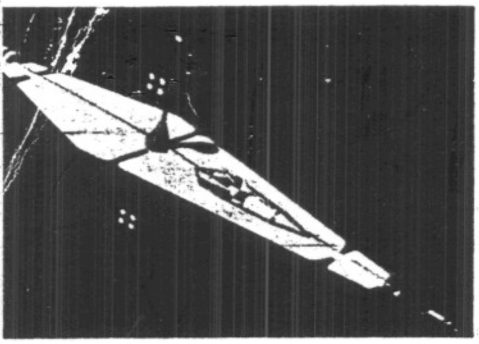
Electric Spacecraft—Progress 1962



The ARS Electric Propulsion Conference reveals a field sure of its promise in space missions and driving to establish efficiency and reliability in designs

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ONLY THREE years ago, discussions of electric propulsion under ARS auspices were confined to individual sessions at national conferences. Now, the second ARS Electric Propulsion Conference, held March 14-16 in Berkeley, Calif., provides striking evidence of the growth of this new field of technology. Some 500 professionals attended the conference, which featured a program of 74 papers arranged in 13 sessions. The discussions were lively, and interest continued at a high level through all three days.

By way of preface, to put this considerable activity into some perspective, let me state briefly principles common to all electrical propulsion systems.

Rocket researchers seeking higher specific impulse (Isp) have been tempted for many years by the essentially unlimited ion-beam velocities obtainable in devices which are commonplace in physics laboratories. The availability of nuclear power makes it worthwhile to ask whether the high Isp potential in such devices can be developed for practical space propulsion systems.

The answer depends heavily on weight and life of the power supply. The performance obtainable, in a nutshell, is as follows: the velocity which could be given to the powerplant, if all its energy were used to accelerate its own mass (assumed constant), is about equal to the velocity increment which could be imparted to a small payload. This velocity is also about equal to the optimum exhaust velocity. If powerplants weighing 1 kg/kw can be produced a decade or two hence with an operating life of 1 yr, this critical velocity will be 250 km/sec, and engines should then operate at Isp = 25,000 sec. A more immediate outlook centers around the Snap-8 system, which offers 30 kw at about 35 kg/kw. The critical velocity in this case is 42 km/sec, giving an optimum Isp near 4000 sec, and a maximum thrust of 0.3 lb, reduced by any inefficiency in the thrustor.

The low thrusts, power levels, and accelerations ($\cong 10^{-4}$ G), which apply to all electric propulsion systems, often seem surprising, but are compensated by the long time of continuous operation.

The potential importance of this approach to space propulsion problems was made clear in a Jet Propulsion Laboratory (JPL) paper (ARS Preprint 2389-62; henceforth here we will just cite the preprint number itself, i.e., 2389). This study showed that 50% of the unmanned planetary and interplanetary missions of major scientific interest cannot be performed by chemical systems based on Nova, and that approximately 40% cannot be performed by nuclear-heat-exchanger systems boosted by Saturn S-1. Most missions, however, can be performed with electric-powered spacecraft launched by a Saturn C-1 booster. As shown in the table from this paper on the next page these missions, however, will require 300 to 1500 electrical kilowatts (kwe). The paper estimates that specific weights of 12–14 lb/kw will be obtainable at this level.

Reaching much farther out was the paper (2374) on a manned Mars expedition from NASA Marshall Space Flight Center. Looking toward 1980 and beyond, the paper postulated powerplants delivering 40 Mw at a specific power of 0.5 kw/kg for five 360-ton space vehicles each carrying three men (as illustrated on this page). This and a somewhat similar discussion (2442) by North American Aviation were received with enjoyment—perhaps as a relief from problems of a more short-term nature.

