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Pulsed Power, Plasma, and Interior Ballistic Simulations for Application to Electrothermal-Chemical Guns

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13. ABSTRACT *(Maximum 200 words)*

Under U.S. Army Research, Development, and Engineering Center contract DAAA21-93-D1003 (subcontract GC-2539-45-93-024), Princeton Combustion Research Laboratories (PCRL) recently completed the development of a PC-based, end-to-end electrothermal-chemical (ETC) gun ballistic simulation code called the pulsed power plasma interior ballistics (PPIB). PPIB is a time-dependent, lumped parameter, electrothermal-chemical gun ballistic simulator which has a one-dimensional plasma submodel. The PPIB code is used to simulate the three main subsystems of the overall ETC gun system, including the pulse power subsystem, the plasma cartridge, and the interior ballistic process. PPIB is a linkage of three well-established systems models: (1) P2SIM for pulse power, developed by PCRL to model electric gun pulse power supplies, (2) the plasma cartridge code of Powell and Zielinski from the U.S. Army Research Laboratory (ARL), and (3) the latest version of the interior ballistics code IBHVG2 from ARL. PPIB is written in American National Standards Institute (ANSI) standard formula translator (FORTRAN) and is designed to run on any 386, 486 or Pentium-based PC platform. The code has been validated against a 4-MJ pulsed power system, 30-mm ETC plasma experiments, and plasma capillary calculations from the stand-alone Powell code, all of which are presented here. In addition, results obtained for high energy plasma simulations are provided. Included in this study are 1) the electrical behavior and transfer efficiencies of various plasma capillary tubes; 2) the amount of energy partitioned to each of the constituents within the plasma such as internal, kinetic, and work energy; and 3) the radiant energy partitioning of the plasma inside the capillary tube during the electrical discharge. The study is concluded with an estimate of the overall energy delivered for the entire process of power supply discharge to electrical plasma generation and radiation for a given test case.

14. SUBJECT TERMS

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1. INTRODUCTION

The electrothermal-chemical (ETC) propulsion concept represents an advanced weapon technology in which a conventional gun tube and combustion chamber are used to accelerate a projectile. The system differs, however, from typical cannon weaponry in that it relies upon the discharge of electrical energy from a power supply through an insulating capillary tube forming an electrical plasma, which is injected into the gun chamber for ignition and combustion control of propellant. The discharge forms an arc that generates a hot, high pressure, low molecular weight plasma source. The high temperature plasma in the interior of the capillary causes ablation and vaporization of surrounding insulation, which is enveloped by hot gaseous material and sustains the original plasma arc. The energetic plasma is then injected into a bed of chemical propellant in the gun combustion chamber. The input plasma is used to first ignite the propellant and later, it is proposed to drive and control the combustion process of the gun. It is hypothesized that control of the combustion could result from burn rate modifications of the propellant as a result of interaction with the high temperature plasma.[1] The effects of electrical plasmas on burn rates of some JA2 sample propellants have been investigated in closed chamber ETC experiments at the U.S. Army Research Laboratory (ARL). The results, although preliminary and still being studied, indicated potential burn rate increases compared to those in conventional JA2 tests.[2] Because of the importance of the plasma source with regard to the ETC technology, it was decided to examine some of the basic properties of plasma generation as well as characteristics of the plasma itself, which are described later in this report.

1.1 Pulsed Power Plasma Interior Ballistic (PPIB) Code Description

PPIB is a time-dependent, lumped parameter, end-to-end computer model of an ETC gun system.[3] PPIB simultaneously models the performance of the pulse power system, the plasma cartridge, and the interior ballistics of a solid propellant ETC gun. It is a linkage of three established models: (1) P2SIM,[4] (2) Powell's plasma cartridge code,[5] and (3) IBHVG2,[6] for interior ballistic calculations. The pulse power code (P2SIM) is linked to the plasma cartridge code by having the plasma cartridge act as the pulse power system load. Any change in the output of the pulse power system (e.g., increase in current) is directed into the plasma cartridge and will cause a change in the state of the plasma. Any variation in the plasma (e.g., change in temperature) will be reflected in the pulse power system as a change in plasma cartridge resistance, thereby altering the pulse power system load. Similarly, any change in the plasma discharge into the gun will cause a concurrent change in the combustion of the gun propellant, the gun chamber pressure, and ultimately the projectile. A change in the combustion of the gun propellant is reflected back into the plasma cartridge as a change in the pressure inside the cartridge, which, during certain conditions (e.g., unchoked flow) affects the output of the cartridge and the state of the plasma. This will also affect the thermodynamic properties of the plasma. Obviously, this change in plasma property is reflected back to the pulse power system as a change in the plasma cartridge resistance.

