The Electric Propulsion Experiment (EPEX) is a Japanese space experiment program for the quasi-steady MPD (magnetoplasmadynamic) propulsion system. The EPEX is planned to be conducted on a Japanese free flying platform in the 1990s. The ground test with the development models for the EPEX was conducted in 1987. The design requirements and the results of the ground test are summarized in this paper for the development of the capacitor bank in the power conversion subsystem of EPEX. The power conversion efficiency in the pulse forming network (PFN), which is a main component of the capacitor bank, was found to be approximately 85% in the ground test. The number of the repetitive discharges amounted to 3 millions in net operation period of 25 days. The basic requirements for the EPEX was confirmed to be feasible by the ground test.

1. INTRODUCTION

The Electric Propulsion Experiment (EPEX) is a Japanese space experiment program for the propulsion system with the quasi-steady MPD (magnetoplasmadynamic) arcjet. The EPEX is planned to be conducted on a Japanese unmanned free flying platform, which is designated SFU, in the 1990s. The ground test with the bread board models for EPEX was conducted from Dec. 1987 to Feb. 1988 at the Institute of Space and Astronautical Science in co-operation with Mitsubishi Electric Corporation and Ishikawajima-Harima Heavy Industries, Ltd.

The power supply subsystem of an MPD propulsion system consists of a charge controller unit and a capacitor bank. The capacitor bank condenses the power supplied constantly from the power source of spacecraft into pulses for high power discharges. The capacitor bank consists of a pulse forming network (PFN) for main arc discharges and power conditioners for fast acting valves (FAVs) and high voltage trigger arc discharges. The objectives of this paper are

1) to clarify the design requirements for the capacitor bank and
2) to clarify the feasibility of the requirements verified by the ground test.

2. DESIGN REQUIREMENTS FOR CAPACITOR BANK

The basic design requirements for the electrical power subsystem of EPEX were reported in our previous paper. Here summarized again are the principal requirements, since some revisions and additions were made through later analyses.

2.1 PFN Power Conversion Efficiency

The present design target for the power conversion efficiency in the EPEX PFN is 85%. Although the target for future applications will be higher than that for EPEX, it should be determined by the trade-off analysis, accounting its weight or mass allocation resources on the spacecraft. The efficiency is improved with lower resistive current path in PFN and with the impedance matching condition, where they cost more massive inductor, cables, or capacitors. Since the thrust-power ratio of the thruster itself has been improved to exceed 50 mN/kW in low Isp range, the required system thrust-power ratio of 30 mN/kW will be achieved by the allocated efficiency as shown in Fig. 1.

Fig. 1. Power distribution in EPEX system.

2.2 Interface with the Segmented Anode

Since the discharge head with the segmented anode is adopted to the EPEX, it is required to provide each anode segment with the equal discharge current pulse. The similarity of the current pulses will not be required to be perfect, but to the extent that the segmented anode works effectively and that the required over all thrust-power ratio is achieved.
2.3 Durability and Endurance

For future applications, an endurance of at least 100 days or 10 million shots will be required. For the EPEX, the allocated mission period will be a few days at most, which will allow the repetitive operation of tens of thousand shots. Although the EPEX system should have a potential endurance sufficient for the future applications, the EPEX system will be designed as durable as the allocated mass resource permits. In general, the more derating for electronic parts costs the more mass, though the capacitor bank has no life limited parts in it.

A discharge head is a life limited component because of the cathode erosion. If an endurance exceeding the life of a head is required for missions, the capacitor bank is required to be capable of operation with multiple heads alternatively.

Since the EPEX is not an application mission, but just an experiment mission, a fully redundant system will not be required for recovery from prospective failures during its operation. At least a function to resume its operation, however, will be required even though its performance is degraded by the failures.

2.4 Modular Design

A propulsion system should be optimized for its mission and the modular design is not consistent with the optimization. For the EPEX, however, the modular design should be preferred to the optimization, since derivation of design rules by the experiment is easier with the generalized modular design than with the peculiar design for optimization. The modular design is effective to adapt the experiment system to changes in the resources allocated to the EPEX on the SFU.

