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Electromagnetic Propulsion Test Facility

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ELECTROMAGNETIC PROPULSION TEST FACILITY

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SUMMARY

A test facility for the exploration of electromagnetic propulsion con-
cepts is described. The facility is designed to accommodate electromagnetic
rail accelerators of various lengths (1 to 10 m) and to provide accelerating
energies of up to 240 kJ. This accelerating energy is supplied as a current
pulse of hundreds of kA lasting as long as 1 msec. The design, installation,
and operating characteristics of the pulsed energy system are discussed. The
test chamber and its operation at pressures down to 1300 Pascals (10 mm-Hg)
are described. Some aspects of safety (interlocking, personnel protection,
and operating procedures) are included.

INTRODUCTION

To support rail accelerator research, an Electromagnetic Propulsion Test
Facility has been established within the Lewis Research Center's Electric Pro-
pulsion Laboratory. The major objectives of the Lewis rail accelerator re-
search program are:
1. Understanding of accelerator physical phenomena
2. Characterization of the plasma armature
3. Definition of fundamental limitations and loss mechanisms
4. Exploration of scaling relationships
These objectives established the need for an accelerator test facility that
can provide electrical energy pulses over a range of both peak current and
duration with adequate safety for personnel and equipment. Such a test facil-
ity was commissioned in July 1983. This report presents the overall facility
design, details of major component construction, operating characteristics,
and safety aspects.

FACILITY DESCRIPTION

The Electromagnetic Propulsion Test Facility is designed to accommodate
tests of rail accelerators of various lengths from 30 cm to 6 m (potential ex-
tention to 10 m) and to provide accelerating energies of up to 240 kJ. Rail
accelerator function requires that the accelerating energy be supplied as a
current pulse of hundreds of kA lasting as long as 1 msec. In addition, the
capability of testing at sub-atmospheric pressures to reduce drag on the pro-
jectile is quite desirable. The following presents a brief discussion of the
electrical principles involved, followed by an overview of the facility. Spe-
cific details of component construction are discussed individually later.

To accommodate the range of peak current and pulse duration required, en-
ergy storage capacitors were selected as the power source. Figure 1 is a sim-

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plified schematic of a capacitor-based pulsed energy system. Also indicated on the schematic are the major test facility components. A DC power supply is used via a relay to charge the storage capacitor through a charging resistor. When the desired capacitor voltage has been reached, the charging power is disconnected from the capacitor by the relay. To discharge the stored energy, the feed-forward ignitron is switched on (fired) to allow energy flow through the inductor to the rail accelerator. If the crowbar ignitron is not fired, the circuit (capacitor, inductor, inherent resistance) "rings". That is, positive current flow is followed by negative current flow, followed by a second reversal, etc. until the energy is dissipated in the circuit resistance. Projectiles can be successfully accelerated with a ringing energy source. However, requiring the accelerator's plasma armature arc to restrike when the current reverses is an energy loss. Therefore, a crowbar ignitron is used to short out the capacitor at, or shortly after, the first positive current peak. Firing the crowbar at this point effectively disconnects the capacitor from the circuit. The circuit energy now stored in the inductor is released into the rail accelerator as an extended pulse of positive current.

Figure 2 is a plan view of the Electromagnetic Propulsion Test Facility showing the major system components. The Control Console (located in the adjacent control room) provides capacitor charging power, feed-forward and crowbar trigger signals, and other power system control functions. The accelerating energy is stored in four (4) pulse power modules. Each module contains charging resistors and storage capacitors plus feed-forward ignitrons, the crowbar ignitron, and their firing circuity. The outputs from the modules are paralleled into a header which is a passive current collector assembly. From the header the current is directed through an Inductor, if one is used. For some tests, the inherent circuit inductance provides adequate pulse shaping. From the Inductor, the current is brought into the vacuum Test Chamber on a Coaxial vacuum feed-thru to the rail accelerator.

Pulse Power System

Energy pulses of up to 240 kJ for rail accelerator testing are generated by the pulse power system which consists of a control console and four storage capacitor bank modules. The system is a modified version of an industrial metal-forming machine that uses a strong magnetic field for forming. The modifications made are an increase in the maximum stored energy capacity and consolidation of the modules' controls and the charging power supply into a console. Figure 3 is a sketch of the console and one module. Each of the four modules is an energy storage capacitor bank which can store a maximum of 60 kJ. Each module contains six 200 µF, 10 kV capacitors which are specifically designed for high current discharge service. The six capacitors are connected in parallel by bus work to provide a 1.2 mF, 10 kV storage bank. Each capacitor can deliver 33 kA peak current under maximum operating conditions, thus providing 200 kA per module. Each capacitor has its own 330 ohm charging resistor which is also used for current limiting when the bank's energy must be dissipated internally (dumped). The capacitors are discharged into the output bus through individual feed-forward ignitrons.

Figure 4 is a photograph of a module interior section showing one of the capacitors, its feed-forward ignitron, and charge/dump resistor. Also shown is the large single ignitron that is used to crowbar the module. The crowbar,

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when fired, effectively isolates the capacitor bank from the load circuit so that the current in the load is sustained as a single pulse with a decay time constant determined by the load inductance and resistance. The feed-forward and crowbar ignitrons are fired by trigger signals from the control console through pilot ignitron circuits within the module. Each module also contains a solenoid operated, gravity driven high-voltage relay safety switch. When the module is in use (activated) the switch connects the module's energy storage capacitors to the high voltage charging power supply. When the switch is de-energized, the capacitors are connected to ground and any stored energy is safely discharged within the module through the charging resistors.

