the firing of three PC23s in parallel in system A

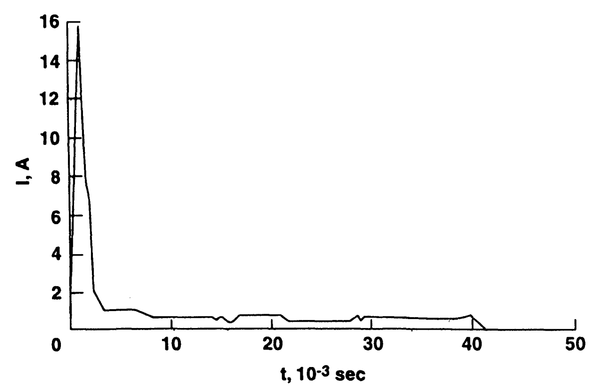

Fig. 4 Current drawn in firing three PC23s in parallel in MSLS, flight 1, system A: two PC23s in two 0.95-cm ($\frac{3}{8}$-in.) nuts and one PC23 in an isovalve.

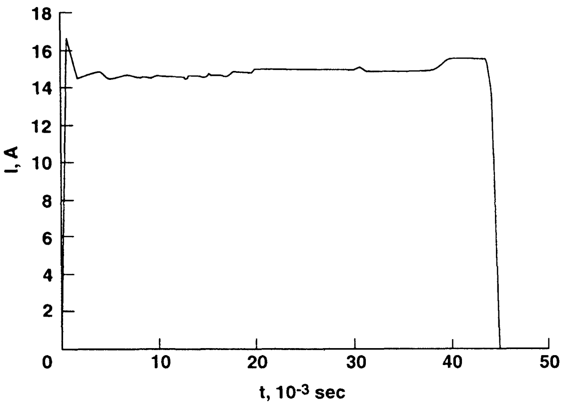

Fig. 5 Current drawn in firing three PC23s in parallel in MSLS, flight 1, system B: two PC23s in two 0.95-cm ($\frac{3}{8}$-in.) nuts and one PC23 in an isovalve.

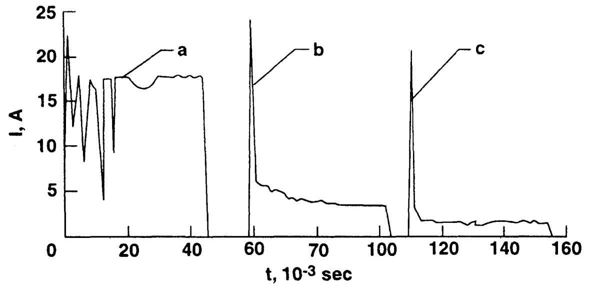

Fig. 6 Total current drawn in three MSLS flight 1 firing circuits: a, four PC23s in two 0.95-cm ($\frac{3}{8}$-in.) and two 1.27-cm ($\frac{1}{2}$-in.) nuts; b, four PC23s in four 1.27-cm ($\frac{1}{2}$-in.) nuts; and c, two PC23s in two 1.27-cm ($\frac{1}{2}$-in.) nuts and four PC178-1 bridgewires.

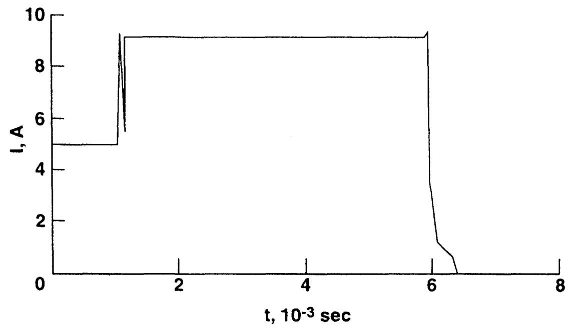

Fig. 7 Single GDSI 5-A firing current trace in a 10-cm^3 closed-bomb test.