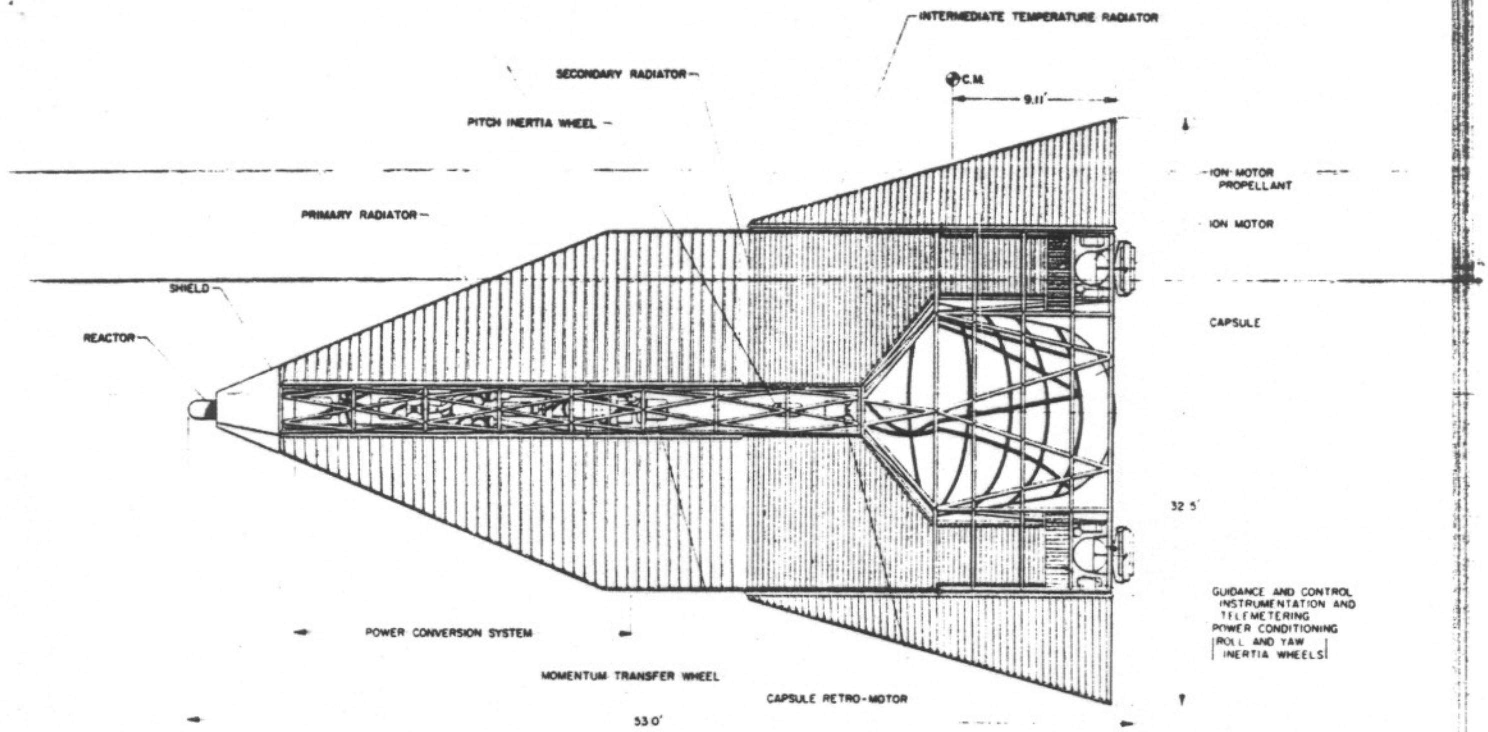
The possibility of replenishing propellant and/or fuel supply without returning to earth was the subject of papers from Boeing (2391) and Northrop Space Laboratories (2438). Both of these schemes proposed to collect and liquefy ambient gases and to use them for expellants. Both would require electric propulsion to overcome drag associated with the scooping operation.

Paper 2370 reported a continuation of JPL's extensive mission studies. The inclusion of engine efficiency as a function of specific impulse in the optimization added an additional level of sophistication. Major simplifications of computing procedure, which could be employed with small loss of precision, were introduced. Interesting calculations on electric propulsion applied to lunar exploration were reported by GE-Evendale (2373).

The main concern of the conference, however, was more narrow than such studies. Namely, how can electric power be employed efficiently to accelerate mass to specific impulse (Isp) in the 1000 to 5000-sec range? Approaches to this question fall into three quite distinct categories.

Arcjets

In these electrothermal devices, the propellant is heated by an electric arc and ejected through an orifice. The specific impulse is limited by the temperature and molecular weight of the gas; and the technology involves thermodynamics, heat transfer, and fluid flow, in addition to arc technology.



Planning for the future of electric spacecraft has included system studies such as the one illustrated here—a nominal 300-kwe nuclear-electric space bus with a gross weight of 16,000 lb for delivering a landing capsule to the inner planets. Described by Beale and Speiser of JPL (2390), such a spacecraft might provide real-time television transmission from the vehicle and possibly from the landing capsule also.