1.2 Technical Methods Employed

Given the plasma cartridge length and radius, its resistance is given by

$$R = \frac{l}{\sigma \pi a^2} \tag{1}$$

in which l is the length of the cartridge, a is the radius, and σ is the conductivity of the plasma. The conductivity is given by

$$\sigma = \frac{n_e e^2}{m_e(\upsilon_{en} + \upsilon_{ei})} \tag{2}$$

in which n_e is the density of electrons in the plasma, e is the electron charge, m_e is the electron mass, υ_{en} is the collision frequency for electrons and neutral atoms, and υ_{ei} is the collision frequency for electrons and ions. The resistance value from Equation 1 is the load resistance for the pulse power part of PPIB. The current density J in the plasma is given by

$$J = \frac{I}{\pi a^2} \tag{3}$$

in which I is the current from the pulse power system flowing into the plasma cartridge. The current density is used in the energy equation (Equation 3 in Reference 4) for the plasma cartridge. This equation is

$$\frac{\partial}{\partial \xi}\left[\rho\omega\left(U + \frac{1}{2}\omega^2\right)\right] + \frac{\partial}{\partial \xi}(\wp\omega) = \frac{J^2}{\sigma}L - \frac{\partial q_z}{\partial \xi} - 2\frac{q_{rs}L}{a} \tag{4}$$

in which $\wp$, ρ, and w are the pressure, density and flow speed; q_z and q_{rs} are the longitudinal and radial heat fluxes; U is the internal energy of the plasma (per unit mass) and ξ is the dimensionless parameter z/L.

The linkage of the P2SIM and Powell codes was accomplished by using P2SIM's "user-defined load" capability with Powell's code being the load. In addition, with PPIB, the user has the option of including the plasma cartridge parasitic inductance, the cartridge lead resistance, and the power cable resistance.

To simulate the start of the event, an exploding wire is simulated in the model. The expression for temperature of the exploding wire is based on the power in the wire and the assumption that the energy leaves the wire as thermal (black body) radiation, i.e.,

$$T = (I^2 R / kA)^{0.25} \tag{5}$$

in which A is the surface area of the wire and k is the Stefan-Boltzmann constant. To simulate the coupling of the radiant energy from the exploding wire to the plasma liner, the absorptivity of the plasma liner is also included as a model parameter.

The coupling between the Powell plasma cartridge code and IBHVG2 is likewise very straightforward. The plasma energy, determined from the time integral of input plasma power, is added directly to the energy balance equation. This equation is modified for an ETC gun system model and is given as

$$\sum_{ij} m_{ij} c_{vij} T_{fij} + \sum_{k} m_k c_{pk} T_{pk} + \int_0^t P dt = \left[\sum_{ij} m_{ij} c_{vij} + \sum_{k} m_k c_{pk} \right] T_{mean} + L \tag{6}$$

in which the first sum is over every surface j of each propellant charge i; the second sum is over every species in the plasma. The propellant gas mass is given by m_{ij}, c_v is the specific heat at constant volume for the propellant gases, and T_f the flame temperature of the propellant. The plasma species mass is m_k, c_p is the specific heat of the plasma species, and T_p is the plasma temperature. P is the plasma power injection term and the integral is from the start of the event until the time, t. T_{mean} and L are the mean temperature of the system and the energy loss terms, respectively.

The plasma output power, P, is comprised of three different terms. The first is the term attributable to the thermal internal energy of the plasma and is given by the product of the plasma specific internal energy at the discharge orifice, e (in J/kg), and the mass flux rate, F (in kg/s), at the discharge orifice,

$$P_1(t) = e(t)F(t) \tag{7}$$

The second term is the kinetic energy of the plasma and is given as

$$P_2(t) = 0.5\, F(t)(v(t))2 \tag{8}$$

in which $v(t)$ is the gas linear speed.

