SPACE POWER EXPERIMENTS ABOARD ROCKETS

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ABSTRACT

SPEAR II examined issues of the operation of high electrical power systems in space. It built upon the successful SPEAR I flight in 1987 that demonstrated the feasibility of operating light weight high voltage systems without volume or surface breakdown when innovative insulation techniques were employed. The SPEAR II payload contained both low and high impedance packages which modeled the power supplied needed for SDIO directed energy and electromagnetic launcher systems. A high voltage system provided 100 kV, 100 amp, (1 MW) pulse up to 50 microseconds in length to the cathode-anode structure of a klystrode radio frequency power tube. A high current system consisted of 140 kA, 6 kV electromagnetic launcher with a 10 mm bore to accelerate a one gram lexan projectile to over 1 km/sec. SPEAR II was successfully and extensively tested in the NASA Plum Brook Space Power Facility space chamber. These tests included a validation of a number of techniques, models, and innovative designs.

INTRODUCTION

The Strategic Defense Initiative Organization (SDIO) was formed in 1984 to perform research, advance technologies, and develop systems associated with ballistic missile defense. Two types of weapons systems have emerged from this work: kinetic energy and directed energy weapons systems. Some of the kinetic energy weapons first considered by SDIO were electromagnetic launchers (EMLs) or railguns, coil guns, and electrothermal guns. The directed energy systems include neutral particle beams (NPB), space-based free electron lasers (SBFEL), ground-based lasers (GBL), laser radars (LR), charged particle beams (CPB), and high power microwaves (HPM). All of these kinetic and directed energy systems have one thing in common--they require the use of a pulsed power system to generate either high voltage (hundreds of kilovolts), and/or high current (hundreds of kiloAmps) to be delivered to the load in less than a few milliseconds. The operation of these pulsed-power systems in the low earth orbit (LEO) is a significant challenge[1].

To attempt to understand the LEO environment and its potential effect on space-based system operations, SDIO sponsored the Space Power Experiments Aboard Rockets (SPEAR) program[3]. The SPEAR program, managed by the Defense Nuclear Agency, was created in 1986 to investigate LEO environment effects and demonstrate innovative technology options for operating high-power systems in space. Specifically, the SPEAR program examines the use of LEO space 'vacuum' for electrical insulation. This insulation technique has the potential for major reductions in weight/volume of high-power electrical components. A variety of communication and surveillance satellites also employ high voltage components. These systems too will benefit by improving high voltage insulation techniques and associated power conditioning components.

At its inception the fundamental element of the SPEAR program was the concept of replacing the normal insulation required by high power systems on the Earth's surface by the reduced ambient pressure of the upper atmosphere[2]. If feasible, this concept could lead to a marked reduction of weight and volume of insulation required for high power space systems. Another positive feature, recognized at the onset of the program, was that the proposed insulation, the space vacuum, was automatically 'replenished' and would not deteriorate with time, or breakdowns, as do solid, liquid, and enclosed gas insulators.

Participants in the SPEAR program recognized that there could be problems in using space vacuum as an insulator because the upper atmosphere is a plasma containing both neutral molecules and atoms, and charged particles, electrons, and positively charged ions. Possible difficulties for exposed power system components introduced by the presence of charged particles include: current drain from the ambient, reducing the efficiency of exposed high power components; breakdowns between components with high potential differences; and breakdowns between the ambient and components with high potentials relative to the plasma. The difficulties are compounded because the appearance and magnitude of the problems might be dependent on the geometry or placement of components as well as dependent on the ambient plasma characteristics.

During the early planning stages of the SPEAR program, it was determined that the available information on spacecraft charging and subsequent current collection was inadequate for high power operation in LEO. Therefore, a science flight, SPEAR I [3,4,5], was developed to investigate these phenomena, with a follow-on technology validation flight, SPEAR II.

SPEAR II

SPEAR II was designed to validate space vacuum insulation technology for high power space-based systems. It included component design, construction, integration, testing and extensive theoretical and experimental efforts focused on developing and testing a payload for a sounding rocket flight. The SPEAR II payload contained both low and high impedance packages which modeled the power supplies needed for SDI directed energy and electromagnetic launcher systems.