The devices appear to be limited to Isp below 2000 sec (1350 was highest reported at the meeting). While below optimum for most applications, this range is not now achievable in any other way, and excites the interest of system designers for orbit adjustment, attitude control, and other missions involving relatively short times of operation and small velocity increments.

Major contributions were presented by Plasmadyne (2346), General Electric, Evendale (2347), and Avco (2345), all of whom are active at the 30-kw level. Plasmadyne also described a 1-kw thrustor designed for space testing (2346, 2350) that gives an efficiency of 35% at an Isp of 1100 sec.

There seems to be agreement among the different groups working on arcjets on the following points:

1. Hydrogen is a much more promising propellant than ammonia. Operation with the latter involves severe problems of life, efficiency, and low Isp.

2. Larger thrust units offer hope of much better performance than smaller, largely because boundary-layer effects are proportionately less.

3. Radiation-cooled engines, running at wall temperatures of 3000 C or more, give higher Isp but also higher heat losses than devices in which the nozzle is cooled regeneratively.

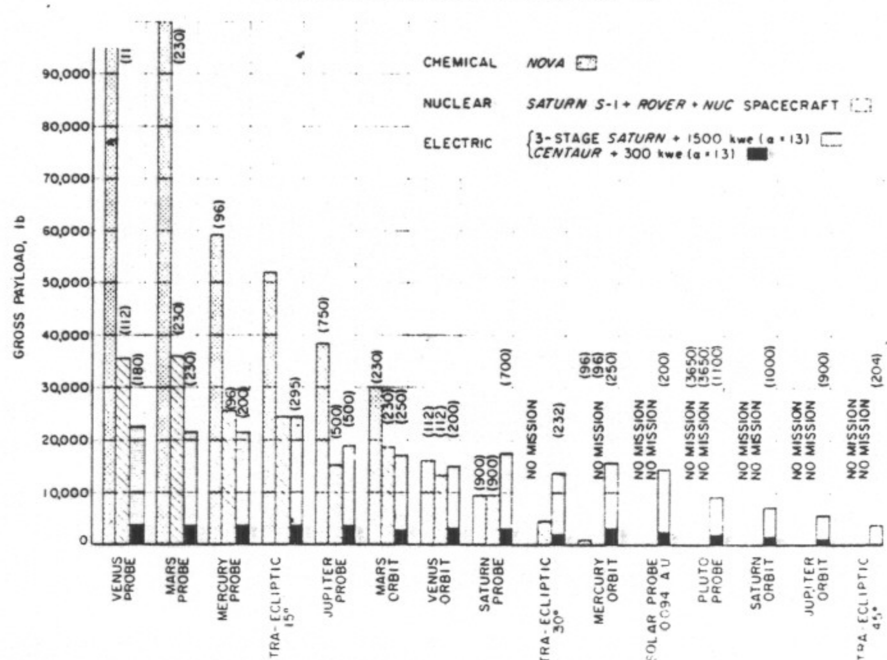
4. The life of the devices is limited by erosion at the nozzle constriction.

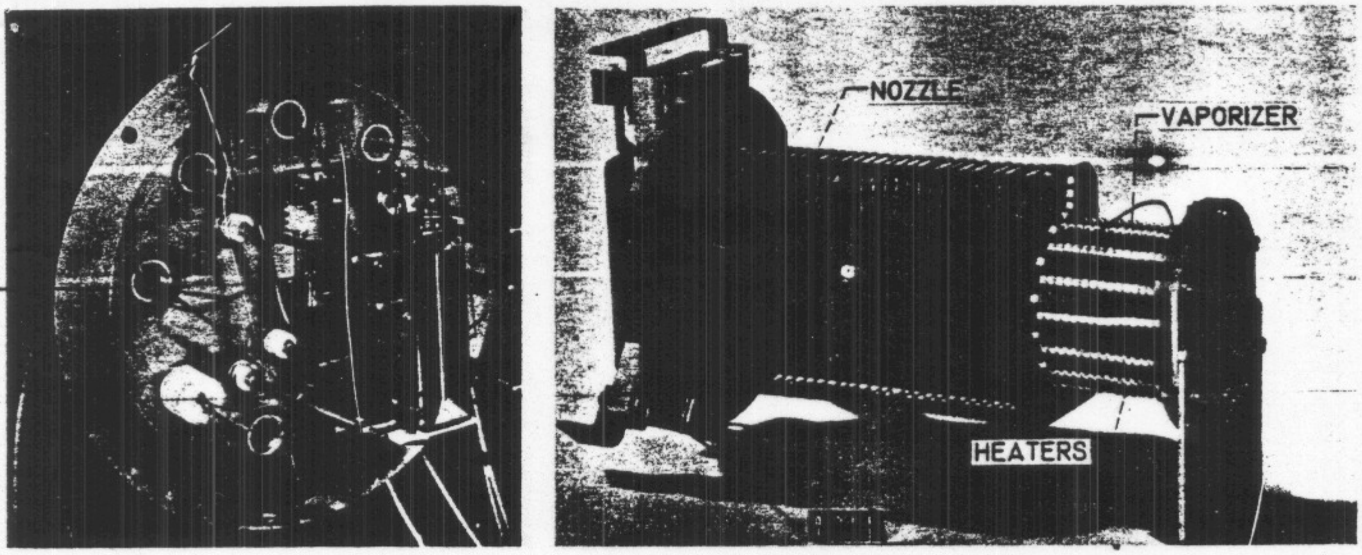
5. Operation at chamber pressures higher than the present levels (1 to 5 atm) will improve the performance, but will aggravate problems of erosion and life.