Each pulse power module had been equipped by the manufacturer with eight 4/0 welding cables for the output. The cables were bundled together to provide the lowest possible inductance. Several schemes for maintaining bundle configuration were tried, but none was strong enough to combat the electromagnetic repulsive forces between the cables. At the expense of flexibility, we elected to replace the eight cable bundle with a set of four output coaxes for each module. Each coax has a 4/0 welding cable terminated with lugs as the center conductor. For added high voltage stand-off capability, the center conductor was placed inside vinyl extruded tubing with a nominal wall thickness of 0.88 mm. Standard copper tubing (nominal 3.2 cm diam) was used for the outer conductor. Machined brass fittings were silver-soldered to the tubing to form the end terminations. Figure 5 shows the power modules with their installed coaxes.

The system control console is located in a control room adjacent to the test facility, as indicated in figure 2. It contains the charging DC power supply and all the controls needed to charge and discharge the modules, one at a time or in tandem. All of the system interlocks, which are detailed in the section on Safety, are monitored by and operate through the console. Input power to the control console is 480 VAC, single phase. A step-down transformer provides 120 VAC power for controls.

Each power module is controlled by an illuminated selector switch which controls the module(s) to be connected to the high voltage charging power supply. Modules which are not selected are disconnected from the power supply and remain grounded by the module's relay safety switch. The charging power supply consists of an in-rush current limiting reactance, a step-up transformer, and a full-wave rectifier bridge. This high voltage DC supply (10 kV, 2 A maximum) is capable of charging all four modules in less than 60 seconds. A front panel potentiometer is used to select the percent energy level (up to 60 kJ per module) to which the modules are to be charged. When the module voltage reaches the selected level, the charging power supply is disabled. Bank voltage is read out at the console by a digital voltmeter.

The console contains a trigger generator and time delay generators which provide the control signals for the feed-forward and crowbar ignitrons. The module(s) can be discharged either by a manual push-button or a +10 V trigger signal. After firing, the selected modules are de-activated (re-grounded by the modules' safety switches) by the Stop button. Interlocking and fault detection functions of the console are discussed in the Safety section.

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Header Assembly

The currents from the capacitor bank modules are paralleled into the header as shown in figure 6. The header is a pyramidal assembly of copper (OFHC) bus bars, each 2.5 cm thick, insulated by blocks of fiberglass-epoxy laminate (G10 or G11). The purpose of the assembly is to present equal resistance paths for the output of each capacitor bank module. Figure 7 is a sketch of the header top surface (note the exaggerated vertical dimension). As shown, the bank currents are brought into the center two copper plates and are bussed to the outer two. To withstand the large repulsive magnetic forces, the header is held together by threaded Inconel rods fitted with stainless steel washers and Monel nuts. The bolts are insulated from the copper bus bars by fiberglass-epoxy tubular sleeves with a nominal 3.2 mm wall thickness.

During assembly of the header, it was found that the somewhat rough surface of the sleeves was wiping-up copper as the sleeves were inserted through the bus bars. Even slightly conductive surfaces cannot be tolerated in a system with a maximum working voltage of 10 kV. To provide lubrication without compromising high voltage stand-off capability, the sleeves were liberally coated with high quality, silicone transformer oil. When the assembly was completed, testing showed that the header can withstand 20 kV (10 min) without arc-over or significant leakage current.

Inductors

The pulsed power system, as currently configured, has an inherent inductance of about 1.6 µHenries. For many rail accelerator tests, this inductance provides adequate shaping of the output pulse. For longer pulses, the facility currently has two inductors (3 and 12 µHenries) that can be added in series with the header.

The inductor shown in figure 6 is the 12 µHenry inductor. The inductor is a single layer, nine-turn solenoidal inductor wound with two parallel conductors. It is made of aluminum bus bars (1.2 cm thick, 3.7 cm wide) wound on a wooden mandrel to form a inductor 91 cm long with a 42-cm diameter. The windings are terminated at the top and base of the inductor by welding to aluminum channel. The return from the base of the inductor is made with a central aluminum rod 5 cm in diameter. The inductor is coated with fiberglass reinforced epoxy to provide mechanical strength to combat the repulsive magnetic forces.

A smaller inductor of 3 µHenries is also available. It is a single conductor, six and a half turn solenoid 25 cm long, 15 cm in diameter. The inductor was wound from 750MCM stranded cable on a 12.5-cm diameter plexiglas cylinder. Two pairs of C-shaped clamps at right angles to each other are bolted across the winding to provide mechanical support. The inductor is terminated at top and bottom with lugs crimped to the cable and then solder-filled.

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Transition and Feed-Thru

The transition shown at the left in figures 6 and 8 connects the header to the 12 μHenry inductor and the test chamber coaxial feed-thru. Like the header, it consists of copper and fiberglass-epoxy laminate plates bolted together with threaded Inconel rod. The lower copper plate (fig. 6) is bolted to the negative output of the header and to the top termination of the inductor (fig. 8). The upper copper plate is bolted and clamped to the inductor's coaxial return bus bar. At the time of the photograph, the inductor was shorted out by three short welding cables (4/0) seen at the right in figure 8.

Figure 9 is a side view of the coaxial feed-thru assembly from the inductor and header through the test chamber wall to the rail accelerator. The coax consists of a solid copper rod 2.5 cm in diameter inside of 6.4 cm diameter copper tubing with a 0.6 cm thick wall. At the left end of the transition's upper plate, the smaller copper block clamps the plate to the inner conductor of the coaxial feed-thru. The larger block clamps the feed-thru's outer conductor and is bolted to the header's positive output. Between the two clamp blocks, an acrylic flange with O-rings supports the center conductor and forms the inner-to-outer conductor vacuum seal. The center conductor is also supported within the copper tubing at the opposite end by an acrylic block, triangular in shape with rounded corners. A similar block supports the outer conductor within the vacuum feed-thru port. This 15-cm port is fitted with an acrylic flange in which the outer conductor is vacuum sealed by an O-ring. Within the test chamber, the rail accelerator is clamped to the coaxial feed-thru as shown in figure 10.