DESCRIPTION

A general configuration of the SPEAR II payload is shown in figure 1. A SPEAR II circuit block diagram appears in figure 2.

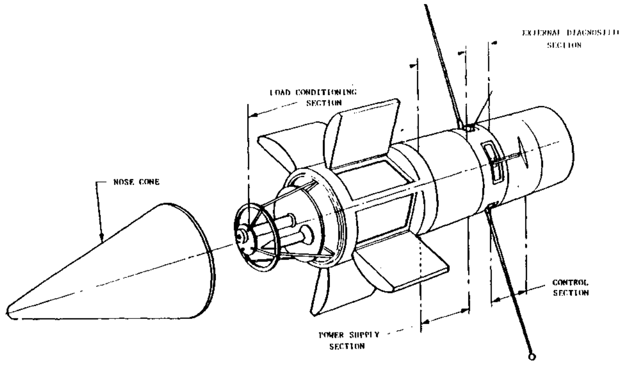

Figure 1

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14. ABSTRACT

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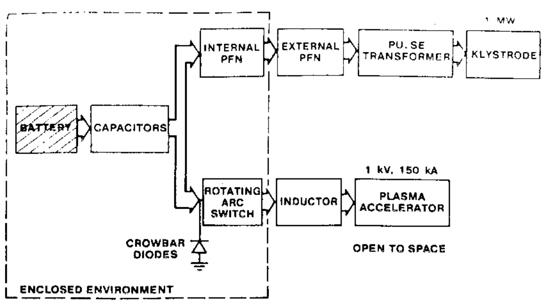

Figure 2

SPEAR II consisted of two experiments. The first, a high voltage experiment, used a voltage up to 100,000 volts. All of the high voltage components were exposed to the ambient space plasma environment. The HV load was the electron beam cathode-anode section of a klystrode RF tube which represented a typical device that could be used in a future space accelerator for an NPB or FEL. Circuitry included a pulse transformer and pulse-forming networks which produced a nominal power pulse of one megawatt. A high voltage matrix was developed to examine voltage and pulse duration dependence on performance.

The second experiment, a high current experiment, used a high current load, consisting of an electromagnetic launcher. This device, operating at a load current of 150,000 amperes, accelerated a projectile down its barrel and into the space environment at a high velocity. The power conditioning circuit included a high energy density capacitor bank storing 15 kJ, a high charge transfer switch, high power diodes and an exposed storage inductor.

PAYLOAD SKINS AS A VACUUM CHAMBER

Due to the extended period of time required for proper outgassing of materials the SPEAR II payload skin was designed to act as a vacuum chamber to facilitate the outgassing process. Since the flight experiment was suborbital, sufficient time was required to allow outgassing to take place on the ground prior to launch. Several outgassing calculations were made in addressing this issue with models developed by Auburn University and Maxwell Laboratories of the complex payload components to determine the time required to assure the payload would be below 10E-4 torr. This pressure was analytically and empirically derived by Westinghouse to represent the maximum allowable pressure for reliable operations of the high voltage system. The design of the spacecraft skin was therefore based on providing a vacuum environment with pressures not to exceed this level.

The idea of back filling the payload with an electrically benign gas such as dry nitrogen or dry air and allowing the payload volume to outgas during the rocket ascent was thoroughly examined with the Maxwell and Auburn models. The concept was found to be unsatisfactory due to the geometric complexity of the pulse transformer. Insufficient outgassing would take place during the flight to achieve a pressure below that required for reliable high voltage operations. The penalty for this was the additional weight required for the skin of the payload to also act as a vacuum chamber.

Two vacuum pumps were designed to adapt to the nose tip of the payload section. A cryogenic pump was designed to fly with the payload and a turbomolecular pump was to support the cryo pump during ground operations. It was then to be removed prior to the flight to save weight. The cryo pump had sufficient pumping capacity to keep the payload at a sufficiently low sustained pressure for the flight. External high pressure supply lines to the cryo pump were attached through umbilicals to be automatically disconnected within two minutes prior to launch. The cold head would stay cold enough for a sufficient length of time to still keep the payload pressure within the operating region until the vehicle had climbed to an altitude where the ambient pressure was well below 10E-4 torr. The payload was then to be exposed to the environment by opening the large doors and ejecting the nose cone with the cryo pump attached.

