AIAA 81-0711R

Ignitor Plug Operation in a Pulsed Plasma Thruster

Graeme Aston* and Lewis C. Pless*
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, Calif.

Results are presented of a 1-mlb pulsed plasma thruster ignition system study. An ignitor plug, producing a plasma stream is used to ignite this type of electric thruster. Parameters investigated during these tests were ignitor plug deposition, erosion, optimum plug electrical coupling to the thruster cathode, and the manner in which the ignitor plug arc is initiated. The results of these tests indicate that inductive rather than resistive coupling of the ignitor plug to the thruster cathode and the use of a high-current, short-pulse-length plug trigger circuit offer significant increases in ignitor plug lifetime.

Introduction

THE 1-mlb pulsed plasma thruster (PPT) has been developed as a viable alternative to hydrazine thrusters for large satellite stationkeeping and drag makeup functions. Figure 1 illustrates, schematically, the basic components pertinent to PPT operation. As indicated, the ignitor plug semiconductor breaks down upon the application of a fast risetime voltage pulse from the plug trigger circuit. The plasma puff produced from this semiconductor arc breakdown initiates an arc discharge between the thrusters cathode and anode electrodes. This arc is sustained by the depolymerization and ionization of Teflon fuel bars (not shown in Fig. 1) until the energy stored in the discharge capacitor bank has been consumed. Electromagnetic body forces within the discharging arc accelerate the dense Teflon plasma along the rail-type cathode and anode electrodes. The accelerated plasma pulse is ejected from the thruster with exhaust velocities which can be as high as 50,000 m/s. Typically, the 1-mlb PPT arc discharge pulse length is of the order of 30 μs. Increasing the total energy per pulse and/or the pulse repetition rate results in a corresponding increase in the time-averaged thrust. Presently the 1-mlb PPT has an efficiency (less power processor) of 35%, a specific impulse of 2000 s, and a nominal equivalent steady-state thrust of 4.45 mN. The PPT design lifetime is 1.4×10^7 pulses, yielding a total impulse of 312,000 Ns. However, the demonstrated lifetime of the 1-mlb PPT is approximately 2×10^6 pulses. The PPT ignitor plug has been identified as a major life-limiting component of the thruster.[1]

Although ignitor plugs have been used successfully in several flight qualified and flight tested micropound pulsed plasma thrusters their use in the 1-mlb pulsed plasma thruster has met with minimal success.[1] Early tests showed that the ignitor plug cathode underwent severe erosion when the plug was pressfitted into the thruster cathode with the plug cathode and thruster cathode electrically connected directly, as in the case of micropound thruster designs. An apparent remedy for this problem was to isolate the ignitor plug from the main cathode by a 0.76-mm vacuum gap and use a 1.0-Ω resistor to electrically connect the plug cathode and thruster cathode. However, this approach resulted in large amounts of carbonaceous deposits accumulating on the plug face. Eventually these carbonaceous deposits would become sufficiently thick and conducting to effectively short circuit the ignitor plug semiconductor element and prevent plug firing with the subsequent cessation of thruster operation. To overcome this deposition problem a different trigger circuit design was implemented. This new trigger circuit produced a low-voltage, high-current pulse which continued to fire the plug reliably with large deposits accumulated on the plug face. Using this redesigned trigger circuit, Palumbo and Begun were able to continue a thruster life test until approximately 2×10^6 thruster pulses were obtained on a 1-mlb PPT before voluntary shutdown.[2] However, the ignitor plug face was heavily encrusted with deposit at the termination of these tests and it is not known how much longer the ignitor plug would have continued to operate reliably.

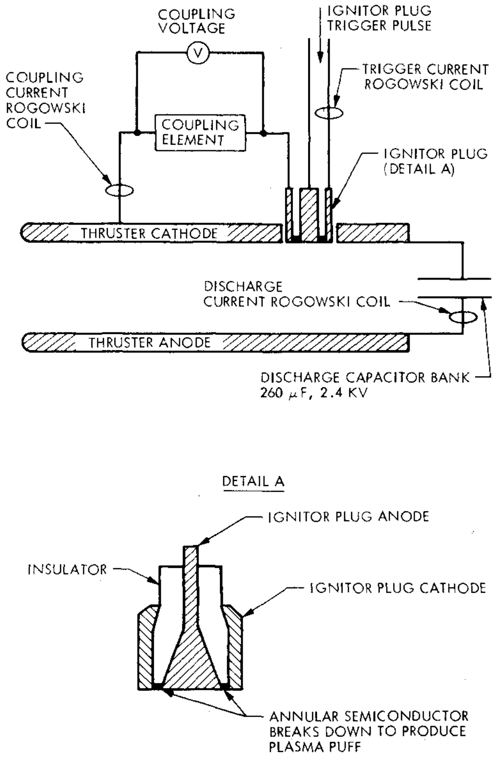


Fig. 1 1-mlb pulsed plasma thruster discharge chamber component locations.

Presented as Paper 81-0711 at the AIAA/JSASS/DGLR 15th International Electric Propulsion Conference, Las Vegas, Nev., April 21-23, 1981; submitted April 29, 1981; revision received Oct. 9, 1981.

*Member Technical Staff, Electric Propulsion and Advanced Concepts Group. Member AIAA.

The results of the above 1-mlb PPT life tests illustrated the sensitivity of the link between ignitor plug erosion, deposition, and thruster lifetime. In order to better understand ignitor plug erosion and the arc initiation processes in a 1-mlb pulsed plasma thruster, a study was initiated to examine these phenomena. The specific objectives of this study were 1) to determine the coupling required between the 1-mlb PPT ignitor plug cathode and the main discharge cathode to give the best thruster system lifetime and 2) to develop a basic understanding of the PPT ignition process in order to provide guidelines for ignition subsystem improvements.