Various approaches were detectable on many other problems. Plasmadyne uses a DC constant-current source designed by Marshall Space Flight Cen-

POTENTIAL OF CHEMICAL, NUCLEAR, AND ELECTRIC SYSTEMS IN DEEP-SPACE MISSIONS

From JPL study by Jaffe et al. (2389).





NASA Lewis Research Center's work on electron-beam-welding large porous-tungsten emitters advanced the state of the art of engine design and construction. The cesium-ion engine shown at the left, mounted on a test plate, described by Cybulski and Kotnik (2382), ran for more than 50 hr with accelerator and power efficiencies of 90 and 70%, respectively, at an Isp of 8680 sec. The photo at the right shows a colloid generator for electrostatic engines described by Norgren (2380) of NASA-Lewis.

ter; it reported conversion losses under 20%. The General Electric design is based upon three-phase, thousand-cycle-per-second AC. Avco uses Paschen's law of electric breakdown as a basis for its starting system, while Plasmadyne employs a mechanically moved cathode to make physical contact between cathode and anode.

An intriguing feature of future arc-jet development is the theoretical possibility that much higher Isp might be obtainable. Above about 1400 sec, the theoretical cycle efficiency with hydrogen as a propellant rises so that theoretical power-to-thrust ratio remains about constant at 95 kw/lb up to 1900 sec. Closely related is the current emphasis on the "nonuniform flow model" and "profile losses." Elementary theory has dealt with arcjets in terms of one-dimensional flow. The evidence now seems clear that the core of the arc has much higher temperature and Isp than the boundary layer near the walls, and it is suspected that the gas temperature may not be limited to the melting point of tungsten. The implications of this are being vigorously explored.

Arcjet thrustors at higher power levels will benefit from experience with impressive devices described by NASA Lewis Research Center (2349) and NASA Langley Research Center (2453). These are arcs for air heating and arc-tunnel applications operating at powers in the 200 to 1200-kw range, (see illustration on page opposite).

Electromagnetic Propulsion

A large contrast is presented by the electrothermal- and electromagnetic-propulsion fields. While the former is developing hardware with quite definite and predictable performance, quite clear limitations, and possibility of immediate application, the latter deals with a wide variety of techniques, a broad spectrum of potentialities, and many uncertainties in the basic technology. The problem is to couple a magnetic field to currents flowing in a plasma so as to accelerate it. The possible configurations are many, and there are potential advantages in thrust per unit area, specific impulse, and other respects. The conference did not provide a fully representative discussion of the electromagnetic-device field, but some conclusions of general validity can probably be drawn.

A paper (2376) from Republic Aviation described the pulsed plasma-pinch accelerator. This device causes a ring of plasma to contract while at the same time undergoing deflection by curved electrodes so that ejection occurs in the axial direction. The paper was concerned chiefly with diagnostic techniques and the characteristics of the pinch discharge which could be deduced from simultaneous measurements by different forms of instrumentation. Electric probes, transient fluctuating loops, fiber optical bundles for radiation measurement, and microwave transmission and reflection devices were used. With 3-kv, 540-joule pulses, plasma velocities up to 90 km/sec were measured. Electron densities of the order of $10^{13}/cm^3$ were deduced.