INTEGRATION OPERATIONS

Difficulty in voltage conditioning within the payload skin became readily apparent at the higher energy pulses. Experience showed fewer breakdowns occurred with pressures below 10E-5 torr. Further improvement was achieved by allowing two to three days of pumping to take place before starting high voltage operations. Removal of absorbed water was found to be a significant factor in operating the system effectively. The difficulties were initially thought to be due to surface contamination of the pulse transformer. After the transformer was removed from the payload, cleaned, and replaced the same difficulties in conditioning reappeared. The voltage could not be maintained on the higher energy pulses (80 and 100 kV with pulse durations of 10 and 50 microseconds) without breakdown.

Even with pressures as low as 10E-6 torr for two or three days, significant numbers of breakdowns would occur when high voltage conditioning sequences were tested. Conditioning would rarely achieve the standoff voltage of the higher energy pulses. In general, a summary of the integration test results showed voltages could be maintained on the 50 microsecond pulses only at the 50 kilovolt level. Ten microsecond pulses could be conditioned at 80 kilovolts and 3 microsecond pulses could be conditioned up to 100 kilovolts.

A residual gas analyzer was used to examine the gas environment within the payload during these conditioning operations. Data showed significant levels of gas was produced in the localized environment near the transformer where the conditioning took place. The relatively small volume of the payload and the limited gas conductance path between the transformer and the vacuum pumps contributed to a higher pressure around the transformer during conditioning operations. Species were primarily water and nitrogen.

The pumping rate became another critical parameter for proper gas management. Rates of gas removal were superseded by the gas production rate during conditioning operations. A theory was thus put forth that the system would condition much more effectively if the volume containing the high voltage system was much larger. Gas liberated during the conditioning process would be able to escape the local payload environment unimpeded by the payload containment structure. The large vacuum chamber tests, with a chamber diameter of 100 feet, would hopefully answer this question.

CHAMBER TESTING

NASA's Plum Brook Station in Sandusky, Ohio maintains the Space Power Facility (SPF) vacuum chamber with a height of 120 feet and a diameter of 100 feet. SPEAR II tests conducted in the chamber were at a pressure of 1 x 10E-5 torr in both vacuum and with a background argon plasma. The argon plasma was produced by two plasma thrusters providing an electron density in the lower 10E+4 per cubic centimeter range with a thermal energy in the 1 to 2 ev range.

In testing SPEAR II in both vacuum and plasma, the high voltage matrix was successfully conditioned. This matrix is described in table 1. Table 2 depicts the peak power, average power, and energy per pulse for the matrix. The theory of high voltage operations in unconstrained environments (as stated above) was readily verified. Breakdowns showed a strong energy and pulse duration dependence. Table 3 depicts the number of high voltage sequences needed to obtain reliable high voltage operations by conditioning. It should be noted that the conditioning steps were stepped up continuously in voltage and pulse duration in a manner which may or may not have optimized the conditioning process. A different procedure used in conditioning would most likely have changed the data somewhat. Examination of the data should focus on the general trends and demonstrations of concepts which the data best represents.

Table 1

SPEAR II High Voltage Matrix
Showing the Order of Events

	3 us	10 us	50 us
50 kV	1	2	3
80 kV	4	5	6
100 kV	7	8	9

NOTE 1: Each combination of pulse duration and voltage occurred over a one second period at 10 pulses per second during the conditioning sequence and at 50 pulses per second during the regular sequence. For example, the 3 microsecond pulses are first tested at 50 kV for 50 pulses over one second. A PFN is then changed to fire 10 microsecond pulses at 50 kV for 50 pulses over one second, and so on, as the matrix order shows. Each time through the matrix is called one sequence.

NOTE 2: An entire matrix took 45 seconds including data transmission times.