Vacuum Test Chamber

Within the facility, rail accelerators are tested in a vacuum chamber. The primary function of the chamber is to permit accelerator testing at sub-atmospheric pressures. To avoid high voltage breakdowns, testing would be restricted to pressures above 3×10^4 Pascals (300 mm-Hg). It also would serve to contain debris in the event of a mechanical failure in the accelerator assembly. To efficiently accommodate the planned range of accelerator lengths (1 to 10 m), the chamber consists of a number of separate aluminum tank sections. One tank is stationary and the others (five currently exist) are mounted on casters. Each section has an inside diameter of 61 cm and is 122 cm long. Four of the sections are equipped with several feed-thru ports (15 cm inside diam) for instrumentation. The ports can be fitted with either brass or acrylic flanges 20 cm in diameter. As can be seen in figure 10, the tanks are equipped with rails for test hardware installation. At the time of the photograph only three sections were being used for the 30-cm rail accelerator. The chamber is evacuated by a single stage, mechanical roughing pump having a free-air displacement of 35 liters/minute.

SYSTEM OPERATING CHARACTERISTICS

Accelerating energies, from 1 to 240 kJ for all four modules, can be provided by the facility. The magnitude and duration of the current pulse must be adjustable to accommodate testing of a variety of accelerator lengths, projectile masses, and desired velocities. To make these adjustments, the elec-

trical characteristics (capacitance and inductance) are varied. The amount of capacitance can be varied by the number of modules used. This, together with the choice of inductor, provides flexibility in the peak current, time to peak, and pulse decay time for any given accelerator test.

The measured capacitance of each storage bank module (1.27 mF average) was supplied by the manufacturer. The resistance and inductance of the total system were experimentally determined as follows. A short was installed inside the test chamber at the coaxial feed-thru. The 12-μHenry inductor was also shorted out. The bank modules were charged to 5 percent energy and discharged into the short. Each module was individually tested and all combinations of modules in tandem were also tested at approximately the same total energy level. From the first peak current level and the time to first peak, the circuit inductances and resistances were calculated. The table below presents the averaged data for one, two, three, and four modules with and without an inductor in the circuit.

PULSE POWER SYSTEM CIRCUIT PARAMETERS

	Number of modules Capacitance, mF	1 1.3	2 2.5	3 3.8	4 5.1
No Inductance	Inductance, μH Resistance, m	1.6 3.3	1.4 2.3	1.3 1.8	1.2 1.5
3 μH Inductance	Inductance, μH Resistance, m	4.8 4.3	4.6 3.3	4.5 2.8	4.4 2.5
12 μH Inductance	Inductance, μH Resistance, m	13.8 4.2	13.6 3.2	13.5 2.7	13.3 2.6

These data do not include the resistances and inductances of accelerator rails and the plasma armature. However, the data do allow a rough estimate of overall system performance capability. Figure 11 shows the calculated peak current as a function of percent energy level and bank voltage for one to four capacitor bank modules with the currently available inductances. The times to peak current are also listed. From the figure, a peak current of 100 kA is available with a time to peak current of 70 to 400 μsec depending on the selection of the number of modules and the choice of inductor. On the other hand, a peak current of 300 kA is restricted to the 91 to 229 μsec range.

SAFETY

It is the policy of LeRC to manage and conduct its research and development operations in such a manner as to eliminate or minimize all potential

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hazards and to avoid accidents involving injury to personnel, damage to property, or loss of research operating time and effectiveness. The main potential hazards associated with the facility are high velocity projectiles, the presence of high currents and voltages, and the substantial noise generated when the accelerator's plasma armature arc is struck. There is also a potential for exposure to noise and flying debris should a component fail mechanically. These potential hazards are managed by a combination of physical isolation, electronic interlocking, and procedural control. All testing requires the presence of at least two knowledgeable persons. Each accelerator test, including pre-test checkout, is governed by a check-list which becomes part of that test's record.

Whenever the pulse power system is to be activated, all personnel must leave the test facility and move to the adjacent control room. Caution signs are posted on the facility doors and flashing yellow beacons signify that the power system is active. This procedure, enforced by electrical interlocks as described below, prevents possible contact with conductors at high voltage and controls noise exposure. The facility and control room are separated by a 20-cm thick concrete block wall. Observation of the test chamber is provided by a 120- by 150-cm window which is double-paned with 0.6 cm thick polycarbonate. For all accelerator tests at bank energies of 24 kJ or more, all personnel present must wear hearing protection. In addition, during such tests the adjacent test cells are evacuated and monitors are posted to prohibit access to the immediate area.

The facility incorporates a number of electrical interlocks for automatic personnel protection and limited equipment protection. Pressure sensitive switches are used to interlock the personnel doors to the facility, all doors and access panels on the capacitor modules, and the acrylic shields that cover the high voltage charging power supply in the control console. These interlocks are monitored by and operate through the control console, which is also under key switch control. When all of the interlocks are closed, the pulse power system can be activated. Upon activation, the console controls are readied for module charging and the header shorting plate (fig. 8) is retracted by solenoids. This copper plate, engaged by gravity, is the ultimate safety short for the power system and is always in place (visibly so) when the system is inactive. When one or more modules are selected for operation, the individual charge/dump relay disconnects the module high voltage components from ground and transfers them to the charging power supply. If any interlock is opened after system activation, the module charge/dump relay transfers back to ground and any energy in the system is dissipated inside the module. Approximately 1 second after the modules dump, the header shorting plate engages. These safing actions also occur when the console "Stop" button is pushed or under a general power failure.