The third term is the work done against the gas pressure and is given as

$$P3(t)=PoAv(t) \qquad (9)$$

with P_0 being the pressure at the discharge orifice and A the orifice area. The total power is then the sum of these three terms.

There is no attempt to calculate the effects of incomplete mixing and transfer of energy to the propellant combustion gas. Therefore, the model will tend to overestimate the amount of energy transfer. Aside from a complete treatment of the mixing of plasma and propellant gas, which is beyond the scope of this project, the only way to accommodate incomplete mixing as well as to control the contribution from the terms in Equations 8 and 9 is to introduce a set of energy "coupling" factors. There is one factor for each power term. A coupling factor of one (1) denotes perfect coupling of the plasma power for that contribution to the combustion gas, while a factor of zero denotes no coupling. The default values in the program are 1, 0, and 0 for Equations 7, 8, and 9, respectively, which indicates total transfer of internal plasma energy into the gun chamber and no energy transferred from kinetic and work energy components.

The execution of the code is similar to that of P2SIM. However, termination of the event will be controlled by IBHVG2, which in most cases occurs at projectile exit. Data are input to the program via three separate data files: one for pulse power, one for plasma, and one for IBHVG2. The pulse power input is virtually identical to the P2SIM input deck, and the plasma input is virtually the same as the original Powell code. The interior ballistic input deck is similar to an ETC IBHVG2 deck. Output data from the end-to-end PPIB code consist of three data files, one for each subsystem.

2. SIMULATIONS

2.1 Validation of P2SIM (pulsed power simulations)

P2SIM was validated through comparisons with simulations obtained from electronic circuit analysis software. For this task, Microcap III (Spectrum Software) was used as a standard to predict the performance of an electric gun type pulsed power supply discharging into a fixed resistive load.[7] Although the fixed resistive load does not model the exact electrical behavior of the electric gun plasma load, it does provide a reasonable approximation of the electrical behavior of the power supply. The results of simulations from P2SIM and Microcap III for a 4-MJ pulsed power supply configured from a network consisting of capacitors, inductors, switches, and other components are given in Figure 1, where the two sets of predicted curves are within 5% of perfect agreement. Other validation exercises have been performed for other power supply configurations that are not detailed here but were performed under contract to the U.S. Army.[8] Included among the types of power supply configurations that can be modeled by PPIB are compulsators and homopolar generators as well as capacitor-based pulse-forming networks (PFNs) as illustrated in this report. The input deck for P2SIM used to generate the data in Figure 1 is given in Appendix A, Part 1.