Table 2

The SPEAR II Matrix Showing Peak Power,
Average Power, and Energy per Pulse (Calculated)

Voltage (kV)	Peak Power (MW)	Pulse Duration (us)	Average Power (W)	Pulse Energy (J)
50	0.5	3	75	1.5
		10	250	5.0
		50	1,250	25.0
80	0.8	3	120	2.4
		10	400	8.0
		50	2,000	40.0
100	1.0	3	150	3.0
		10	500	10.0
		50	2,500	50.0

Table 3

Conditioning Sequences to
Achieve Reliable Operations
In Vacuum at the Plum Brook
SPF Chamber

	3 us	10 us	50 us
50 kV	2	3	4
80 kV	3	5	7
100 kV	5	9*	11#

* 75% pulses without breakdown
\# 90% pulses without breakdown

NOTE: This test was at 20 pulses per second

Conditioning was typically performed at 20 pulses per second to allow more time for the gas, generated by the high voltage pulses, to exit the localized area. Table 4 shows similar data except this test was performed in the presence of a background plasma. This voltage conditioning test was performed twelve hours after the vacuum test took place. At longer pulse durations the vacuum and plasma results diverge. One theory (certainly not the only theory) is that at longer pulse durations all plasma dynamic effects are involved. Full participation in the process by electrons, ions, gases, and ionization processes are working during the 50 microsecond pluses. At 3 microseconds the greatest physical contribution to the microscopic processes are by electrons. The 10 microsecond pulse was chosen as a transition zone where ions are beginning to contribute.

Table 4

The Number of Conditioning Sequences to
Achieve the Best Operations
In Plasma at the Plum Brook
SPF Chamber

	3 us	10 us	50 us
50 kV	1	2	6
80 kV	2	5-95	12-45
100 kV	3	12-50	12-10

NOTE 1: "5-95" is interpreted as the fifth sequence having 95% of the pulses occurring without breakdowns. "12-10" likewise shows the twelfth sequence having 10% of the pulses occurring without breakdown.

NOTE 2: This test was at 20 pulses per second.

Data depicted in table 5 shows the results of the full flight functional test at Plum Brook. This test was performed 24 hours after the plasma conditioning test described above. The purpose of this test was to assure the spacecraft was functionally ready for transport and launch. The full functional test was therefore performed as an end-to-end systems test, performed in as realistically demanding conditions on earth as feasible. A second purpose was to further examine applied scientific issues in high voltage and high current operations in low density plasmas.

Table 5

Flight Sequence
Performance of the SPEAR II
High Voltage Matrix
In Plasma at the Plum Brook
SPF Chamber Showing the Percentage
of Pulses Occurring Without Breakdowns

	Sequence Number	Pulse Duration		
		3 us	10 us	50 us
50 kV	1	100	95	10
	2	100	100	84
	3	100	100	100
	4	100	100	100
80 kV	1	100	0	0
	2	100	88	10
	3	100	92	60
	4	100	94	74
100 kV	1	100	0	0
	2	100	40	10
	3	98	62	26
	4	100	86	74

NOTE: This test was at 50 pulses per second and included a single 20 pulse per second sequence which took place immediately prior to the four 50 pps sequences.

As can be seen in Table 5, the pulse power system was ebnning at 75% reliability at full power at 50 pulses per second. If this payload had been on an orbital vehicle, unconstrained by a flight profile lasting only a few minutes, operations could have been continued, further enhancing performance.

These results imply extreme care which must be taken in designing high voltage components using vacuum insulation. The constraining volume surrounding the component must be designed with the pumping rate, gas production rate, overall target pressure, and conditioning effects well in hand. Empirical and theoretical techniques and tools capable of providing these guidelines are in the first or second iterations.

The ambient conditions in the Plum Brook SPF tests on SPEAR II were more severe than would be experienced in space. The plasma temperature and the plasma density were both an order of magnitude higher than in space. The neutral density surrounding the payload was also significantly higher than at low earth orbit altitudes. Argon was also used in the chamber providing a worse neutral background for high voltage operations than species consistent with low earth orbit altitudes. The chamber test was therefore a significant engineering milestone in determining the system performance and overall payload readiness for flight.

The high current system was also successfully tested in the SPF chamber during a full functional check of the SPEAR II payload. With successful operations concluded at Plum Brook the payload was transported to White Sands Missile Range where further tests were planned prior to launch.