Apparatus and Procedure

The 1-mlb pulsed plasma thruster used to obtain the results contained in this paper was a laboratory model developed originally to investigate thruster exhaust plume characteristics and has been described in detail elsewhere.[3] For this study, several changes to the thruster were made to incorporate recent thruster performance improvements. These changes included the installation of long-rail-type cathode and anode electrodes which previous test programs had shown increased electrode life and substantially increased the thrust efficiency and specific impulse.[4] Also, the ignitor plug mounting was modified to permit a 0.76-mm vacuum gap separation between the plug cathode and thruster cathode electrode. Finally, the redesigned trigger circuit of Palumbo and Begun,[2] which utilized a 1½: 1 step-down impulse transformer to supply a 400-V high-current pulse to fire the plug, was also incorporated into the thruster.

All thruster testing was done in a 1.8×3.0 m vacuum chamber pumped by a single 0.5-m oil diffusion pump. Average background tank pressure was 2×10^{-5} Torr during normal thruster operation. This tank had a LN_2 cooled liner. The thruster was positioned immediately above a large LN_2 cooled plate to facilitate thruster temperature control. Normal thruster operation was at a pulse repetition rate of 0.2 Hz and a capacitor voltage of 2.4 kV. The vacuum tank and associated thruster power supplies were capable of maintaining normal thruster operation, barring unforeseen facility breakdowns, in an unattended mode for an indefinite period.

Rogowski current pickup coils were selected as the principal thruster diagnostic. Figure 1 shows the placement of the Rogowski coils used on the thruster. In turn, these coils measure the main discharge or arc current from the discharging thruster capacitor bank, the current supplied by the trigger circuit to fire the ignitor plug, and the coupling current exchanged between the plug cathode and main discharge cathode. All Rogowski coils used 100-μs passive integrators. Also shown in Fig. 1 is a differential voltage probe which was used to measure the voltage developed across the plug cathode to main cathode coupling element.

Coupling Resistance Variation

From observations and conclusions made during other test programs[2] it was apparent that there must be an optimum amount of carbonaceous deposit required on the ignitor plug face for reliable plug operation. It was hypothesized that too much deposit acted as a low impedance in parallel with the plug semiconductor element, tending to short-out the plug and resulting in unreliable plug firing. Conversely, too little deposit meant that the plug microplasma was composed primarily of ablated semiconductor and plug cathode and anode electrode material, leading to excessive plug wear. Preliminary experiments suggested that the amount of plug deposition might be affected by the value of the resistor used to electrically couple the plug cathode and discharge cathode electrode.[2] A series of experiments was conducted to further investigate this relationship. Figure 2 illustrates the results of these tests. For these tests, ignitor plug resistance was selected as the variable most representative of a change in the carbonaceous deposit on the plug face. Ignitor plug resistance was measured using a constant current, 0.1-mA, dc, resistance measuring circuit. The selection of 0.1 mA as the measuring current was not arbitrary. Tests indicated that the plug resistance was temperature sensitive and that larger values of applied current could heat the 0.5-mm-thick plug semiconductor material significantly. Plug resistance measurements were taken at selected times during the test period. The thruster was turned off and the plug was not firing during the time the plug resistance was measured. The accuracy with which the plug resistance was measured was ±0.5 Ω. The results shown in Fig. 2 indicate that varying coupling resistance from 0.050 Ω to a near zero value had a detrimental effect on plug operation. Thruster misfiring became evident when the plug resistance reached about 1.4 Ω. Shortly thereafter the PPT ceased operating and the tests were terminated.

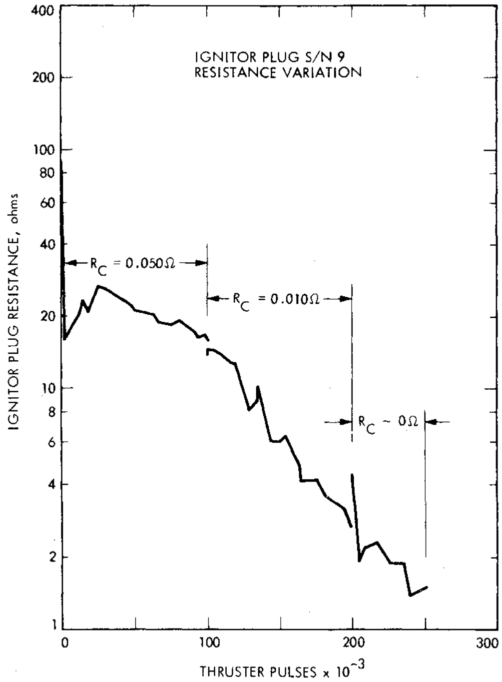
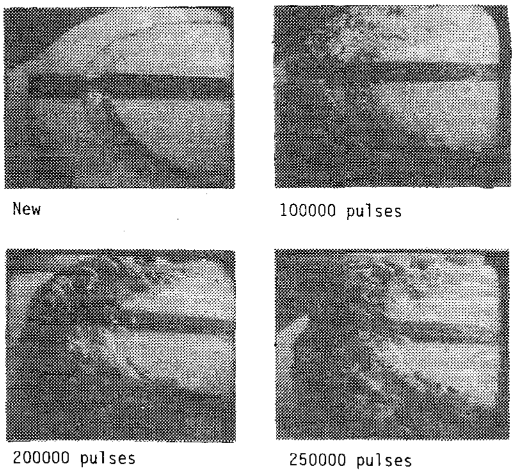


Fig. 2 Resistance variation for ignitor plug S/N 9.