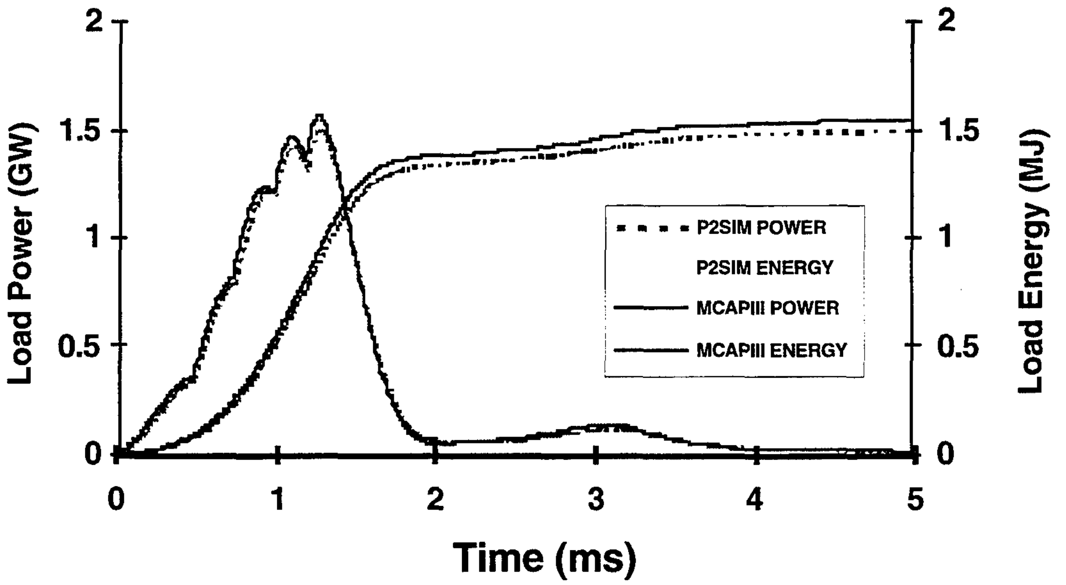

Figure 1. Validation of PPIB with Microcap III Showing Delivered Electrical Power and Energy to a 120-mΩ Resistive Load.

2.2 Validation of the Plasma Model

To validate the pulse power and plasma linkage, experimental data were compared to predictions from the linked code. These data were taken from test firings from the ARL five-module PFN with the capacitors charged to 7 kV, which was discharged into an open air type plasma capillary. The switch firing times were set for a short pulse at 0 s, 40 s, 80 s, 120 s, and 180 s. The plasma cartridge dimensions used were length 10.92 cm (4.3 inches) and inner diameter 0.95 cm (0.375 inch). The model input included the pulse power parameters (capacitor voltages and switch times), the plasma cartridge parameters (capillary radius and length), the number of iterations per time step and the physics parameters of the plasma (partition function data, ionization potentials, etc.). The PFN and plasma cartridge input decks for these calculations are given in Appendix A, Parts 2 and 3. For the purpose of validation, the measured load current was compared to the current predicted by the model. The agreement between the two current waveforms is quite good, with the model slightly over-predicting the peak current value at an earlier time than the actual data. The predicted peak current is 64.3 kA, occurring at approximately 237 s, while the measured peak is 61.5 kA, occurring at 280 s. The reason for the difference in peak values is probably attributable to added resistive losses in the actual system, and the difference in time is most likely attributable to inductive effects in either the pulsed power/plasma system or in the measurement apparatus.

In addition, the linked plasma model was further validated by comparing output data with the stand-alone Powell plasma model. For these simulations, the model input parameters adjusted were the current magnitude, capillary radius, and capillary length. The predicted bulk plasma temperature and plasma resistance from the two models are shown in Table 1. The conductivity model assumed for these calculations is that of Kurilenkov and Valuev,[9] and a surface temperature lower than the bulk plasma temperature is also assumed. Note that the linked plasma model in PPIB incorporates the entire end-to-end code including P2SIM and IBHVG2. Since it is necessary to test the plasma model in a condition independent from the interior ballistic portion of the code, a large chamber volume containing a small propellant charge was modeled by the IBHVG2 subroutine. This allowed for a choked flow condition in the plasma model for the duration of the calculation, which was the case for the stand-alone model. The results of the calculations from the two codes are given in Table 1, where the current magnitude varies from 16 kA to 287 kA. Once again, the agreement between the two models is reasonably good with the largest discrepancy of about 13% occurring for the resistance in the 150-kA case. One possible explanation for this discrepancy is the fact that the Powell model as used here provides output for a single input current data point, whereas the PPIB code predicts output for the entire current waveform. The PPIB code is time dependent whereas the Powell model used here is a steady state code. The output data from PPIB and Powell are compared at a single current data point used in the Powell code. This means that PPIB, in most cases, will have calculated plasma data for many points before reaching the current level assumed in the Powell code. Obviously, any time-dependent changes in capillary conditions could account for errors of this size since the output data are generally a strong function of the initial input parameters. Once again, a sample input deck for PPIB is provided in Appendix A, Part 4.