WHITE SANDS OPERATIONS

Further experimentation was accomplished to increase the level of voltage conditioning within the spacecraft skin. The largest improvement occurred after the SPEAR II dress rehearsal when the payload shelter was removed, exposing the rocket and payload skin to the direct afternoon sunlight. The cryo pump was still operating during this test. The pressure was seen to rise well into the 10E-4 torr range during this period. The skin was felt to be quite warm to the touch from the solar heating.

When the shelter building was replaced around the payload, the building air conditioning turned back on, and the turbo pump reinstalled, the payload pressure dropped to below 5 x 10E-6 torr. By the next day it had dropped to the high 10E-7 torr range.

Eight hours prior to first launch attempt, voltage conditioning was reaccomplished with significantly different results than previously seen. The full matrix was conditioning successfully including the 100 kilovolt, 50 microsecond pulses. Apparently, the hot summer sun had warmed the payload skin sufficiently expediting the removal of adsorbed gases. This further illuminated the extreme sensitivity of the breakdown process to neutral gas.

Several launch attempts ended in cancellations allowing for further ground testing of the payload. On two occasions the payload was brought back up to ambient pressure for battery charging. The environment inside the structure was kept as clean and as dry as possible for the twelve to sixteen hours needed for recharging. Since the time of integration, a clean room had been used whenever the high voltage and high current systems were exposed to air to minimize particulate contamination. At White Sands this procedure continued. Improvements in conditioning performance were noted as time went on. Releasing adsorbed and absorbed gases and controlling particulates were felt to be the most important techniques of clean room and vacuum operations.

Techniques were also developed to maximize the use of the two vacuum pumps. When first pumping the payload down with the roughing pump followed with the turbo pump, the pressure would readily drop to the 10E-5 range. The cryo pump was turned on for another order of magnitude improvement. After the pressure stabilized the cryo pump was turned off and allowed to release condensed gases from the cold head as the temperature gradually rose. As each temperature of condensation was reached for each gas species the pressure would rise as the molecules left the cold head. The pressure would then drop as the turbo pump removed most of the liberated gas. After an hour or so the cryo head temperature would reach about 80 - 90 K. After Nitrogen had been liberated and the pressure had climbed and then dropped, the cryo pump was restarted with usually at least a two or three fold decrease in stabilized pressure.

On 25 July 1990 the payload went through final testing and voltage conditioning approximately six hours prior to launch. During this test the payload was operating consistently and reliably at all voltages and all pulse durations.

The high current system was also tested at White Sands with a shorting plug inhibiting the barrel from actually firing any projectiles. This was done to assure a pristine EML would be used in flight. Prior to placing the payload on the rocket, two projectiles were placed in the breach of the EML, and the shorting plug was removed. Continuity tests were performed consistently prior to the launch assuring the first projectile fuze was in electrical contact with the EML rails.

After launch a frayed wire connecting the pitch rate gyro to the guidance system was responsible for the rocket to enter unstable flight leading to aerodynamic breakup and destruction of the vehicle. The payload internal fiber optic imagery and data acquisition systems were transmitting nominally until impact with the ground. The payload was totally destroyed.

HIGH VOLTAGE OPERATION CONCLUSIONS

Previous papers have shown techniques in designing high voltage components compatible with operations in low density plasmas[2,3,4]. A more detailed examination of these principles will be published in the SPEAR II final report. The overall results of the latter portion of the SPEAR II program was highlighted by successful operations of the payload due to effective gas management. Plasma designs will most likely also enhance vacuum operations. However the converse is not true; simply designing for vacuum insulation will not necessarily mitigate plasma effects.

Though many of the results reiterate common engineering practice and knowledge they are important enough to include in the list of results due to their fundamental importance. The gas management results are summarized as follows:

- Extreme sensitivity of electrical breakdown processes to neutral gas density exists in both volume and surface discharges.

- Component designs utilizing vacuum insulation require a full systematic view including structural limitations and effects, pump usage, gas production, materials, gas flow and flow conductance limitations. A fully dynamic view of all processes involved must be taken into account.

- Fully dynamic modeling tools are undergoing further development and evaluation. These tools will be capable of handling complex plasma and gas management issues.