New

100000 pulses

200000 pulses

250000 pulses

Fig. 3 Deposit accumulation on plug S/N 9 with decreasing coupling resistance and increasing thruster pulse number.

Although only approximately 250,000 thruster pulses were obtained with plug S/N 9, the plug face was very heavily coated with a carbonaceous deposit. The accumulation of this deposit appeared to increase as the coupling resistance value was decreased to a near zero value (~0.001 Ω). Evidence of

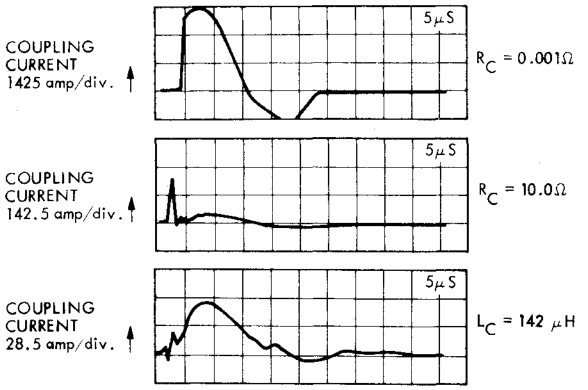


Fig. 4 Effect of coupling element on coupling current.

the accumulation of deposit on the face of plug S/N 9 is shown in Fig. 3. To obtain the scanning electron microscope micrographs shown in Fig. 3, ignitor plug S/N 9 was removed from the thruster at the end of each coupling resistance test. These photos show that the thickness and spread of the deposit on the plug face increases in proportion to the number of thruster pulses. In a similar manner, it can be observed that mild erosion of the plug anode is occurring simultaneously with the heavy deposit buildup on the plug cathode and semiconductor. It should be noted that a slot 0.027 in. (0.69 mm) wide with a depth of 0.020 in. (0.51 mm) was deliberately cut into the face of plug S/N 9 prior to testing. This slot provided a reference mark for the scanning electron micrographs and served as a basis by which erosion and deposition of the plug face could be determined.

As the coupling resistance between the plug cathode and discharge cathode was decreased (Fig. 1), the coupling resistor current increased. Peak coupling current values of approximately 1250-2500 A were observed for a 0.050-Ω coupling resistance. These peak values increased to approximately 3500-4400 A with a shorting wire in place of the coupling resistor. The fact that such large currents were attaching themselves to the ignitor plug and significant deposition still occurred, suggested that it was not feasible to burn off deposited products by intensifying discharge chamber arc attachment to the plug. Rather, just the reverse seems to happen and it appears that arc attachment to the plug face is the medium, or mechanism, by which ablated Teflon products are transferred to the plug face.

Coupling Inductance Tests

From the results presented in the previous section it became apparent that the magnitude of the coupling current exchanged between the plug cathode and discharge cathode, as a result of discharge chamber arc attachment to the plug face, had a strong bearing on the accumulated plug deposit. In an effort to reduce the coupling current, thruster testing was initiated with a 10.0-Ω coupling resistor and then with the coupling resistor replaced entirely by a low-resistance 142-μH coupling inductor. Figure 4 illustrates the variation in the coupling current trace when 0.001- and 10.0-Ω coupling resistors and a 142-μH coupling inductor were used as coupling elements. It is noteworthy that a four-decade change in coupling resistance only produced an order of magnitude change in peak coupling current. From Fig. 4 it is evident that the coupling inductor, with its relatively long charging time constant, has effectively damped the coupling current pulse.

Short (~100,000 pulse) life tests were conducted wherein ignitor plug S/N 2 was used with the 10.0-Ω coupling resistor of Fig. 4 and plug S/N 1 was used with the 142-μH coupling inductor of Fig. 4. The results of these life tests are presented in Fig. 5. Here, the ignitor plug resistance variation of each plug and coupling element tested is plotted as a function of thruster pulse number. For comparison purposes the resistance variation of plug S/N 9 using the 0.050-Ω coupling resistor is shown also. Figure 5 shows the dramatic effect inductive coupling has on the ignitor plug resistance variation. With the 142-μH coupling inductor, plug resistance stayed approximately constant at 120 Ω. Inspection of ignitor plug S/N 1 after this test showed the plug to have significantly less deposit accumulated on its surface than either plug S/N 9 or S/N 2 after the same test period.

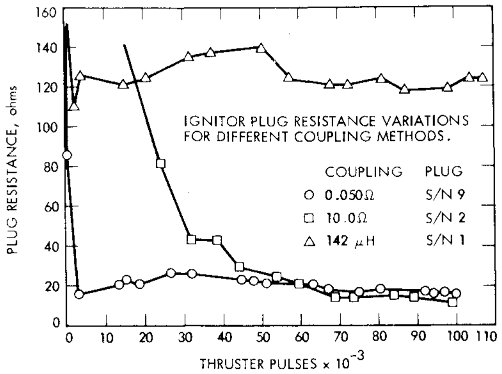


Fig. 5 Effect of coupling element on ignitor plug resistance.