2.3 <u>High Energy ETC Plasma Calculations</u>

The Powell plasma model was used to characterize the energy partitioning of the plasma as a result of a discharge from a portion of a 4-MJ pulsed power supply, specifically a 2-MJ portion of the full 4-MJ power supply.[10] The results from the calculations are given in Table 2 for each of three cases in which the capillary radius is varied from 1.92 to 7.00 mm for a given current amplitude--in this case, 75 kA. The plasma code, which is described in great detail in

Reference 4, predicts the plasma internal, kinetic, and work energies based on the input parameters of plasma capillary radius, length, and input current magnitude. The code was used here to determine the amount of energy contained in each of the three energy components (internal, kinetic, work) for a realistic power supply configuration and with realistic dimensions. The capillary radius is fixed at 11.84 cm (sized for a 120-mm tank cannon application). The internal energy consists of the energy required to vaporize, dissociate, and ionize the plasma material, thermal energy of the plasma, and electronic excitation energy. The kinetic energy is associated with the movement of plasma through the capillary tube ($1/2\ m\ v^2$), while the work energy is the energy against pressure in the capillary (P/ρ). As seen in the data of Table 2, for all cases, the majority of energy is contained in the internal energy component, with the smallest component being kinetic energy. The general trend is for a decrease in internal energy and an increase in kinetic and work energies as the capillary radius is decreased, which seems reasonable since the capillary pressure rises rapidly with decreasing capillary radius. However, the internal energy is fairly stable over the range of radii examined with only 8.5% change from smallest to largest capillary.

Table 1. Comparison of PPIB and Powell Plasma Model Simulations (with Kurilenkov-Valuev conductivity model and surface temperature assumption)

INPUT PARAMETERS			*PLASMA OUTPUT*			
			POWELL		PPIB	
CURRENT (AMPS)	CAPILLARY RADIUS (mm)	CAPILLARY LENGTH (cm)	Temp. (K)	Resistance (mΩ)	Temp. (K)	Resistance (mΩ)
187,000	1.92	11.6	156,349	54.0	164,000	48
16,000	3.17	7.62	28,407	121.0	31,200	109
287,000	4.75	11.84	88,466	20.2	96,000	18
150,000	4.75	11.84	64,000	31.2	69,000	27
75,000	4.75	11.84	46,220	46.0	51,500	40

Table 2. Plasma Energy Partitioning for Three Test Cases With Varied Radii

CASE NO.	CAPILLARY RADIUS (mm)	PLASMA RESISTANCE* (mΩ)	PLASMA ENERGY PARTITIONING (percent) *INTERNAL ENERGY*	*KINETIC ENERGY*	*WORK ENERGY*
1	1.92	138.3	66.5	11.2	22.3
2	4.75	48.6	73.0	9.0	18.0
3	7.00	31.8	75.0	8.4	16.6

*Plasma resistance for an input current amplitude of 75 kA and capillary length of 11.84 cm.

More calculations were performed to approximate the electrical transfer efficiency from the PFN by calculating the electrical efficiency for a fixed resistance load and a modified PFN providing a square current pulse. The power supply is modified as a "transmission line" type supply having inductors of a uniform value separating energy storage capacitors.

This arrangement is used for simplicity and to allow for a more direct method of determining its characteristic impedance. The characteristic impedance is now proportional to the square root of the ratio of total inductance to total capacitance and is calculated here at 146 mΩ. The resistance obtained from the plasma model (shown in Table 2) is now used by an electronic circuit analysis code to predict the electrical transfer efficiency. The resulting values are given in Table 3, column 3. This efficiency is now multiplied by the plasma partitioning percentage numbers in Table 2 to give the last three columns of numbers in Table 3 for plasma energy delivered from the PFN.

Finally, Table 4 provides a prediction from a black body radiation model showing the percentage of radiation belonging to each of the types of radiation.[11] Note that at the high internal plasma temperatures predicted, in all cases the majority of the energy is in the ultraviolet (UV) region. It is worth noting that similar internal (bulk) temperatures (3 eV) for capillaries of this size and input current level have been predicted by other researchers.[12] Assuming that all the energy in the plasma is radiative except for the kinetic energy component, then for Case 1, approximately 72.8% of the energy would be in the form of radiative energy.