2.5 Composition of PFN

The PFN is composed of capacitors and inductors to form ladder circuits. There is no choice to determine the capacity and inductance in PFN, if the pulse duration and the characteristic impedance are given. There, however, are freedom to choice the pulse duration and the characteristic impedance according to freedom of selection of the fast acting valves (FAVs) and of mismatching conditions in impedances of the PFN and the discharge head. The composition of capacity and inductance in PFN should be optimized for the state of the art as following discussions.

Since most of the mass of capacitor bank is allocated to the PFN, the optimization should be done in order to minimize the mass of PFN. The mass of PFN, W_pfn, is given as follows,

\[ W_{pfn} = K_{cap} \times C + K_{cl} \times L, \]  

where \( K_{cap}, C, K_{cl}, \) and \( L \) are mass of the capacitor module per unit capacity, capacity in the PFN, mass of the inductor coil per unit inductance, and inductance in the PFN, respectively.

While \( K_{cap} \) is regarded as a constant approximately, \( K_{cl} \) is regarded to be proportional to \( L \) as explained by the following equations. According to the definition,

\[ K_{cl} = a \cdot \rho \cdot J \cdot S / L, \]  

where \( a, \rho, J, \) and \( S \) are a ratio of mass of the coil module to mass of conductor which composes the inductor, density of the conductor, stretched length of the conductor, and cross section area of the conductor, respectively. \( J \) and \( S \) can be eliminated in Eq. (2), employing following equations,

\[ R = r \times J / S \]  
\[ L = k \times L, \]  
where \( R, r, \) and \( k \) are resistance of the conductor, resistivity of the conductor, inductance per unit inductor length, respectively. Eq. (2) is an approximate relation. Then \( K_{cl} \) is expressed as follows,

\[ K_{cl} = K'_{cl} \times L, \]  
where

\[ K'_{cl} = a \cdot \rho \cdot r / (R k^2). \]  

\( K'_{cl} \) can be regarded as a constant approximately. Thus the mass coefficients of the capacitor module and coil module, \( K_{cap} \) and \( K_{cl} \), are expressed by appropriate design parameters.

In order to eliminate \( C \) in Eq. (1), an approximate relation,

\[ \tau = 2 \sqrt{L \times C}, \]  
where \( \tau \) is characteristic time constant, i.e. pulse duration, of the PFN, is employed, then Eq. (1) becomes

\[ W_{pfn} = K_{cap} \tau^2 / 4 \times 1/L + K'_{cl} x L^2. \]  

Thus the mass of PFN is expressed as a function of two independent variables, \( \tau \) and \( L \). As shown in Eq. (8), the shorter pulse duration, \( \tau \), gives the smaller mass. For the inductance, L, the minimum mass of PFN is given when

\[ L = \left( \frac{\tau}{8} \times K_{cap} \times 1/K'_{cl} \right)^{1/3}. \]  
The minimum value of \( \tau \) is given by the minumum pulse duration of the propellant gas, i.e. the operational limit of the FAV. Then the inductance is determined by Eq. (9), the capacity is determined by Eq. (7), and the minimum mass of PFN is derived by Eq. (8).
2.6 Safety Requirements

SFU is planned to be retrieved by the NASA STS. The NASA STS requires limitation of flammable materials usage in its payload. The plastic film used in the capacitor bank is flammable and indispensable to its primary function. The capacitors should be covered by non-flammable or self-extinguishing materials to fulfill the requirement.

A fail-safe function to short-circuit and to ground the discharge circuits in the capacitor bank will be required, too, in order to preclude the hazards aroused by unexpected charge-up of the discharge circuits.

3. THE LATEST GROUND TEST

3.1 Objectives

For the capacitor bank, the objectives of the latest ground test are

1) to verify the feasibility to achieve the required power conversion efficiency with the real discharge heads,
2) to verify the function to operate the segmented anode discharge head effectively,
3) to verify the endurance sufficient to the EPEX mission and to obtain prospects in endurance sufficient to future applications, and
4) to obtain refined informations for mass estimation of the components such as capacitor modules and the inductor coils.