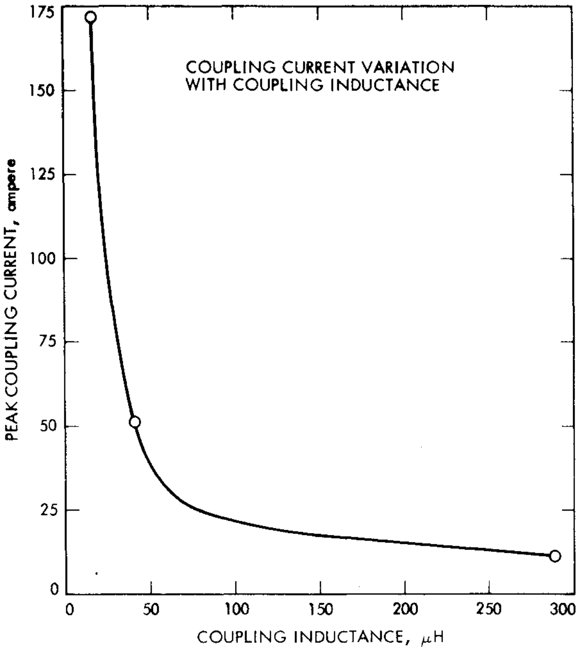


Fig. 6 Effect of coupling inductance on peak coupling current.

From the results presented in Fig. 5 it was evident that inductive coupling promised some control over ignitor plug deposition and the variation of ignitor plug resistance. Since both the these phenomena appeared to be directly related to the peak coupling current, a range of coupling inductor values were investigated experimentally to determine their effect on peak coupling current. Figure 6 shows the results of these tests. From Fig. 6 it is apparent that increasing the coupling inductance value much above 100 μH has only a small effect on the peak coupling current. It should be noted that all the coupling inductors tested in Fig. 6 were wound to give similar resistance values. Also, peak coupling currents varied appreciably from pulse to pulse for each coupling inductor tested. Consequently, the magnitude of the peak coupling currents presented in Fig. 6 are average values only.

Trigger Circuit Tests

The coupling inductor tests with ignitor plug S/N 1 (presented in Fig. 5) indicated that inductive coupling was likely to result in a constant plug resistance at least an order of

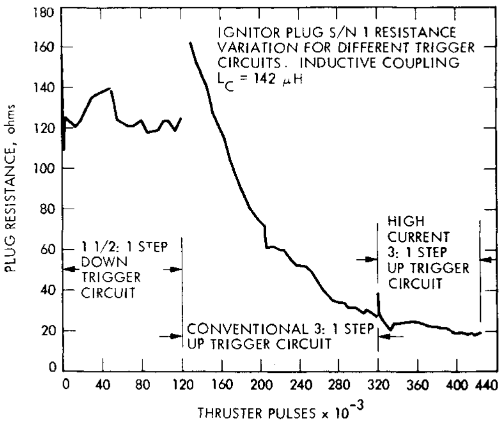


Fig. 7 Effect of different trigger circuits on ignitor plug S/N 1 resistance.

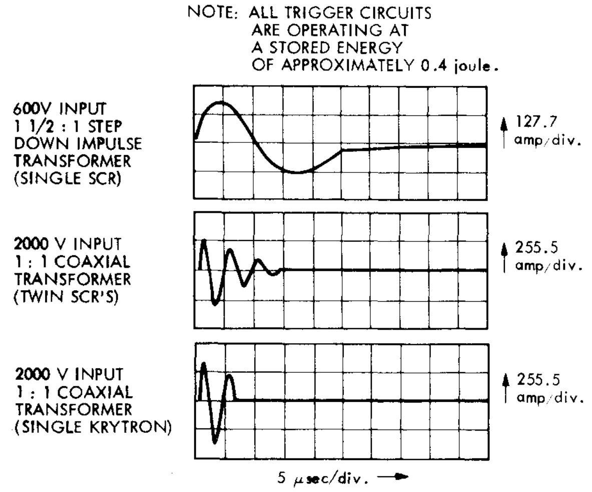


Fig. 8 Effect of different trigger circuit designs on trigger current pulse width.

magnitude larger than typically obtained with resistive coupling. Since the ignitor plug trigger circuit used thus far in the experiment had been designed specifically to fire efficiently heavily deposited ignitor plugs of low-resistance value, it was thought that this trigger circuit might not be appropriate for the cleaner, higher-resistance plugs characteristic of inductive coupling. To test this hypothesis the plug trigger circuit originally developed by Guman[5] for the microthruster, which used a 3:1 step-up 1800-V output impulse transformer, was connected to the thruster, and life testing of plug S/N 1 was continued.

Use of the 3:1 step-up trigger circuit immediately reduced ignitor plug resistance at a rapid rate. After 200,000 pulses with this trigger circuit the resistance of ignitor plug S/N 1 had decreased from an average value of 120 Ω to about 20 Ω. Comparing the trigger circuit current pulse from the previously used 1½:1 step-down 400-V output trigger circuit to that of the 3:1 step-up 1800-V output trigger circuit showed that there was significantly less current flowing from the step-up trigger circuit than the step-down trigger circuit. It was reasoned that this reduction in trigger circuit current flow decreased the amount of carbonaceous deposit blown off the plug face during the ignitor plug discharge. This decreased blowoff apparently leads to an increasing accumulation of deposit on the plug face after each thruster pulse. In an effort to increase the trigger circuit current without altering any other parameters, two of the 3:1 step-up impulse transformers were connected in parallel to produce a higher current 1800-V pulse. This configuration was then used to trigger plug S/N 1 and the thruster discharge for an additional 100,000 pulses. It should be mentioned that the 1½:1 step-down, 3:1 step-up, and dual 3:1 step-up trigger circuits used during the testing of plug S/N 1 all used an identical amount of trigger circuit capacitor energy storage.