Table 3. Percentage of delivered electrical energy from the pulsed power supply to plasma components of internal, kinetic, and work energies

CASE NO.	CAPILLARY RADIUS (mm)	PERCENT ENERGY DELIVERED FROM PFN*	PERCENT ENERGY TRANSFERRED FROM PFN		
			INTERNAL ENERGY	*KINETIC ENERGY*	*WORK ENERGY*
1	1.92	82 (1,361)	54.5 (905)	9.2 (153)	18.3 (304)
2	4.75	57 (946)	41.6 (691)	5.1 (85)	10.3 (171)
3	7.00	44 (730)	33.0 (548)	3.7 (61)	7.3 (121)

*For a square current pulse from a 2-MJ PFN with 1.66-MJ stored electrical energy having a characteristic impedance of 146 mΩ. The values in parantheses indicate the amount of energy, in kJ, obtained from the original 1.66 MJ of stored energy.

Table 4. Black Body Radiation Prediction for Three Plasma Test Cases

CASE NO.	RADIUS (mm)	PLASMA* TEMP. (K, eV)	PLASMA RADIATION PARTITIONING (PERCENT)		
			UV (0 - 0.3 micron)	*VISIBLE (0.4 - O.7 micron)*	*INFRARED (0.8 - 2 micron)*
1	1.92	55,700, 4.8	97.8 (1,182)	2.1 (25)	0.1 (1.2)
2	4.75	34,232, 2.9	92.2 (795)	7.2 (62)	0.6 (5)
3	7.00	27,965, 2.4	87.5 (585)	11.4 (76)	1.1 (7)

* Similar plasma temperature results have been obtained from other plasma researchers (see Reference 12). The values in parantheses indicate the amount of energy, in kJ, obtained from the original 1.66 MJ of stored energy, assuming only internal and work energies contribute to radiation.

While this assumption is somewhat arbitrary and to be taken only as an approximation, it provides a simple way of accounting for energy losses encountered in the generation of the plasma. The results from this analysis indicate that, based on the approximated power supply efficiency and predicted internal plasma temperature for Case 1, of the original 1.66-MJ store of electrical energy, approximately 1.18 MJ are converted to ultraviolet energy. The remaining 27 kJ delivered to the plasma are shared by visible and infrared energy with about 25 kJ in the visible.

In addition, experimental work for the purpose of determining physical interaction of plasmas and propellants is progressing at ARL. In these studies, gun propellant samples are allowed to interact with the radiation from high energy plasmas, typical of those studied in this report. To date, the experimental results indicate a rapid optical reaction or response of the samples exposed to the plasma radiation.[12] These tests also show signs of increased propellant surface areas following plasma exposure and the importance of propellant location and geometry, all of which will also require further investigations.

3. SUMMARY

An electrothermal-chemcial (ETC) gun model, designed by Princeton Combustion Research Laboratories (PCRL), for predicting the pulsed power, plasma, and interior ballistic aspects of an ETC gun system has been completed and delivered under contract to ARL. This model, PPIB, is configured as an end-to-end gun design code incorporating the three main subsystems of an ETC gun, based upon the well-known models of P2SIM, the Powell plasma model, and IBHVG2. This code has been validated against several sets of data, including pulsed power data from a 4-MJ system, 30-mm ETC plasma experiments, and the stand-alone version of the Powell plasma model.

The results from the one-dimensional Powell plasma model indicate that the capillary resistance is a sensitive function of input current and capillary radius. For the calculations performed here, the resistance varied by a factor of 4.3 over the range of radii used for a fixed current amplitude of 75 kA. The partitioning of energy into the various plasma constituents was shown to be fairly insensitive to changes in radius, changing at most by 8.5% over the range of radii used. However, for all capillary geometries and input electrical energies investigated, the predicted internal temperatures are quite high (between 2.4 and 4.8 eV). Similar internal plasma temperatures for capillaries of this size and input current level have also been predicted by other plasma researchers.[12] The generation of a high temperature plasma as seen in the test cases discussed here has the effect of converting most of the stored energy in the capacitor bank into ultraviolet radiation before the plasma expansion process. The usefulness of the ultraviolet radiation, how it changes or re-partitions during the combustion event, and how it reacts with materials such as gun propellants is not clear at the present time and will require further study. Also, experiments characterizing the plasma propellant interactions have been performed at ARL, which indicate rapid optical reaction or response of sample propellants exposed to plasma radiation.[13] These tests show signs of increasing propellant surface area following plasma exposure as well as the importance of propellant location and geometry, all of which will require further investigations.