Demonstrating projectile velocities of up to 15 km/sec are among the research objectives. After a free-flight distance for diagnostics, the projectiles are stopped by a target. The target consists of a number (up to 24) of acoustical ceiling tiles, 12.5 mm thick, mounted in an aluminum framework. Containment of projectile and/or target fragments is provided by the vacuum test chamber. The chamber would also contain debris in the event of mechanical failure of the accelerator assemby. Similarly, the capacitor bank modules are housed in heavy-duty (NEMA-12) steel enclosures which would contain debris in the event of an internal failure.

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Limited safeguarding of the test facility equipment and the acquired test data is also provided by adherence to the checklist procedure and by some power system fault detection. If any fault occurs, the charging power supply is disabled, the bank modules are discharged internally, the header shorting plate is engaged, and the system is deactivated. To recover from a fault condition, a separate "Reset" button must be pushed before the system can be reactivated. The individual module control cables are interlocked and the connectors are distinctively keyed to prevent inadvertent charging of the wrong module or one that is not activated. The system also faults if charging is attempted with either no module selected or with zero percent energy selected. During capacitor bank charging, the bank voltage is continually compared to the desired voltage. If, due to control logic failure, the bank voltage exceeds the setpoint by about 10 percent, the system faults. The last safeguard is a timer which starts when bank charging begins. The timer serves two functions. It will prevent charge/discharge cycles more frequent than once a minute. Also, if more than 1 minute elapses after start of charge and more than 800 V remains on the bank, the system faults.

CONCLUDING REMARKS

The design, operating characteristics, and safety features of the LeRC Electromagnetic Accelerator Test Facility have been described. The facility can accommodate rail accelerators up to 10 m in length and provide accelerating energies of up to 240 kJ. A storage capacitor bank is used in conjunction with inductance to provide the energy over a wide range of peak currents and pulse durations. The facility is easy to operate, relatively error proof, and fail-safe.
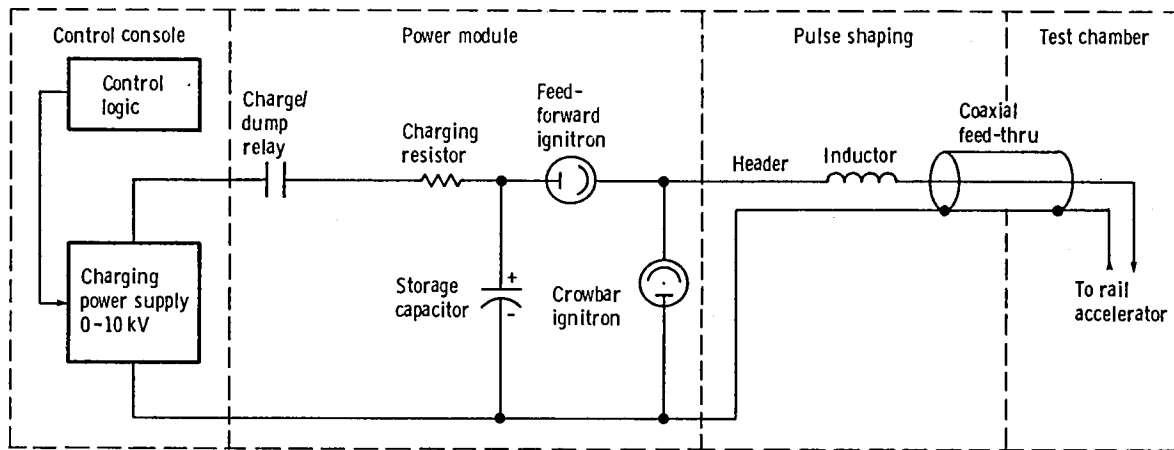
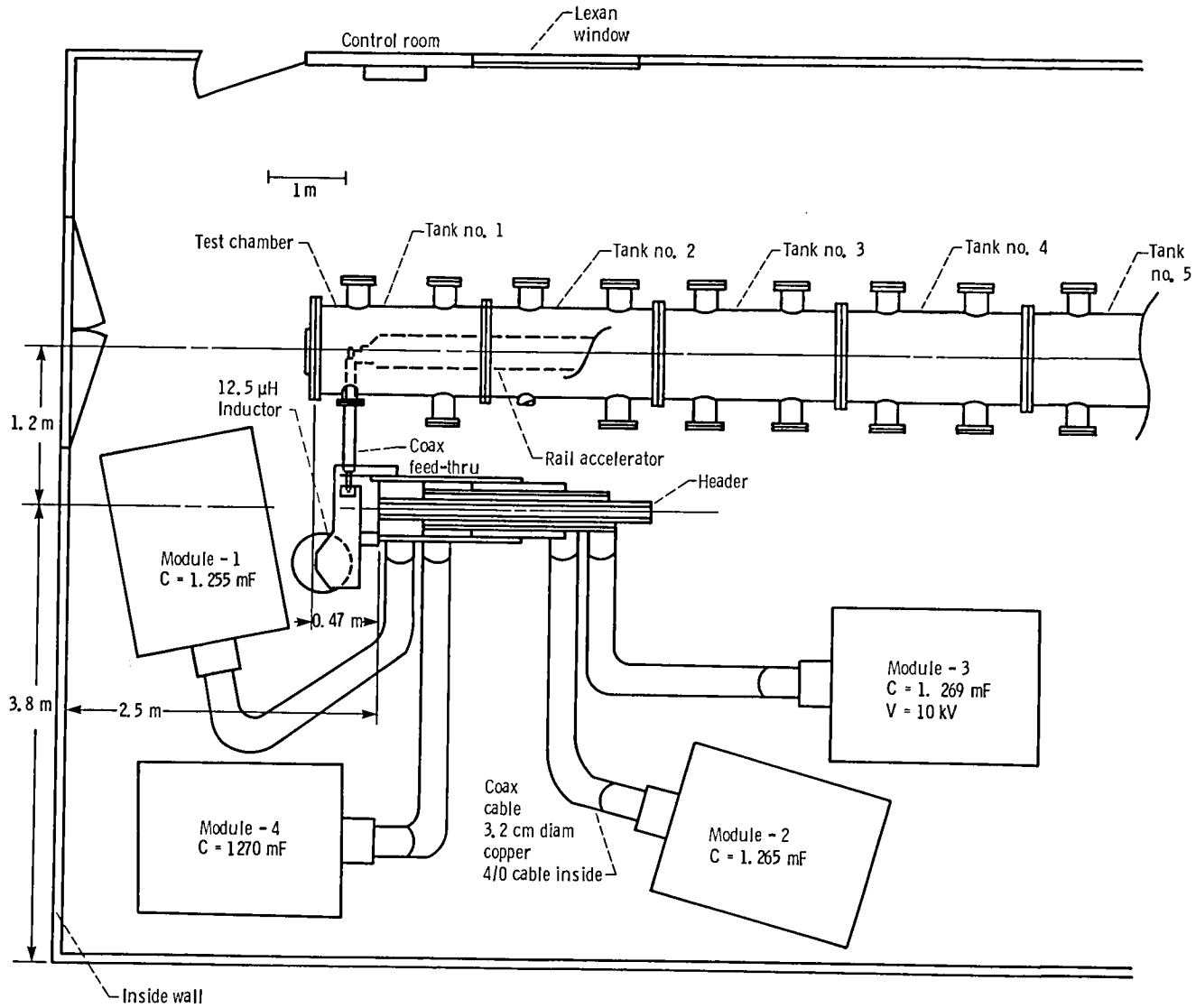Figure 1. - Simplified schematic of pulsed energy system.