Figure 7 details the resistance variation of ignitor plug S/N 1 for each of the three different trigger circuits described above. It is apparent from Fig. 7 that the high-current, dual 3:1 step-up trigger circuit configuration decreased the rate at which plug resistance was declining. The sharp break in plug resistance shown between the termination of plug testing with the 1½:1 step-down trigger circuit and the start of the 3:1 step-up trigger circuit tests was a manifestation of removing the ignitor plug from the vacuum environment for a series of scanning electron micrographs. Experience has shown that exposing an ignitor plug to air tends to increase its resistance. However, this effect is temporary and returning the plug to a vacuum environment with continued plug operation quickly reconditions the plug to its previous resistance trend. Presumably, this behavior is a result of water absorption on the plug face and/or atmospheric chemical modification of the ever present carbonaceous deposit, as suggested by Palumbo and Begun.[2] During testing of the 3:1 step-up trigger circuits shown in Fig. 7 the ignitor plug was not exposed to the atmosphere and this is why no sudden break in resistance is apparent.

The test results presented in Fig. 7 suggested that the trigger circuit current level was important in the control of the carbonaceous deposit accumulated on the face of an ignitor plug in a 1-mlb PPT. Examination of the current pulses characteristic of the 1½:1 step-down, 3:1 step-up, and dual 3:1 step-up trigger circuits showed that these current pulses typically had pulse lengths on the order of the main thruster arc pulse length (~30 μs). Since an ignitor plug discharge was necessary only to fire the thruster, an effort was made to reduce the trigger circuit pulse length to as short a time as possible. By doing this the trigger circuit current would be increased, assuming the trigger circuit stored energy was held constant. It quickly became apparent that the type of impulse transformers normally used in PPT trigger circuits were not capable of the short pulse widths being sought. A coaxial impulse transformer design was ultimately used because this design was capable of very short pulse widths and was very easy to fabricate. The design selected used a 1:1 turn ratio with a 2000-V input voltage. Owing to the high voltage, two methods of switching were investigated. One method used two 1200-V silicon controlled rectifiers in series while the other method used a single Krytron cold cathode gas filled switch tube. Typical trigger circuit current pulses for these two switching methods are presented in Fig. 8. For comparison the current trace from the 1½:1 step-down trigger circuit is shown also. All the current pulses in Fig. 8 were obtained with the trigger circuits firing ignitor plug S/N 7 during normal thruster operation.

A new life test was initiated using ignitor plug S/N 7 and the coaxial impulse transformer trigger circuit designs discussed above. Initially, plug S/N 7 was operated for 100,000 thruster pulses using the new trigger circuit design with the twin SCR switching method. These tests were terminated at the end of this time period because of an SCR failure. At this time, the Krytron switching apparatus was installed in the trigger circuit and the tests were resumed. However, the inherently shorter lived Krytron tube lasted only 50,000 thruster pulses before it failed. A new Krytron tube was installed after this failure but this tube lasted only an additional 70,000 thruster pulses before it also failed. In spite of these mishaps, the overall test results were encouraging. Figure 9 shows that the resistance of plug S/N 7 was increasing throughout these tests (to minimize plug deposition caused by large coupling currents, a 288-μH coupling inductor was used). At the time of the SCR failure the plug was inspected visually. Its face was shiny and showed no obvious accumulation of deposit. Points A and B in Fig. 9 pertain to logic upsets in the thruster control circuitry which caused power supply but not vacuum system shutdown. The failure

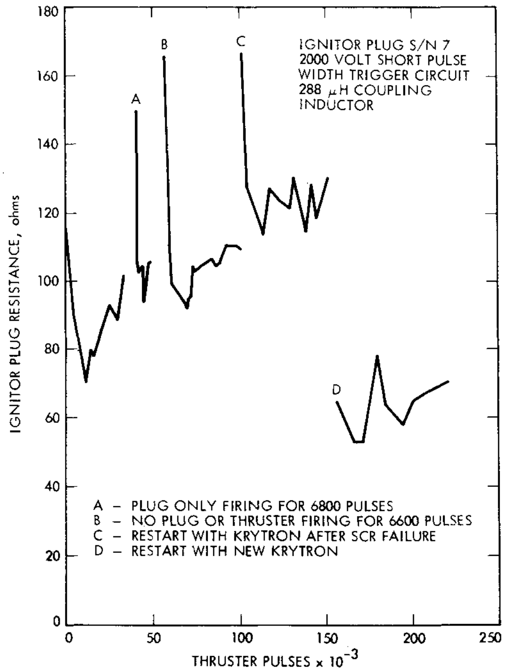


Fig. 9 Resistance variation for ignitor plug S/N 7, using the experimental trigger circuit and a 288-μH coupling inductor.

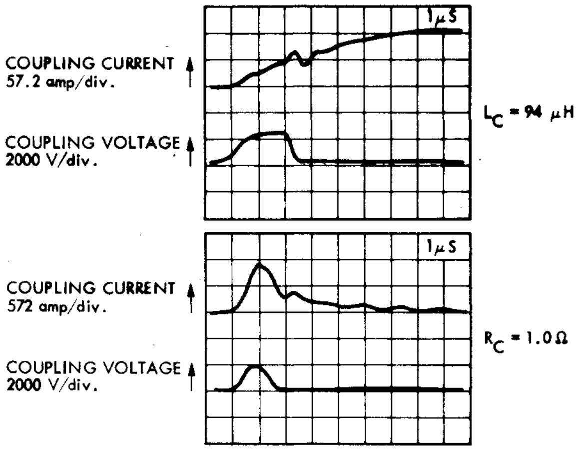


Fig. 10 Relationship between coupling current and voltage for inductive and resistive coupling.

mechanism of the Krytron tube was such that it began firing very rapidly. As a result, an essentially sustained arc was produced within the thruster discharge chamber for several minutes before the failure was detected and thruster shutdown effected. This arc produced a lot of carbonaceous deposit on the plug face and this is why the plug resistance at point D started at a low value. It is noteworthy that the average plug resistance from this point onward still seemed to be increasing.