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APPENDIX A

INPUT DECKS

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1. P2SIM validation input deck

```
CONTROL 5uS 2 0
PULSE 5mS 1 10 10 1
ELEMENT CAPACITOR GENE 3 0 1    .99 0    1400.0uF 0mO 0 0 0 0 0 0 752 446072
ELEMENT CAPACITOR GENE 5 0 1    .99 0    1400.0uF 0mO 0 0 0 0 0 0 752 446072
ELEMENT CAPACITOR GENE 7 0 1    .99 0    1400.0uF 0mO 0 0 0 0 0 0 752 446072
ELEMENT CAPACITOR GENE 9 0 1    .99 0    1400.0uF 0mO 0 0 0 0 0 0 752 446072
ELEMENT CAPACITOR GENE 11 0 1 .99 0 1400.0uF 0mO 0 0 0 0 0 0 752 446072
ELEMENT INDUCTOR GENE 2 3 0  0. 0 120uH 10mO 0 0 0 47 56000
ELEMENT INDUCTOR GENE 4 5 0  0. 0 80uH 10mO 0 0 0 47 56000
ELEMENT INDUCTOR GENE 6 7 0  0. 0 60uH 10mO 0 0 0 47 56000
ELEMENT INDUCTOR GENE 8 9 0  0. 0 43uH 30mO 0 0 0 47 56000
ELEMENT INDUCTOR GENE 10 11 0 0. 0 30uH 10mO 0 0 0 47 56000 ELEMENT
RESISTOR GENE 1 0 0             0. 1 120mO
ELEMENT CLSWITCH GENE 1 2 0mS 10mO 0. 1MO 0 0 0 0 18 44000 ELEMENT
CLSWITCH GENE 1 4               0.5mS 10mO 0. 1MO 0 0 0 0 18 44000
ELEMENT CLSWITCH GENE 1 6    0.75mS 10mO    0. 1MO 0 0 0 0 18 44000
ELEMENT CLSWITCH GENE 1 8    1.0mS 10mO 0. 1MO 0 0 0 0 18 44000
ELEMENT CLSWITCH GENE 1 10 1.2mS 10mO       0. 1MO 0 0 0 0 18 44000
ELEMENT DIODE GENE 0 3 10V 45mO 0nH 1MO
ELEMENT DIODE GENE 0 5 10V 40mO 0nH 1MO ELEMENT DIODE GENE 0 7 10V
37mO 0nH 1MO ELEMENT DIODE GENE 0 9 10V 33mO 0nH 1MO ELEMENT DIODE
GENE 0 11 10V 30mO 0nH 1MO
ELEMENT BATTERY GENE 22KV 1000KJ 100uO 1nH 0 1KA 0 10Kg 1000. 1 ELEMENT
BATMOD GENE 0 0 0 1 1 0. 0
```