is shown in Fig. 4, where very little postfire current draw occurred. All three of the units in system B short circuited (Fig. 5), to draw 5 A each, or a total of 15 A of current. After the initial current decrease, indicating the bridgewire burnout, the current stayed at a high level throughout the firing command of 0.045 s. Figure 6 shows three current draws in three sequential events: Curve a shows the current drawn for four PC23s in parallel in two 0.95-cm ($\frac{3}{8}$-in.) and two 1.27-cm ($\frac{1}{2}$-in.) separation nuts, indicating transient shorting and finally complete shorting of all four PC23s for the duration of the 0.045-s gated pulse. Curve b shows no indication of shorting of four PC23s in four 1.27-cm ($\frac{1}{2}$-in.) separation nuts. Curve c has no indication of shorting of two paralleled PC23s in two 1.27-cm ($\frac{1}{2}$-in.) separation nuts and in one bridgewire each of four PC178-1-actuated thrusters. Subsequent flights experienced more shorting in 0.95-cm ($\frac{3}{8}$-in.) separation nuts than did the 1.27-cm ($\frac{1}{2}$-in.) separation nuts with the 70% larger internal working volume. Again, it must be pointed out that several lots of PC23s were used on these missions; the possibility exists that more than one PC23 type was used (with and without a slurry and with and without a Viton binder).

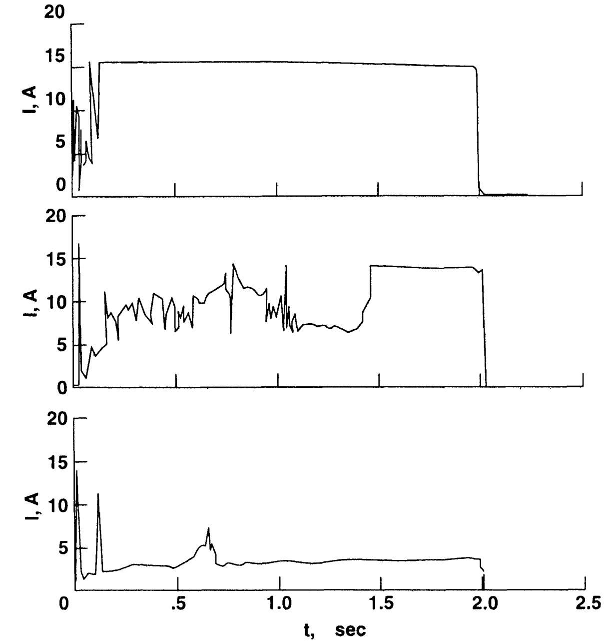

Fig. 8 Total currents drawn in firing three parallel GDSIs in Atlas Centaur flights.

GDSI in the Atlas Centaur

The GDSI exhibited postfire short circuiting in 10-cm^3 closed-bomb firings in lot acceptance testing, as shown in Fig. 7. The constant current firing circuit used in these tests was a solid-state system that could control the current level until the voltage source of 28 V was exceeded. The firing level was set at 5 A for the 0.006-s gated pulse, but the system was clearly unable to control the level once the bridgewire burned out and short circuiting occurred. In seven of the last eight flights, some of these initiators experienced postfire short circuiting for the entire 2-s duration of the firing signal. Figure 8 shows three traces of the currents drawn in flight with three GDSIs fired in parallel. The first trace indicates all three units experienced postfire short circuiting to draw 16.5 A shortly after bridgewire burnout. The second trace indicates intermittent and, finally, a complete short circuit of all three units. The bottom trace indicates that only one unit shorted to draw 5.5 A. The lack of Viton in the GDSI propellant was the likely leading contributor to short circuiting. This lack of Viton resulted in a composition that exhibited a higher initiation sensitivity, a faster burn rate, a higher combustion temperature, and higher electrical conductivity in the burning material and postcombustion residue.