3.2 Apparatus and Conditions

3.2.1 Test Configuration

A schematic diagram of the configuration of the latest ground test is shown in Fig. 2. The capacitor bank was located in a vacuum chamber with two discharge heads, three FAVs for each head, and water cooled base plate. Three DC power supplies outside the chamber were employed to charge the capacitor bank. The capacitor bank has no intelligent function. The control signals were supplied and the internal status were monitored by the control and monitor subsystem outside the chamber through discrete signal lines. Propellant, hydrazine decomposed gas simulated by mixture of hydrogen and nitrogen, was supplied by the pressure and mixing control device outside the chamber. The FAVs, which were mounted on the discharge head, introduced the propellant into the discharge region between the electrodes in short pulses. High voltage for triggering the arc discharge was imposed on the electrodes, synchronizing with the propellant pulse. The repetitive discharges were thus conducted with a frequency of approximately 1.3 Hz in most period of the test.

3.2.2 Capacitor Bank Tested

The capacitor bank tested is composed of the PFN, which consists of four capacitor modules and four coil modules, and two redundant units for FAV driving and TRG discharge as shown in Fig. 3. The characteristics of the capacitor bank tested are summarized in Table 1.

![Fig. 2. Test configuration.](image)

![Fig. 3. External view of the capacitor bank tested.](image)

Table 1. Characteristics of the capacitor bank tested.

<table>
<thead>
<tr>
<th></th>
<th>FFN</th>
<th>L-C Ladder Circuits</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Stages</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18 Channels</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10000 µH 30 mΩ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 µH 600 µsec</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FAV and TRG Driver</td>
<td>420 µF for Lift Pulse</td>
<td>280 µF for Break Pulse</td>
</tr>
<tr>
<td></td>
<td>5.5 µF for Trigger Arc</td>
<td></td>
</tr>
</tbody>
</table>
Each of capacitor modules consists of 18 plastic film capacitors. The characteristics of the capacitor used in the module are shown in Table 2. A fuse is equipped in series to each capacitor for separation in case of short-circuited failure of the capacitor. The external view of the module is shown in Fig. 4. While the total mass of the 18 capacitors was 3.1 kg, the mass of the module was approximately 5 kg. Since the measured capacity of a capacitor was 141 μF, the total capacity of the module amounted to 2540 μF.

Table 2. Characteristics of the capacitor tested.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Film Thickness (μm)</td>
<td>3.8</td>
</tr>
<tr>
<td>Polyester Film Capacitance (μF)</td>
<td>142</td>
</tr>
<tr>
<td>Weight (g)</td>
<td>173.3</td>
</tr>
<tr>
<td>BDV (V)</td>
<td>700</td>
</tr>
<tr>
<td>Mass/Energy at BDV (g/J)</td>
<td>5.0</td>
</tr>
<tr>
<td>Mass/Capacity (g/μF)</td>
<td>1.2</td>
</tr>
<tr>
<td>Rated Voltage (RV) (V)</td>
<td>336</td>
</tr>
<tr>
<td>Mass/Energy at RV (g/J)</td>
<td>21.6</td>
</tr>
</tbody>
</table>

Each of coil modules is composed of 18 wires, a bobbin made of GFRP, and epoxy compound for molding. The insulated wires were wound in a spiral slot carved on the bobbin. The coil was finished by molding with epoxy compound as shown in Fig. 5. The average of the measured inductances of the wires in the module was 3 μH. The wire used in the coil was AWG 12 and had a conducting cross section of 5 mm², approximately. While the total weight of the wires in one module was approximately 1.5 kg, the mass of one module was approximately 5 kg.