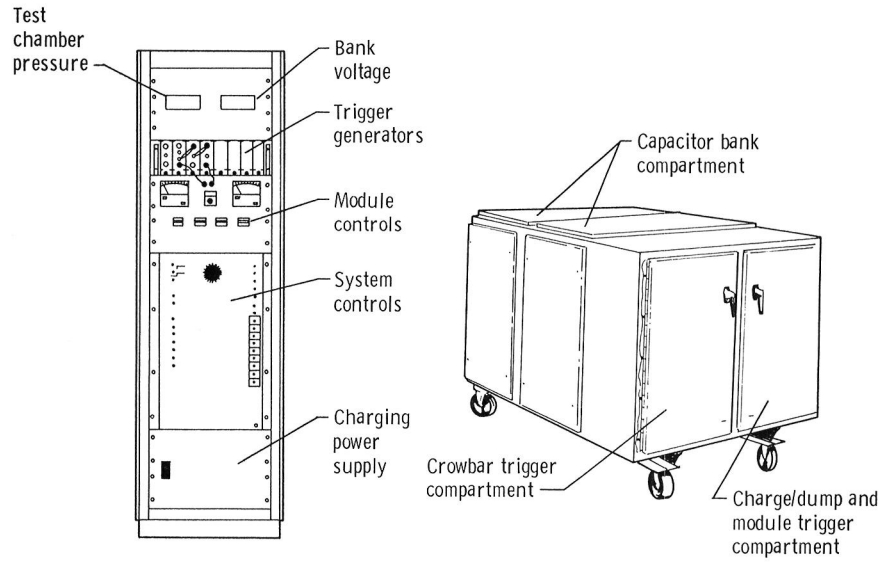Figure 2. – Plan view of the facility.

Test
chamber
pressure

Bank
voltage

Trigger
generators

Module
controls

System
controls

Charging
power
supply

Capacitor bank
compartment

Crowbar trigger
compartment

Charge/dump and
module trigger
compartment

Figure 3. - Pulsed power system control console and one power module.

FEED-FORWARD
IGNITRON

CHARGING
RESISTOR

CAPACITOR
200μF (1 OF 6)