Conclusions

This study has documented and analyzed the occurrence of postfire short circuiting of the electrical initiators used in pyrotechnically actuated devices. This short circuiting not only can degrade the performance of the pyrotechnic devices but also can affect the electrical firing circuit itself. Both can potentially degrade the success of flight programs. The current levels drawn from 28-V firing circuits in two launch vehicles, utilizing two different NSI equivalents, indicated that short circuiting occurred frequently. Several parameters affect postfire short circuiting: 1) Highly conductive plasma and hot gases are generated during the burning of the zirconium/potassium perchlorate propellant, causing conduction between the electrical pins, as well as between the electrical pins and the initiator body. 2) The propellant is fuel (zirconium) rich, which leave deposits of conductive, unburned fuel and residue. 3) The presence of a slurry mix on the bridgewire apparently assists in jettisoning conductive, unburned fuel and residue. 4) The presence of a Viton binder in the propellant enhances combustion and reduces the amount of conductive unburned fuel and residue; in contrast, the lack of Viton causes a more rapid combustion and higher conductivity of the burning gases and propellant residue. 5) Higher voltage levels in firing circuits force greater conduction through the plasma and hot gases of burning propellant. 6) Small initial volumes in mechanisms into which initiators are fired induce more vigorous and more complete combustion, as well as higher, longer duration pressure pulses to prolong conductivity. Although the electrical interface to the propellant of the NSI was not totally immune to short circuiting in this evaluation, the two types of NSI equivalents exhibited a much higher sensitivity to the listed parameters. The most likely cause is the lack of a slurry mix on the bridgewire and elimination of the Viton binder. Although there is apparently a low-frequency occurrence of postfire short circuiting with the NSI electrical interface (only observed with high-voltage firing systems), this study can offer no guarantees. The parameters in manufacturing and applications could eventually produce the conditions that allow postfire short circuiting.

Recommendations from this study fall into two categories: coping with the potential of postfire short circuiting of initiators and investigating the opportunities to reduce this phenomenon.

Users of any electrical initiator should be aware of the potential for experiencing short circuiting and should design and demonstrate that their systems can accommodate this phenomenon. The electrical initiation characteristics of initiators should be evaluated in the actual pyrotechnic mechanisms, using the actual electrical circuits intended for flight. Capacitor-discharge firing circuits with short-duration gated pulses will reduce the possibility of current overloads and long-term conduction.

To reduce the opportunity of postfire short circuiting through initiator redesign, further investigations are needed to determine the effects of the six parameters listed here.

Acknowledgments

The author wishes to acknowledge the support of the following in providing historical, management, design, and performance information: B. Wittschen and C. Hohmann of NASA Johnson Space Center; F. Silverman of Hi-Shear Technologies; S. Barlog of UPCO; E. G. Anderson and M. Kirchoff of Lockheed Martin; and J. J. Dougherty, B. Kliewer, J. N. Mason, J. C. McMunn, J. W. Wee, and E. J. Kovacic of TRW. A special acknowledgment is due to L. J. Bement of NASA Langley Research Center for his encouragement in writing this paper, for providing the bulk of the references, and for many discussions and a critical review of this paper.

References

[1]"Military Standard, Electroexplosive Subsystems, Electrically Initiated, Design Requirements and Test Methods," U.S. Air Force, MIL-STD-1512, March 1972.

[2]"Military Standard, Electroexplosive Subsystems, Safety Requirements and Test Methods for Space Systems," U.S. Air Force, MIL-STD-1576, July 1984.

[3]"Military Specification, Explosive Ordnance for Space Vehicles (Metric), General Specification for," U.S. Air Force Space Div., DOD-E-83578A, Los Angeles AFB, CA, Oct. 1979 and Oct. 1987.

[4]"Air Force Regulation, Range Safety Manual for the Western and Eastern Test Ranges," U.S. Air Force, AFR 127-1, Dec. 1997.

[5]"Design and Performance Specification for NSI-1 (NASA Standard Initiator-1)," NASA SKB26100066, rev. D, March 1992.

[6]Bement, L. J., and Schimmel, M. L., "Cartridge Output Testing: Methods to Overcome Closed-Bomb Shortcomings," *SAFE Symposium*, Survival and Flight Equipment Association, Nashville, TN, Dec. 1990.

[7]Bement, L. J., and Schimmel, M. L., "A Manual for Pyrotechnic Design, Development and Qualification," NASA TM 110172, June 1995.

[8]Bement, L. J., Schimmel, M. L., Karp, H., and Magenot, M. C., "Development and Demonstration of an NSI-Derived Gas Generating Cartridge (NGGC)," *1994 NASA Pyrotechnic Systems Workshop*, Albuquerque, NM, NASA CP 3258, Feb. 1994, pp. 177–190.

[9]"Initiator, Electrical Hotwire," Space Ordnance Systems, Inc., Qualification Test Rept. 1055, El Segundo, CA, May 1965.

[10]"Single Bridgewire Apollo Standard Initiator (SBASI)," Space Ordnance Systems, Inc., Qualification Test Rept. 6068, El Segundo, CA, Oct. 1966.

I. E. Vas
Associate Editor