The PFN is assembled in such a manner that a capacitor in the module is connected only to a wire in the coil module and to one of the segments of the anode as shown in Fig. 6. Thus hot lines in the PFN are insulated from each other, while the return, which is connected to the cathode, is common. Though the simple mono-layer solenoidal coils, which are independently equipped in the PFN stage nearest to the head as shown in Fig. 7, are employed to divide the output current to supply each
segment of anode with equal amount of discharge current in the previous conceptual design for the PFN, the present configuration is adopted to utilize mutual inductance between electrostatically insulating channels and to reduce the mass of the inductors, since the number of anode segments have increased to 18 in the present design for EPEX. Another feature of the PFN is the diodes connected in the direction anti-parallel to the discharge electrodes. The diodes recover the inversely charged energy after normal discharge in the case of under dumping mismatching condition of the impedances.

A unit for FAV driving and trigger discharge includes two capacitor modules, 420 \( \mu F \) and 280 \( \mu F \), for FAV driving and one capacitor module, 5.5 \( \mu F \), for trigger arc discharge. The FAVs tested were the double pulse type, in which the first driving current pulse generates the force to lift up the actuator disk and the second current pulse generates the force to break the returning speed of the disk for shock relaxation and rebound suppressing. SCRs for discharge triggering and a pulse transformer for high voltage generation for trigger arc are also included in the unit. The SCRs are driven by the sequential trigger pulses for repetitive discharge operation. The winding ratio of the transformer is 1:4. The two units compose an redundant system as shown in Fig. 8. The mass of a unit was 5 kg, approximately.

3.2.3 Test Conditions

The charging voltage of PFN was 336 v, while the charging voltages for the FAV driver and the trigger arc discharge were 365 v and 400 - 450 v, respectively. The charging repetition rate was effectively 1.3 Hz, since there were interruptions due to erroneous detection of anomalies by the controller, although the rate was set to be 1.4 Hz in the sequencer? The input power to the capacitor bank was 825 w, which is consistent with 1 kw input to the EPEX system. The pressure in the vacuum chamber was kept less than \( 10^{-2} \) Torr in most of the test period. The pressure increased, however, up to \( 10^{-2} \) Torr due to failure in the vacuum system, which damaged the monitor circuits in the capacitor bank and required interruption of the test and mending of the unit to resume the test.

![Fig. 8. Redundancy in capacitor bank.](image)

3.3 Test Results and Discussions

3.3.1 Power Conversion Efficiency

Fig. 9 shows the total discharge currents and the averaged discharge voltages of 18 channels in the PFN at intervals of 2 hundred thousand shots during 3 million repetitive shots operation. The total discharge current, the discharge voltage, and the half value width of the discharge currents averaged over 16 sets of data in Fig. 9 are 6.5 kA, 125 v, and 600 usec, respectively. The energy output per shot from the PFN was then 488 J. The energy stored in the PFN was 574 J. The residual voltage after every discharge was approximately 30 v, which implies that approximatively 5 J was recovered to be available in the next discharge. The recovered energy scarcely contributed to improve the efficiency, since the head impedance was larger than that expected previously and there was no serious mismatching condition.

![Fig. 9. Discharge current and voltage during 3 million shots operation, 0.2 msec/div.](image)
Table 3 shows the energy balance in the PFN derived from these data. The required power conversion efficiency in the PFN was achieved as shown in Table 3. The impulse bit was measured by the pendulum method together with the discharge head and the PFN on the same discharge condition and found to be 24 mSec, which is consistent with the data obtained with the same discharge head and current source stabilized by a sufficiently large resistance for each segment. Since the effective repetition rate was 1.33 Hz, the time averaged thrust was 32 mN. It was confirmed that the required thrust can be obtained by the PFN combined with the discharge head. Moreover, the feasibility of the system thrust-power ratio of 30 mN/kW was confirmed, too, although practicability of the allocated efficiency for the charge controller has not yet been verified by test.