PPT Current Interactions

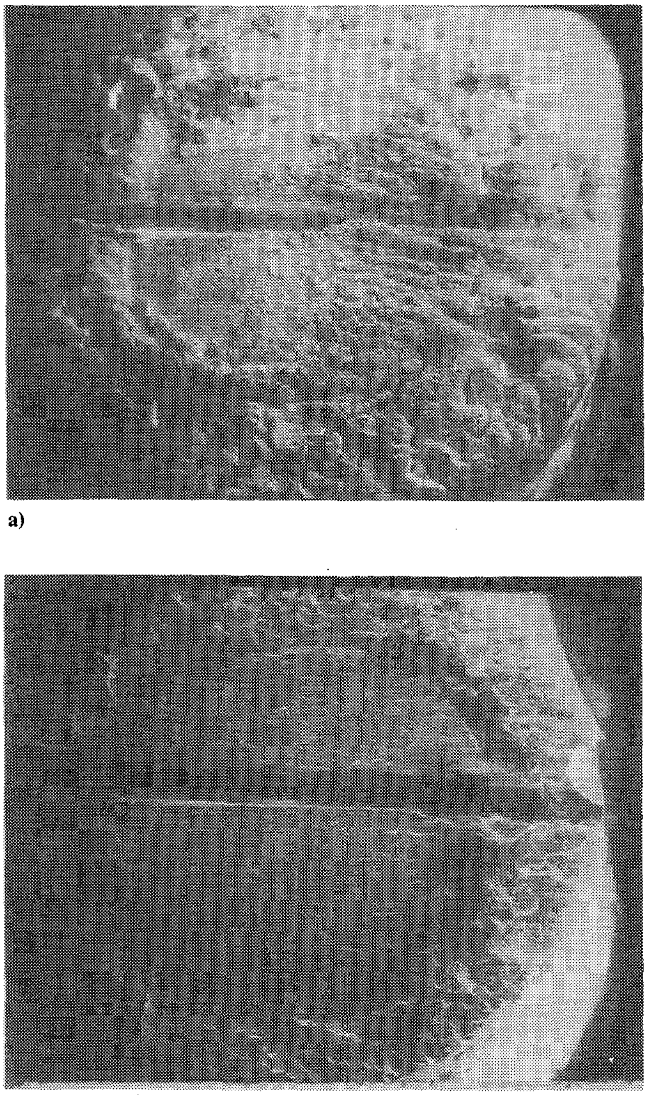
Although they are not presented here, numerous data collected during this test program indicated the presence of many plasma current flow paths between the ignitor plug discharge, the thruster discharge, and the coupling element. One of the physically more interesting relationships was that between the coupling current and coupling voltage. Figure 10 shows oscilloscope traces of these parameters for a 94-μH coupling inductor and a 1.0-Ω coupling resistor. In both cases the start of the coupling current and voltage rise corresponds to the instant the ignitor plug has fired. It can be observed from Fig. 10 that for both resistive and inductive coupling a voltage of approximately 2000 V is impressed across the coupling element very soon after the plug has fired. Careful study of the thruster discharge current pulse showed that the current flowing through the coupling element during this time was coming from the thruster energy storage capacitors. Thruster firing is accompanied by a sudden drop in coupling element voltage, either a rise or fall in coupling element current, and an extremely rapid rise in the thruster capacitor discharge current of the order of 10^{10} A/s.

From Fig. 10 the following insight into the arc initiation process in a PPT can be obtained. Since only the thruster energy storage capacitors can supply the amount of sustained voltage seen on the coupling elements, it follows that immediately after the plug begins firing, its microplasma creates a low impedance path between the plug and the thruster anode electrode. Owing to the extremely low inductance of the thruster capacitors and strip lines (a few nanohenrys), these capacitors begin discharging almost instantaneously through the current path between this plasma shunt and the coupling element (Fig. 1). Evidence of the low impedance of this microplasma shunt is given by the large voltage drop appearing across the coupling element which is almost equal to the thruster capacitor charging voltage. This arc attachment to the plug face occurs until such time as the thruster cathode electrode is linked into this plasma current path. When this linkage occurs, the main discharge starts in earnest and is fed from the ablating and ionizing Teflon fuel bars. With the initiation of the thruster discharge, observations show that the coupling element voltage is reduced to a near zero value, while the thruster capacitor voltage still has a large value. The implication is that the discharge plasma creates a shorting current path between the ignitor plug cathode and the surrounding thruster cathode electrode. Further evidence for such a path is given by other data (not presented here) which show a definite link between the trigger circuit current pulse and the coupling current pulse after the main discharge has been initiated. The conclusion reached in this case was that for the typical long-pulse-length trigger circuits that continued to fire the plug long after the thruster discharge was initiated, the discharge plasma formed a current path between the plug anode and the thruster cathode. The desire to eliminate this extraneous current path was part of the motivation in designing the shorter-pulse-length trigger circuits described earlier.