CROW BAR
IGNITRON

C-83-3787
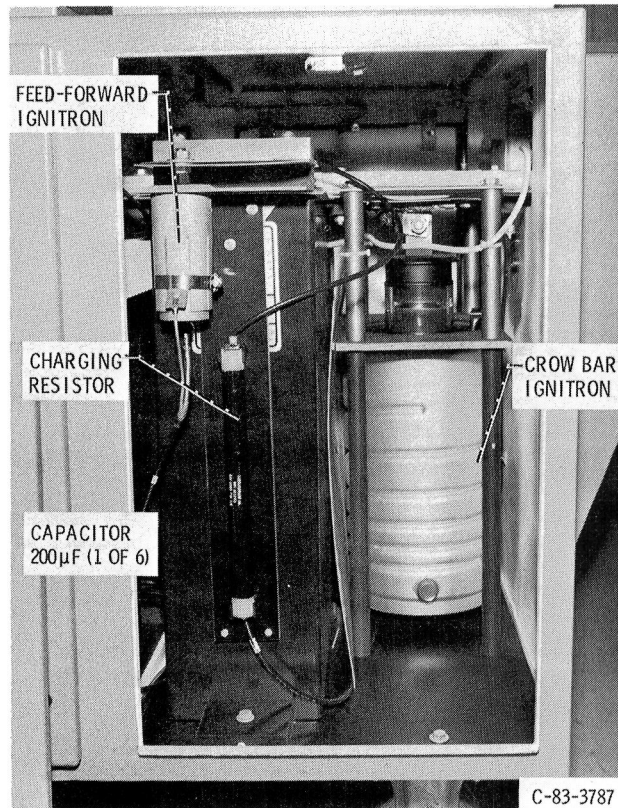
Figure 4. - Interior of power module.
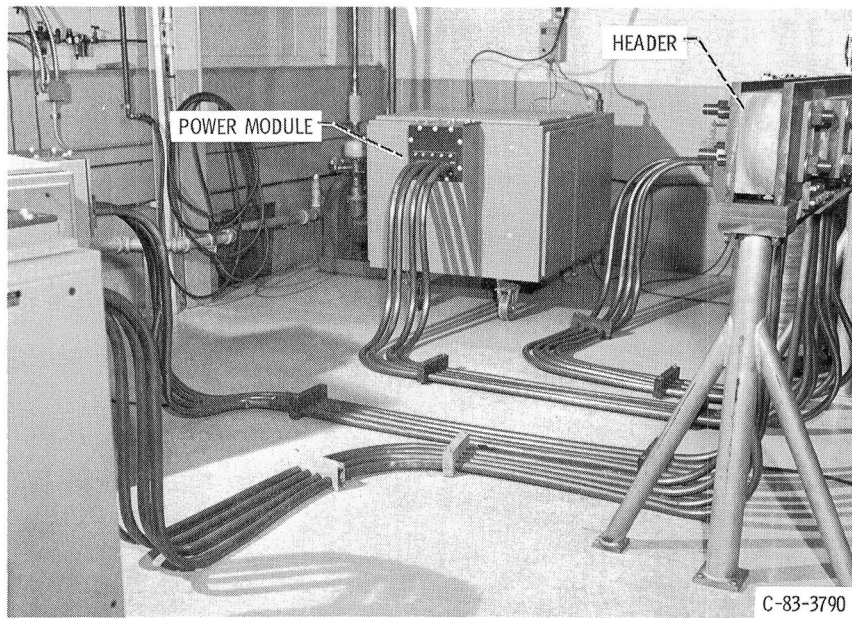
Figure 5. - The four power modules, showing the coaxial output cables.
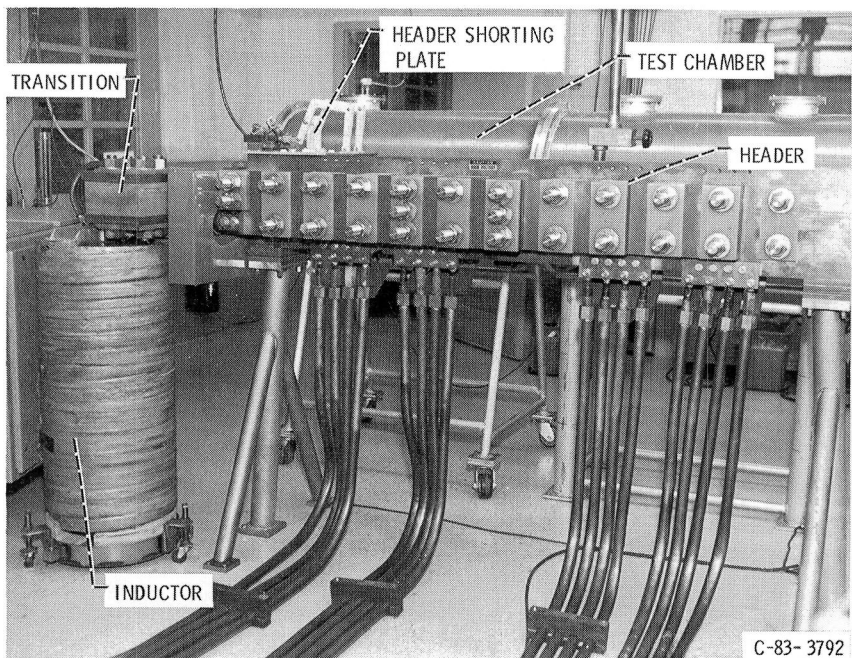
Figure 6. - Side view of header assembly.
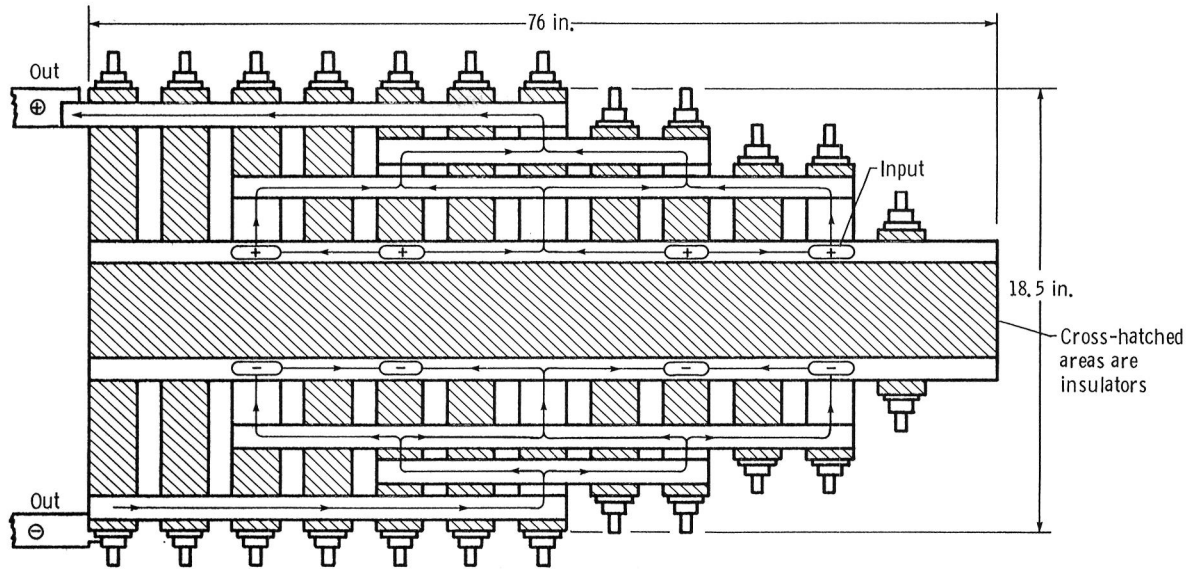
Figure 7. - Top view of header assembly showing current paths. Drawing not to scale, exaggerated vertically for clarity.