3.3.2 Interface with Segmented Anode
Figs. 10 and 11 show typical discharge currents for a segment of anode and for 6 segments, respectively. Though the discharge currents for the smaller number of segments showed fluctuation as shown in Figs. 10 and 11, the total discharge current, sum of currents for 18 segments, showed no significant fluctuation as shown in Fig. 12. Since consistent data were obtained both by the configuration tested here and by the test with the stabilized current sources, the non-uniformity to the extent shown in Figs. 10 and 11 seems to be permitted, though the segmented anode was adopted for uniform current distribution in azimuthal direction in the discharge head. The condition for effective operation of the segmented anode is not clear, so far. Anyway, it was confirmed that the segmented anode head is operated effectively with the present configuration of PFN.

Table 3. Energy balance in PFN.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged Energy</td>
<td>574 J</td>
</tr>
<tr>
<td>Output to Head</td>
<td>488 J</td>
</tr>
<tr>
<td>Residue in PFN</td>
<td>13 J</td>
</tr>
<tr>
<td>Recovered Residue</td>
<td>5 J</td>
</tr>
<tr>
<td>Loss in PFN</td>
<td>81 J</td>
</tr>
<tr>
<td>Efficiency</td>
<td>85 %</td>
</tr>
<tr>
<td>Heat Dissipation in Induction Coils</td>
<td></td>
</tr>
<tr>
<td>Coil 1</td>
<td>25 J</td>
</tr>
<tr>
<td>Coil 2</td>
<td>22 J</td>
</tr>
<tr>
<td>Coil 3</td>
<td>17 J</td>
</tr>
<tr>
<td>Coil 4</td>
<td>10 J</td>
</tr>
<tr>
<td>Total Heat Dissipation in Coils</td>
<td>74 J</td>
</tr>
</tbody>
</table>

3.3.3 Endurance
3 million shots were conducted without failures in the PFN, though some failures in the FAV drivers and trigger arc circuits occurred. Approximately 10% of the capacitors in the PFN were broken in short-circuited state in the course of the endurance test of 1 million shots in 1985. In the latest test, there occurred no trouble in the capacitors during operation. The differences, which seem to have been effective for the preclusion of failures, are:

1) Lowering of charging voltage from 440 v to 336 v,
2) Lowering of maximum operation temperature from over 100 deg. C to under 60 deg. C, and
3) Raising of screening voltage from 500 v to 600 v.

After the 3 million shots test, however, lowering of breakdown voltage was found in 30% of the tested capacitors. Although all the tested capacitors passed the test with 600 v prior to the module assembling, the break downs occurred in the test with statically imposed voltage of up to 500 v. The cause of the breakdown was verified by test. After the 3 million shots test, however, lowering of breakdown voltage was found in 30% of the tested capacitors. Although all the tested capacitors passed the test with 600 v prior to the module assembling, the break downs occurred in the test with statically imposed voltage of up to 500 v. The cause of the breakdown was verified by test.
voltage lowering is not clear so far. The self-healing function, which is peculiar to plastic film capacitors, might have worked effectively to conduct the repetitive operation without interruption during the test. Though 3 million shots is sufficient for the EPEX, more endurance and the analysis to clear the cause of the break down voltage lowering will be required for future application missions. The failures found in the capacitor bank during the test are

1) failures of SCRs used in the trigger arc discharge circuits,
2) failures of dumping relays, and
3) breakdown failures in voltage monitor circuits.

The causes of 1) and 2) were found to be incorrect usage or selection of the parts. The parts were replaced and the operation was resumed. 1) and 2) can be precluded by correct design. The cause of 3) was unexpected ambient pressure increase due to failure in the vacuum system. All the failures occurred in the test, therefore, will be precluded by correct design and with appropriate test conditions.

Alternating operation of two discharge heads by a PFN was successfully conducted in the final phase of the test. While the charged voltage of PFN was imposed on both of the two heads, propellant pulse and trigger arc were given alternately to one of the two heads. It was confirmed that endurance of a system is not limited by life of a discharge head.