Another paper (2443) from the same group discussed the difficulties of thrust measurement. By mounting the entire engine on the thrust stand, they established that a ballistic pendulum in the same tank gave apparent thrust levels as much as five times too high, probably as a result of ablation. This work, apparently supported by recent findings in other laboratories, illustrates the need for the careful measurements and basic diagnostic studies which are now being emphasized in the electromagnetic-propulsion field.

The work at Advanced Kinetics, Inc. (2395) dealt with plasma pulses ejected by pulsed currents through massive single-turn coils. About 25% of the initially stored capacitor energy is converted into useful magnetic field, of which about 20% is converted into the kinetic energy of the plasma moving at speeds from 10^4–10^6 m/sec. Major technological difficulties applicable to the whole field were also discussed; namely, the present limitation on the lifetime of most storage and switching elements to around 10^6 pulses, and the limitation (for reliable operation of storage elements) to a volume density of 1 joule/cu in. and a specific weight of 25 joules/lb (about 2 kg/kw at 10 pulses/sec).

A pulsed coaxial thrustor was described by General Electric, Valley Forge (2377). Interesting features of this device were the two-stage control system and the use of continuously flowing propellant. The first stage was driven by a 1-μf capacity, and the second by 15 μf. The relatively low power of the first stage permitted it to be triggered by an ignitron. The second stage was then fired by the arrival of the plasma pulse. Sixty hours of operation at 1000 pulses/min and 7-kw average power were reported. The average power to the first stage was only 70 w. It was considered a significant achievement that 10^7 condenser discharges were expended without sign of deterioration. Specific impulse of around 5000 sec was indicated, and apparent thrust of 0.2 lb was recorded using a ballistic pendulum. The authors pointed out the possible unreliability of this result.

An Aerospace Corp. group described an experiment (2378) in which a plasma pulse was caught by a traveling wave in a transmission line and carried along at the phase velocity of the line. With the line not excited, the shock velocity from the ejection device dropped from 1.65×10^5 to 0.3×10^5 m/sec in progressing down a one-meter tube. When the transmission line was excited by timed discharges of 25-kv condensers, the shock velocity was maintained at 1.1×10^5 m/sec. Hydrogen at a pressure of 175μ was present in the tube. The authors emphasized that this work was to be considered as a research experiment and not a propulsion device.

The "J×B" type of device was discussed in two papers. Northrop Space Laboratories (2438) has constructed a continuous Lorentz accelerator using an arcjet plasma source. Directly measured thrusts up to 3.6 lb were reported, exclusive of the arcjet, with acceleration efficiencies as high as 54%. This seems to be by far the largest thrust reported for any electric-propulsion device. Avco people (2345) questioned whether this performance could be maintained in the hard vacuum of outer space.

In general, the spirit of the meeting with regard to electromagnetic propulsion was that very careful measurements and interpretations are needed in order to understand better the fundamentals of these devices, which may ultimately provide performance superior to other approaches, particularly in the intermediate range of Isp.

Electrostatic Propulsion

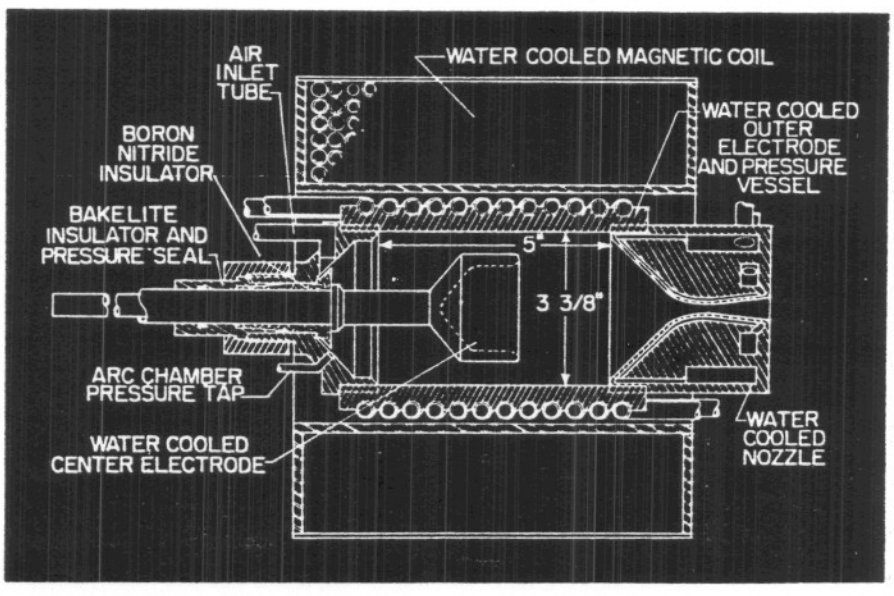
The field of electrostatic propulsion attracted the greatest variety and number of papers at the conference. Classification rules make discussing these adequately rather difficult. The Friday morning session, at which the most recent Hughes and Electro-Optical Systems results were presented, compared, and debated, was a particularly interesting one, and it is unfortunate that it cannot be described at this time.