Ignitor Plug Erosion Mechanisms

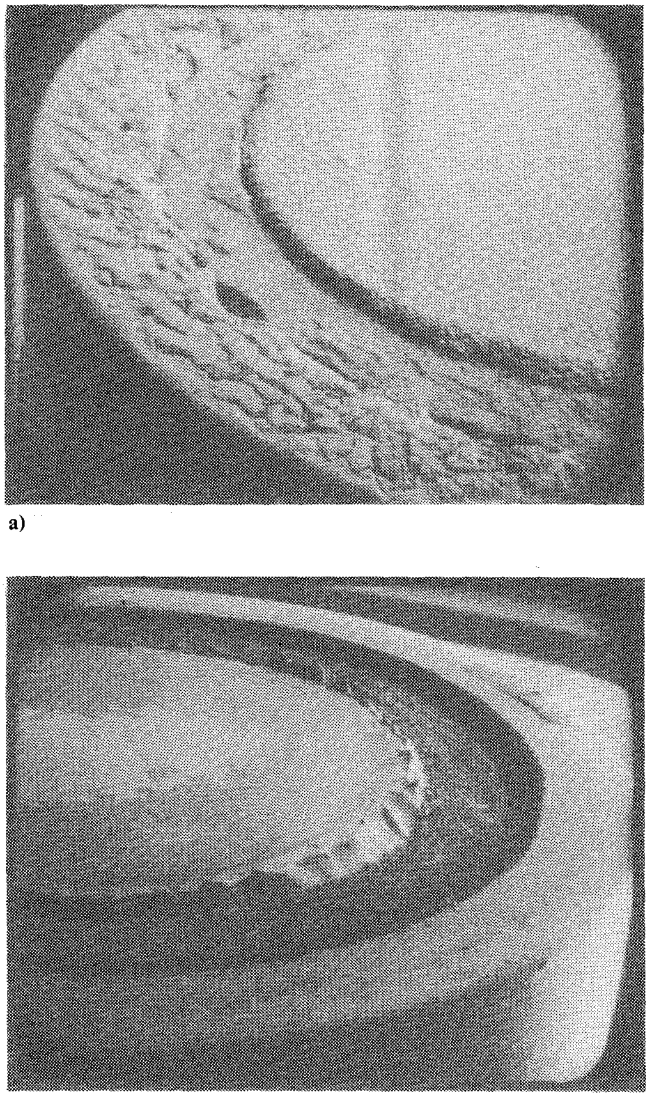
Throughout the PPT ignition study a consistent effort was made to examine all the ignitor plugs used before, during, and after the various test programs in order to determine those erosion mechanisms acting to degrade the plug face. Perhaps the most obvious plug erosion mechanism encountered during this test program was the plug embrittlement problem, which has been reported elsewhere.[2] After the resistive coupling tests of plug S/N 9 (Fig. 2), this heavily deposited plug was cleaned of deposit on its face using a high-speed nylon brush. The results of this cleaning operation were dramatic. Beneath those areas where the deposit lay on the plug face, the base material was embrittled and flew off in small chunks as the rotary brush was applied. Figure 11 compares the cleaned face of plug S/N 9 to the uncleaned face of this plug at the end of the test period shown in Fig. 2. The relationship between previous plug deposit and plug embrittlement is striking. Most of the embrittlement has occurred on the plug cathode (outer ring in Fig. 11) where the deposit was heaviest. It is interesting to note that on those areas where no deposit lay, only the slightly textured appearance reminiscent of plasma sputtering is evident.

An analysis of the deposit on plug S/N 9, and on other plugs used during this test program, was performed. These analyses showed the deposit to be a very complex fluorocarbon with small amounts of oxygen also incorporated. The C/F ratio of this deposit was 1.1 which was significantly more than the C/F ratio of 0.5 for the virgin Teflon used as the thruster fuel bars. Analysis of the ignitor plug face immediately below the carbonaceous deposit


a)

b)

Fig. 11 Face of ignitor plug S/N 9 a) before and b) after cleaning, showing the embrittlement phenomena.


a)

b)

Fig. 12 a) Face of ignitor plug S/N 7 showing embrittlement and plasma sputter erosion. b) Face of ignitor plug S/N 3 showing damage caused by trigger circuit current pulse.

showed a higher proportion of carbon with a C/F ratio of 2.7. Some of the fluorine on the plug face was found to exist as F^- and to be in good electrical contact with the metals making up the ignitor plug (the plug cathode is Inconel, while the plug anode is Kovar). Other tests on the deposit that normally accumulates on the copper thruster electrodes indicated the presence of copper fluorides with a F/Cu ratio of about 1.2. From these test results it appears that the cause of the plug embrittlement problem may be fluorine chemical attack of the base metals composing the ignitor plug and/or the formation of brittle metallic carbides.

It was realized early in the ignition study that reducing the amount of plug deposit and consequently the amount of plug embrittlement (since the two do seem to be directly related) was very important so that the more subtle effects of plasma sputter erosion would not be completely masked. The test sequence using plug S/N 7 described earlier (Fig. 9) represented a situation where ignitor plug deposition was minimized. Inspection of plug S/N 7 provided some estimation of ignitor plug plasma sputter erosion. Figure 12 shows the face of ignitor plug S/N 7 after its surface had been cleaned with a nylon brush at the end of the test sequence documented in Fig. 9. For comparison with plug S/N 7, ignitor plug S/N 3, which was fired for approximately the same number of pulses and trigger circuit energy but not with an accompanying thruster discharge, is shown also in Fig. 12.