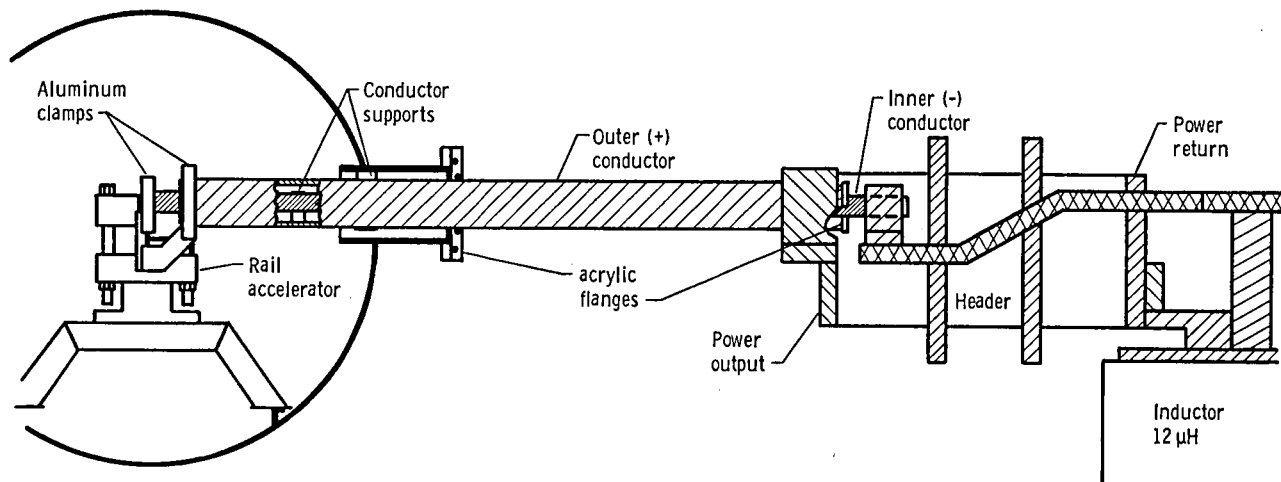Figure 8. - Atmosphere side of coaxial feed-thru.
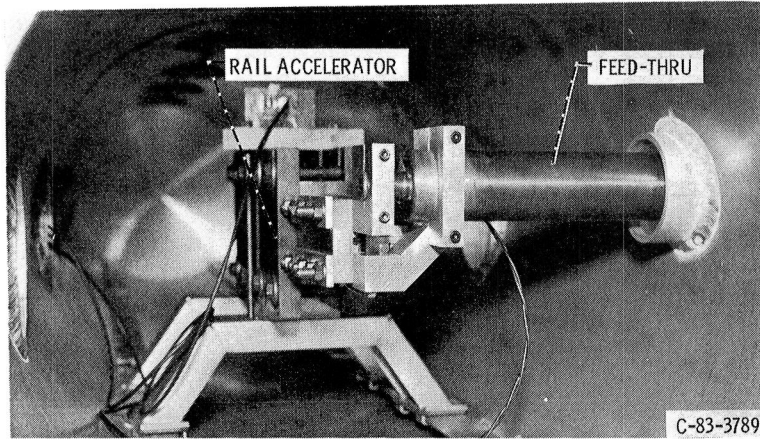
Figure 9. - Side view of coaxial feed-thru.

Figure 10. – Coaxial vacuum feed-thru with 30 cm rail accelerator installed.
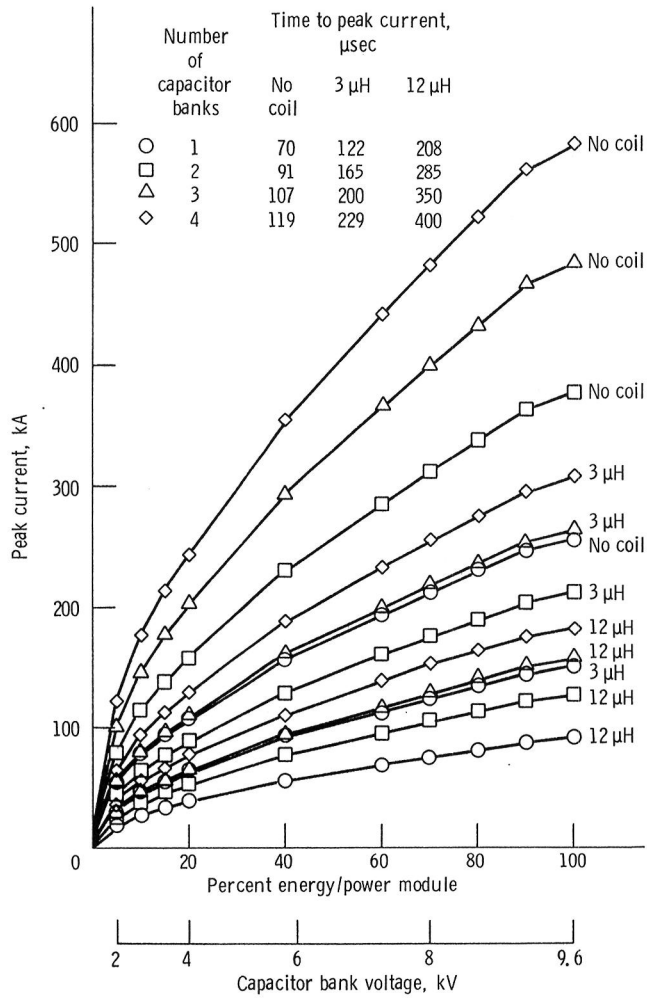