2. PPIB validation input deck for ARL five module PFN

```
CONTROL 5uS 2 0
PULSE 1mS 1 10 10 1
ELEMENT CAPACITOR GENE 3 0 1    .99 0 1020uF 0. 0. 0. 0. 0. 0. 0. 1. 1000. 1
ELEMENT CAPACITOR GENE 4 0 1    .99 0 488uF 0. 0. 0. 0. 0. 0. 0.  1.  1000. 1
ELEMENT CAPACITOR GENE 6 0 1    .99 0 615uF 0. 0. 0. 0. 0. 0. 0.  1.  1000. 1
ELEMENT CAPACITOR GENE 8 0 1    .99 0 195uF 0. 0. 0. 0. 0. 0. 0.  1.  1000. 1
ELEMENT CAPACITOR GENE 10 0 1 .99 0 400uF 0. 0. 0. 0. 0. 0. 0. 1. 1000. 1 ELEMENT
INDUCTOR GENE 1 2 0             0. 0 7uH      0.    0. 0. 0. 10. 1000. 1
ELEMENT INDUCTOR GENE 1 5 0     0. 0 16uH 0. 0. 0. 0. 10. 1000. 1
ELEMENT INDUCTOR GENE 1 7 0     0. 0 28uH 0. 0. 0. 0. 10. 1000. 1
ELEMENT INDUCTOR GENE 1 9 0     0. 0 58uH 0. 0. 0. 0. 10. 1000. 1
ELEMENT INDUCTOR GENE 1 11 0 0. 0 15uH 0. 0. 0. 0. 10. 1000. 1 ELEMENT
RESISTOR GENE 1 0 0             0. 1 35mO
ELEMENT CLSWITCH GENE 2 3 180uS 10uO       0. 1MO 0. 0. 0. 0. 10. 1000. 1
ELEMENT CLSWITCH GENE 5 4 120uS 10uO       0. 1MO 0. 0. 0. 0. 10. 1000. 1
ELEMENT CLSWITCH GENE 7 6 80uS 10uO 0. 1MO 0. 0. 0. 0.   10. 1000. 1
ELEMENT CLSWITCH GENE 9 8 40uS 10uO 0. 1MO 0. 0. 0. 0.   10. 1000. 1
ELEMENT CLSWITCH GENE 11 10 0uS 10uO       0. 1MO 0. 0. 0. 0. 10. 1000. 1
ELEMENT DIODE GENE 0 10 10V 10uO 0nH 1MO 0. 0. 0. 0. 1. 1000. 1 ELEMENT
DIODE GENE 0 8 10V 10uO 0nH 1MO 0. 0. 0. 0. 1. 1000. 1
ELEMENT DIODE GENE 0 6 10V 10uO 0nH 1MO   0. 0. 0. 0. 1. 1000. 1
ELEMENT DIODE GENE 0 4 10V 10uO 0nH 1MO   0. 0. 0. 0. 1. 1000. 1
ELEMENT DIODE GENE 0 3 10V 10uO 0nH 1MO   0. 0. 0. 0. 1. 1000. 1
ELEMENT BATTERY GENE 7KV 1000KJ 100uO 1nH 0 1KA 0 10Kg 1000. 1
ELEMENT BATMOD GENE 0 0 0 1 1 0. 0
```

3. PPIB plasma capillary input deck

```
4.74E-03,101,10.92E-2,0,1
400,401,1,1 0.5,0.1,0.2,1.0E4,273.,1.0E-04,.001,6.173e7 1.0,1.00E-5
1 13 3 2
2.0     0.00
1.0     0.00
3.0  16.4
5.0  43.5
5.0  10193.70
1.0  21648.4
5.0  33735.2
9.0  60360.0
3.0  61982.0
15.0 64091.0
3.0  68858.0
15.0 69715.0
3.0  70744.0
9.0  71368.0
2.0     0.00
4.0  64.0
12.0 43024.0
1.0     0.00
9.0  52349.0

0.
0.9
1.,1.,1.
5
0. .25 .5        .75 1.
1.,0.,0.
C RI,NZ,XL,IOPT
C ITMAX,IPRINT,ICHOKE,ICALC
C X1C,X2C,X1H,CON,T,XLAM,TCUT,RCUT
C PARTITION FUNCTION DATA
C PEX
```

4. PPIB plasma capillary input deck (table 1 data)

```
4.75D-03,101,11.84D-2,0,1
400,401,1,1 0.5,0.1,0.2,1.0D4,273.,1.0D-04,.001,6.173D7 1.0,1.0D-5
1 13 3 2
2.0     0.00
1.0     0.00
3.0  16.4
5.0  43.5
5.0  10193.70
1.0  21648.4
5.0  33735.2
9.0  60360.0
3.0  61982.0
15.0 64091.0
3.0  68858.0
15.0 69715.0
3.0  70744.0
9.0  71368.0
2.0     0.00
4.0  64.0
12.0 43024.0
1.0     0.00
9.0  52349.0
0.
0.9
5
0. .25 .5       .75 1.
1.,1.,1.
C RI,NZ,XL,IOPT
C ITMAX,IPRINT,ICHOKE,ICALC
C X1C,X2C,X1H,CON,T,XLAM,TCUT,RCUT
C PARTITION FUNCTION DATA
C PEX
```

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