The main emphasis in the electrostatic field concerned the contact-type cesium-ion engines, which are progressing rapidly, with promise of improving efficiency and longer life. NASA Lewis Research Center (2382) reported an efficiency of over 60% at 8000 sec. The Hughes paper (2449) described their annular design, which has led to an engine for flight test producing on the order of 2 millipounds of thrust at about 360 kw/lb. They presented advanced designs which will improve the performance to about 250 kw/lb with efficiencies of over 50% at 6000 sec. The use of several coaxial rings in place of the present single-ring structure will, it was predicted, bring future performance to substantially higher efficiencies.

To complete the picture, the performance of a 61-hole Electro-Optical Systems engine may be stated. This engine delivered 3.2 millipounds of thrust at about 300 kw/lb. More recent results from this group have not yet been cleared for publication.

For Isp of 5000 sec and above, the cesium-ion engine promises to be efficient and long lived, and is already in an advanced state of development.

A notable feature of the conference was the presentation of excellent and extensive background data relating to the processes occurring in electrostatic engines. The Linfield Research Institute presented studies (2358) of the adsorption and diffusion of cesium layers on tungsten electrodes using the point microscope technique. Hughes (2359) and Space Technology Laboratories (2360) presented data on atom and ion emission from porous tungsten. The Hughes group found that current densities up to 22 ma/cm² can be drawn from porous tungsten, a fact which bodes well for im-



Arcjet thrustors for high power levels will gain from NASA work on magnetically rotated arc air heaters (2453, 2349), such as the experimental device illustrated here.

proved future engine efficiencies. Researchers at Electro-Optical Systems presented comparative measurements (2364) on emitters of tungsten, tantalum, and niobium, as well as tungsten coated with platinum and rhenium, and also measurements on secondary electron emission and sputtering due to cesium-ion bombardment. The associated problems of feed supply and corrosion were treated by other authors (2385, 2386, 2387). The NASA Lewis Research Center's success (2382) in beam-welding porous tungsten assemblies (see photo on page 22) was noted with appreciation by those concerned with refractory materials.

Alternative types of electrostatic ion engines are very much in the running, and several types came up for discussion. A notable deficiency in the program, however, was the lack of any paper on the bombardment-type source development at NASA Lewis Research Center. The duoplasmatron is being pushed by Thompson Ramo Wooldridge (2381) and by Goodrich-High Voltage Astronautics (2450), and the proponents of these devices believe that their efficiencies can become competitive with the cesium engines.