As mentioned in an earlier section, ignitor plug S/N 7 had very little deposit on its surface. This is clearly evidenced by the small amount of plug embrittlement that is seen on the plug face. The lightly textured appearance all over the plug face is a result of plasma sputter erosion. That this erosion process is not as devastating as the embrittlement phenomenon is apparent by the presence of a groove across the plug anode. This groove was cut to an average depth of 0.002 in. (0.05 mm) across the plug anode when the plug was new. Figure 12 shows also that a plug used to fire a thruster erodes quite differently from one fired alone in vacuum. Plug S/N 3 in Fig. 12 shows severe anode melting and complete vaporization and removal of a large amount of semiconductor and cathode material. Clearly the presence of a small amount of deposit on plug S/N 7 was significant in preventing most of the damage caused by the trigger circuit current pulse that is evident on plug S/N 3.

Summary

The results of an ongoing 1-mlb pulsed plasma thruster ignition system study have been presented. Preliminary results from this study indicate that inductively coupling the ignitor plug cathode to the thruster cathode is more beneficial to ignitor plug longevity than resistive coupling. These benefits arise from the ability of the coupling inductor to control the buildup of a carbonaceous deposit on the plug face. This deposit buildup is a strong function of the peak coupling current experienced during thruster operation. A decrease in the amount of plug deposition was also demonstrated through the use of an experimental plug trigger circuit which had large peak currents and very-short-pulse lengths. Ignitor plug erosion has been shown to occur simultaneously with the accumulation of this carbonaceous deposit. Most of this erosion is from an embrittlement phenomena which can be related directly to the amount and location of the carbonaceous deposit. A lesser amount of erosion occurs from normal plasma sputter processes and a still lesser amount is caused by plug vaporization from the trigger circuit current pulse. The relationship between the ignitor plug discharge and thruster discharge has been shown to be very complex with equivalent circuit elements which are dynamic in nature.

Acknowledgments

The authors wish to thank Robert Gauldin for his excellent work in obtaining the scanning electron micrographs presented in this paper. The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Air Force Rocket Propulsion Laboratory Contract F04611-80-X-0041.

References

[1] Palumbo, D.J. and Guman, W.J., "Pulsed Plasma Propulsion Technology," Final Rept. AFRPL-TR-77-40, March 10, 1972-May 30, 1977, AFRPL Contract F04611-72-C-0053, Fairchild Republic Corporation, March 1977.

[2] Palumbo, D.J. and Begun, M., "Pulsed Plasma Propulsion Technology," Draft Interim Rept., AFRPL Contract F04611-78-C-0053, Fairchild Republic Corporation.

[3] Guman, W.J. and Begun, M., "Pulsed Plasma Plume Studies," Final Rept. AFRPL-TR-77-2, March 1975-Nov. 1976, AFRPL Contract F04611-75-C-0037, Fairchild Republic Corporation, March 1977.

[4] Palumbo, D.J., "Solid Propellant Pulsed Plasma Propulsion System Development for N-S Stationkeeping," AIAA Paper 79-2097, Oct. 1979.

[5] Guman, W.J., "Pulsed Plasma Technology in Microthrusters," Final Rept. AFAPL-TR-68-132, Air Force Contract F33615-67-C-1395, Fairchild Hiller Corporation, Nov. 1968.

From the AIAA Progress in Astronautics and Aeronautics Series . . .

SATELLITE COMUNICATIONS:

FUTURE SYSTEMS-v. 54
ADVANCED TECHNOLOGIES-v. 55

Edited by David Jarett, TRW, Inc.

Volume 54 and its companion Volume 55, provide a comprehensive treatment of the satellite communication systems that are expected to be operational in the 1980's and of the technologies that will make these new systems possible. Cost effectiveness is emphasized in each volume, along with the technical content.

Volume 54 on future systems contains authoritative papers on future communication satellite systems in each of the following four classes: North American Domestic Systems, Intelsat Systems, National and Regional Systems, and Defense Systems. **A significant part of the material has never been published before.** Volume 54 also contains a comprehensive chapter on launch vehicles and facilities, from present-day expendable launch vehicles through the still developing Space Shuttle and the Intermediate Upper Stage, and on to alternative space transportation systems for geostationary payloads. All of these present options and choices for the communications satellite engineer. The last chapter in Volume 54 contains a number of papers dealing with advanced system concepts, again treating topics either not previously published or extensions of previously published works.

Volume 55 on advanced technologies presents a series of new and relevant papers on advanced spacecraft engineering mechanics, representing advances in the state of the art. It includes new and improved spacecraft attitude control subsystems, spacecraft electrical power, propulsion subsystems, spacecraft antennas, spacecraft RF subsystems, and new earth station technologies. Other topics are the relatively unappreciated effects of high-frequency wind gusts on earth station antenna tracking performance, multiple-beam antennas for higher frequency bands, and automatic compensation of cross-polarization cuoupling in satellite communication systems.

With the exception of the first "visionary" paper in Volume 54, all of these papers were selected from the 1976 AIAA/CASI 6th Communication Satellite Systems Conference held in Montreal, Cnada, in April 1976, and were revised and updated to fit the theme of communication satellites for the 1980's. These archive volumes should form a valuable addition to a communication engineer's active library.

Volume 54, 541 pp., 6×9, illus., $19.00 Mem., $35.00 List
Volume 55, 489 pp., 6×9, illus., $19.00 Mem., $35.00 List
Two-Volume Set (Vols. 54 and 55), $38.00 Mem., $55.00 List

TO ORDER WRITE: Publications Dept., AIAA, 1290 Avenue of the Americas, New York, N. Y. 10019