3.3.4 Mass Estimation

The mass of a capacitor module tested and the sum of capacitors in the module were 5 and 3.1 kg, respectively. The ratio of them were 1.61. Assuming mass reduction of a module down to 4.5 kg, -10 %, the mass ratio becomes 1.45 and according to the notation in section 2.5,

\[ K_{\text{cap}} = \frac{4.5}{0.00254} = 1.8 \times 10^5 \, \text{kg/F} \]  \hspace{1cm} (10)

Provided that power conversion efficiency of PFN is 0.9 and impedance mismatching is not serious, the following relation stands,

\[ \frac{Z_{\text{hd}}}{R + Z_{\text{hd}}} = 0.9 \] \hspace{1cm} (11)

where \( R \) and \( Z_{\text{hd}} \) are internal resistance of the PFN and impedance of the discharge head, respectively. According to the most recent data mentioned in section 3.3.1,

\[ Z_{\text{hd}} = 0.019 \, \text{Ohm} \] \hspace{1cm} (12)

Substituting Eq. (12) to Eq. (11),

\[ R = 0.0021 \, \text{Ohm} \] \hspace{1cm} (13)

Regarding the internal resistance as the resistance of conductor in the inductance coils, \( R \) in Eq. (11) becomes identical with \( R \) in Eq. (3). Substituting \( R \) in Eq. (13) and following ordinary values, the value of \( a \) for the tested model of coil module was approximately 3 and \( a = 2 \) can be expected for the flight model. The shortest duration of propellant pulse is approximately 600 usec with a FAV of the present state of the art. Then

\[ Z = 600 \times 10^6 \, \mu\text{sec} \] \hspace{1cm} (19)

Substituting Eqs. (10), (17), and (19), Eq. (8) is rewritten as follows,

\[ W_{\text{PFN}} = 1.62 \times 10^5 / L + 2.4 \times 10^5 x L \] \hspace{1cm} (20)

The value of the inductance which gives the minimum \( W_{\text{PFN}} \) is derived from Eq. (9) as follows,

\[ L = 7 \times 10^6 \, \text{H} \] \hspace{1cm} (21)

The minimum \( W_{\text{PFN}} \) is then

\[ W_{\text{PFN}} = 35 \, \text{kg} \] \hspace{1cm} (22)

Thus the optimum composition and minimum mass of PFN is obtained for the present state of the art, applying the latest design data. According to the above discussion, the minimum system for MPD propulsion is defined as shown in Table 4.

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass (Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Power Subsystem</td>
<td>54</td>
</tr>
<tr>
<td>PFN</td>
<td>39</td>
</tr>
<tr>
<td>Capacitor Modules</td>
<td>23</td>
</tr>
<tr>
<td>Coils</td>
<td>12</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>4</td>
</tr>
<tr>
<td>PTDU</td>
<td>5</td>
</tr>
<tr>
<td>CCU</td>
<td>10</td>
</tr>
<tr>
<td>Discharge Heads Subsystem</td>
<td>8 (include FAVs)</td>
</tr>
<tr>
<td>Propellant Supply Subsystem</td>
<td>5 (without Propellant Tank)</td>
</tr>
<tr>
<td>Control Subsystem</td>
<td>4.5</td>
</tr>
<tr>
<td>Integration Assembly</td>
<td>3</td>
</tr>
<tr>
<td>Support Structure</td>
<td>12 (15%)</td>
</tr>
<tr>
<td><strong>Total Mass</strong></td>
<td><strong>86.5 Kg</strong></td>
</tr>
</tbody>
</table>
The design point of the tested PFN is close to the optimum as shown in Fig. 13. Since the deviation is primarily due to manufacturing constraints which are not yet taken into account, the basic configuration will not be changed in the flight model. The configuration of EPEX may be modified, however, by reducing the system into a partial model with appropriate similarity law according to available resources on the SFU.

4. SUMMARY

In the latest ground test
1) power conversion efficiency of the PFN with the segmented anode head was verified to be 85 %, and
2) repetitive 3 million shots in net operation period of 25 days, were conducted without serious failures.
1) and 2) verify the feasibilities of basic performance and endurance required for the EPEX. The remaining verifications for EPEX will be implemented through successive development phases.

The refined informations for mass estimation were obtained by the bread board model manufacturing.

REFERENCES