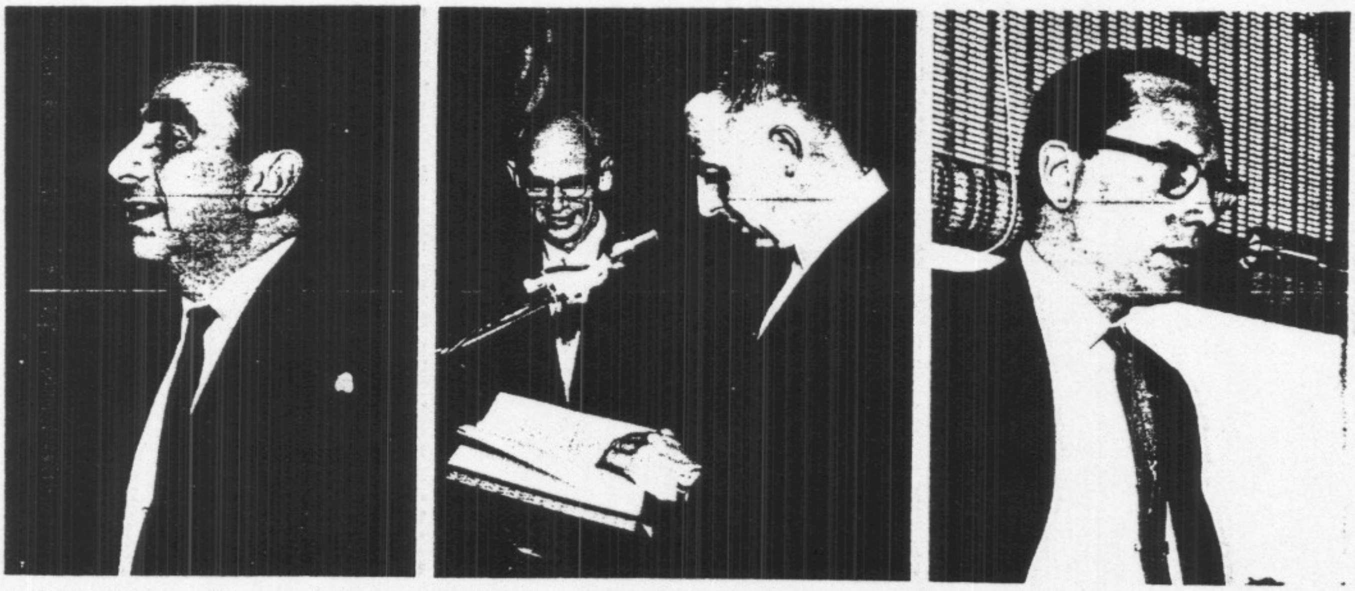
The oscillating electron source, or the modified Penning discharge, was discussed in papers presented by Electro-Optical Systems (2379) and by United Aircraft. The latter, by the group which has worked longest on this subject, was unfortunately classified. This type of device seems to be easily the most complicated to understand of all electrostatic engines, despite the simplicity of its configuration. One of the most intriguing arguments at the conference related to the question of the mechanism by which thrust is exerted by this device and how the reaction is distributed among the walls, the electrodes, and perhaps the solenoid coils. Argument was not resolved.

A preliminary report on an interesting new type of double Penning discharge, the transfer discharge source, was presented by authors from UCLA and Quantatron (2383).

While the problem of ion-beam neutralization absorbed a major portion of the Monterey conference in 1960, progress in the field could be noted by a sharp reduction in the number of papers on this subject at Berkeley. There appears to be no serious doubt that ion beams can be effectively neutralized by the addition of electrons in ways which are unsophisticated and economical of heater power. An interesting paper (2432) form General Atomic showed that, when electrons are supplied by two planes which bound an infinite slab of positive charge, the static, space-charge-limited solution is unstable. The instabilities may provide a mechanism which would contribute to the neutralization process. Papers from General Electric (2401) and Hughes (2366) discussed the effect of the ambient plasma in space upon an ion beam. Currents flowing from the ambient plasma can be, it appears, surprisingly large, and would have to be carefully taken into account in space tests.

The field of ion optics is intimately related to ion propulsion. It is a subject toward which different groups have radically different approaches. Careful ray tracing in the Hughes analog computer is the foundation of their annular optical design. Electro-Optical Systems appears to have excellent ion optics as a result of a purely empirical approach using coaxial hole geometry, with a large number of holes operating in parallel. Goodrich–High Voltage (2431) presented a new analytical approach to the problem, and General Electric, Evendale (2401) described new results using their ion optical digital computer program. Based on the IBM 7090 computer, this approach to ion optics may have a higher ultimate accuracy than the analog method.

Another lively moment of the conference was a debate on design philosophy among Hughes, Electro-Optical Systems, and Space Technology Laboratories. Electro-Optical Systems favors the coaxial-hole geometry, on the grounds that perveance should be higher for a given aperture-to-spacing ratio. The Hughes school believes that annular rings provide the best answer. Space Technology Laboratories feels that the parallel-strip geometry offers much better opportunity for utilization of the emitter area. Again, argument was not resolved.



Left, Dr. Teller addresses the banquet audience. Center, b nquet toastmaster Kurt Stehling presents Ernst Stuhlinger with a token of appreciation from colleagues and the Society—a leather book inscribed by electropropulsion enthusiasts. Dr. Stuhlinger heads the ARS Electric Propulsion Committ:e and chaired the conference. Right, William Woodward of NASA discusses the NASA electric-propulsion program as luncheon speaker the first day of the conference.