Figure 11. – Power system peak current capability.

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15. Supplementary Notes

16. Abstract

A test facility for the exploration of electromagnetic propulsion concepts is described. The facility is designed to accommodate electromagnetic rail accelerators of various lengths (1 to 10 meters) and to provide accelerating energies of up to 240 kiloJoules. This accelerating energy is supplied as a current pulse of hundreds of kiloAmps lasting as long as 1 millisecond. The design, installation, and operating characteristics of the pulsed energy system are discussed. The test chamber and its operation at pressures down to 1300 Pascals (10 mm of mercury) are described. Some aspects of safety (interlocking, personnel protection, and operating procedures) are included.

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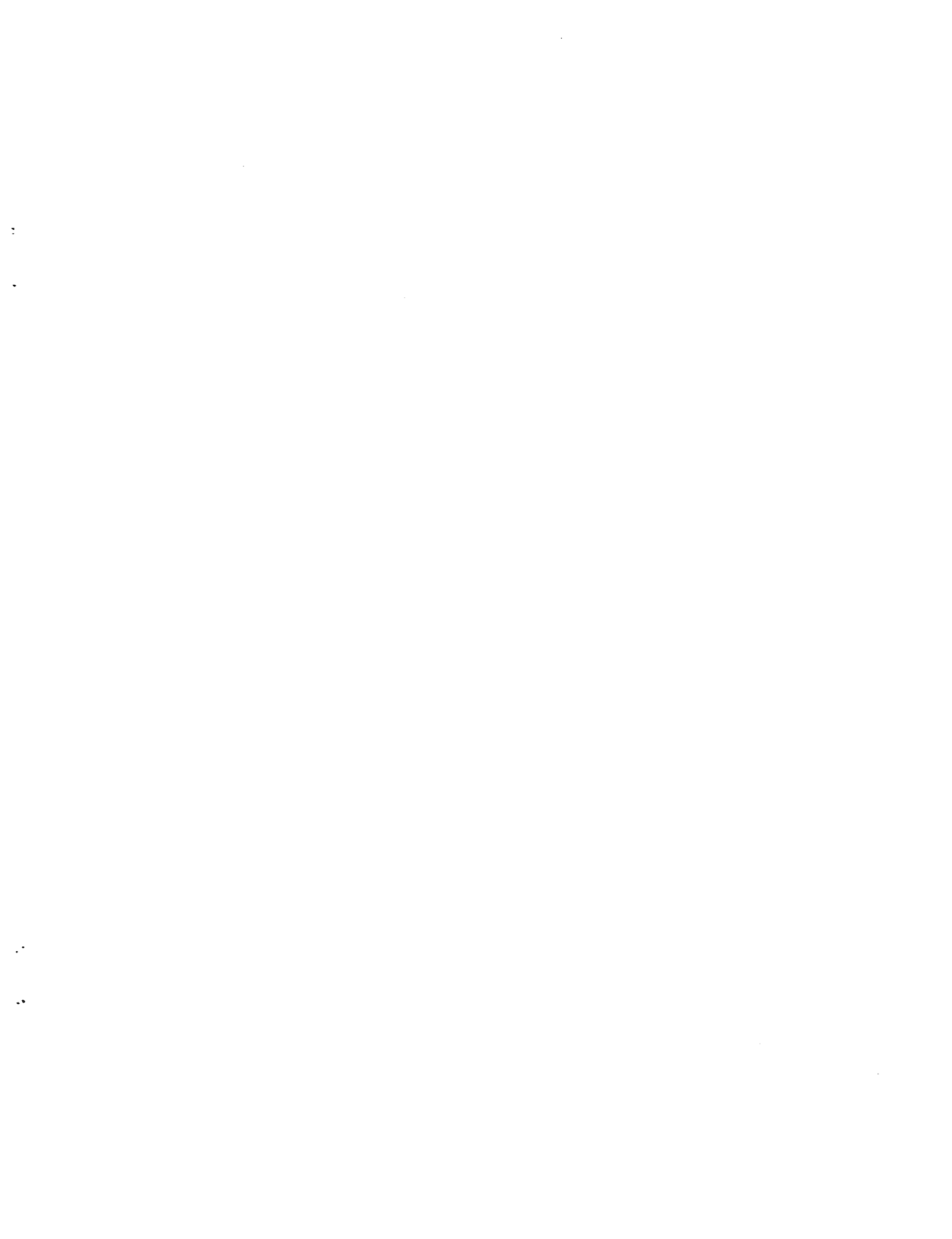
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SPECIAL FOURTH CLASS MAIL
BOOK

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