- Voltage conditioning is essential in operating high voltage systems utilizing vacuum insulation at voltages and energies consistent with pulsed power driven directed energy systems.

- Vacuum insulated components and systems recover from repeated breakdowns with no long term effects.

- Conditioned vacuum insulated components require reconditioning if left unoperated for a period of time, even if left at a low vacuum pressure. Specific details are unique to each set of circumstances and must be empirically derived given the unique environment and component. It is felt that gas re-adsorption and re-absoption are the reasons reconditioning is required.

- Cleanliness is essential to successful high voltage operations.

- Evidence exists showing the removal of gases, absorbed and adsorbed (primarily water vapor), as the primary reason why voltage conditioning works.

- Baking can produce positive benefits in lowering pressures and reducing conditioning times.

- Electrical breakdown shows a stronger dependence on energy and pulse duration rather than on voltage alone.

- Gas and plasma mitigation techniques can be very effective if taken into consideration during initial design of vacuum insulated high voltage components and systems.

- Knowledge of the gas species is extremely helpful in designing vacuum insulated components, developing mitigation techniques, and applying operational procedures.

- Applying different types of pumps with greater capabilities to handle different gas species can help to optimize reliability and efficiency.

- Electromagnetic isolation of pumps, diagnostics, and umbilicals, and other support equipment necessary for high power operations, is essential to assure successful operations and monitoring.

SUMMARY

Though the flight test was not completed, there was a large number of tests of payload components, and the integrated payload, in vacuum chambers both with and without added plasma. Significant results were obtained from these test as well as during the preparations prior to launch at the White Sands Missile Range, New Mexico, which demonstrated the following major accomplishments:

- The first developed and tested space power system which successfully operated at over one megawatt power levels using space vacuum insulation technology.
- The first operation of a high-voltage system (greater than 100 kilovolts) with a space-qualified pulse forming network, pulse transformer, klystrode, and diagnostics.
- The successful design of a high-current system (greater than 100 kiloamps) with a space-qualified inductor, switches, capacitor, and battery.
- Development of a flightworthy vacuum chamber for the load conditioning section which allowed for pre-launch pump down of the elements of the payload which were to be exposed to the LEO environment.
- Validation of computer codes used to predict the ion and electron currents to exposed high voltage components.
- Development and publication of design guidelines and innovative design/test methodologies which document technology options available to designers of future SDI space-based high power systems.

PARTICIPANTS

The diverse expertise required to carry out this program included high pulse power, sounding rocket and telemetry technology, space plasma physics, vacuum chamber experimentation and sensor technology. This expertise is represented by a number of Government, contractor, and university organizations as depicted in Table 6.

Table 6

SPEAR II Team

Group	Contribution
Air Force Geophysics Lab	Theory
Auburn University	Outgassing Predictions
Maxwell Laboratories	Power: Source, Conditioning, & Diagnostics
NASA/Lewis Research Center	Large Chamber Tests
Naval Research Lab	Theory
Polytechnic University of New York	Theory
S-Cubed Division of Maxwell Laboratories	Modeling
Space Data Corporation	Payload Integration and Flight Vehicle
Texas Tech University	Component Testing
University of Maryland	Small Chamber Testing
University of Texas, Arlington	High Voltage Mockup
Utah State University	External Diagnostics
Westinghouse Research & Development Center	Power: Conditioning, Loads, & Diagnostics

FUTURE EFFORTS - SPEAR III

A third suborbital experiment, SPEAR III[7], is currently in development to advance the knowledge base of exposed high power interactions with the LEO space environment. It is a follow-on experiment to SPEAR I to address many of the open issues or new issues raised during the SPEAR I ground test and flight program. As such, SPEAR III will take advantage of many of the lessons learned in SPEAR I. It will use the SPEAR I basic design with modifications for new experiment packages. The primary emphasis for SPEAR III will be the investigation of LEO spacecraft grounding, surface discharge techniques, effluent effects, test chamber fidelity, and solar cell performance. SPEAR III is planned for a launch from the NASA/Wallops Flight Facility aboard a Black Brant X booster in July 1992.

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