The meeting disclosed something of a breakthrough in the field of the heavy-particle, or colloid, propulsion system. Space Technology Laboratories (2398) reported that droplets of glycerol containing antimony trichloride had charge-to-mass ratios of 470 coul/kg when drawn from a positively charged needle by field emission. The spread of Q/M was only about a factor of two. If 100 such points could be operated in parallel at 430,000 v, a millipound of thrust would result at an Isp of 2000 sec. NASA Lewis Research Center (2380) described a system (see photo on page 22) in which colloidal particles are generated by adiabatic expansion in a convergent-divergent nozzle and then are charged and accelerated. Aluminum chloride was used and an average particle diameter of 0.05μ was obtained. Charging was accomplished by passing the stream of particles through a corona discharge. This pioneering experiment is a significant milestone in a comparatively unexplored territory.

It has not been possible for me to comment here on every paper presented at the Berkeley conference, nor could I attend all of the sessions. For inevitable omissions I apologize, and refer the reader to the excellent reprints available through the ARS offices.

In conclusion, let me give a few strong impressions of the field derived from the conference and the preparation of this review.

1. This field is indeed maturing. Perhaps it is now a teenager. It has demonstrated surprising capabilities, is full of promise, is uneven in development. It harbors romantic aspirations.

2. Engines are ahead of power supplies.

3. The engine people now aim at 30 kw, but the mission people want a megawatt.

4. Higher efficiency at low specific impulse (2000 sec) is not yet in sight.

5. The feasibility and promise are now certain. Efficiency and reliability have become the goals.

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2358. Strayer, R. W. et al., "Field Emission Microscope Study of the Stability and Kinetics of Cesium Layers on Tungsten Electrodes."

2359. Husmann, D., "Experimental Evaluation of Porous Materials for Surface Ionization of Cesium and Potassium."

2360. Shelton, H., "Experiments on Atom and Ion Emission from Porous Tungsten."

2364. Kuskevics, G. et al., "Ionization, Emission, and Collision Processes in the Cesium Ion Engine."

2366. Hubach, R. A., "Limitations on the Space Test of a Cesium Ion Engine at Altitudes Below 1500 Kilometers."

2370. Melbourne, W. G. and Sauer, C. G. Jr., "Payload Optimization for Power-Limited Vehicles."

2373. Brown, H. and Nicoil, H. E. Jr., "Electrical Propulsion Capabilities for Lunar Exploration."

2374. King, J. C. and Stuhlinger, E., "Concept for a Manned Mars Expedition with Electrically Propelled Vehicles."

2376. Aronowitz, L. and Duclos, D., "Characteristics of the Electrical Pinch Discharge in a Pulsed Plasma Accelerator."

2377. Gorowitz, B. et al., "Experimental Studies of a Repetitively Fired Two-Stage, Coaxial Plasma Engine."

2378. Mayfield, E. B. et al., "Plasma Propulsion by Means of a Helical Transmission Line."

2379. Kilpatrick, W. D. et al., "Propulsion Application of the Modified Penning Arc Plasma Ejector."

2380. Norgren, C. T., "Onboard Colloidal Particle Generator for Electrostatic Engines."

2381. French, P., "Electron Bombardment Ion Source."

2382. Cybulski, R. J. and Kotnik, T. J., "An Evaluation of a Cesium Ion Rocket Employing a Large Porous Tungsten Ionizer."

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2431. Cheever, R. N., et al., "Optical Design Methods for High Current Density Ion Engines."

2432. Pearlstein, L. D., et al., "The Theory of Beam Neutralization."

2438. Demetriades, S. T., et al., "The Use of Atmospheric and Extraterrestrial Resources in Space Propulsion Systems."

2442. Bell, M. W. J., "Astrobolas—An Electrically Powered Spacecraft."

2443. Guman, W. J. et al., "Measurements of Impulse and Discharge Rate of a Pulsed Plasma Accelerator."

2449. Anderson, J. R. et al., "Annular-Beam Ion Engines."

2450. Beggs, W. C. et al., "The Development of a High Current Density Arc Type Ion Engine."

2453. Mayo, R. F., "Magnetically Diffused Radial Electric Arc Air Heater Employing Water-Cooled Copper Electrodes." ◆◆

A well-attended banquet (above, head table) the evening of March 15 heard Edward Teller (opposite) of the Univ. of California discuss nuclear energy in space. Dr. Teller predicted that thermionic power conversion would prove the key to successful exploitation of electric propulsion and suggested that competition to electric systems would come from spacecraft utilizing hydrogen and oxygen produced by nuclear reactors installed on the moon.