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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-555

European Auxiliary Propulsion–1972

L. B. Holcomb

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JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
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PREFACE

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ABSTRACT

During the last half decade, low-thrust auxiliary propulsion technology in Europe has experienced rapid growth due to the development of new and more complex satellites. To gain insight into the auxiliary propulsion technology state-of-the-art in Europe, the survey presented here was undertaken. The chemical and electric auxiliary propulsion technology of the United Kingdom, France, and West Germany is discussed in detail, and the propulsion technology achievements of Italy, India, Japan, and Russia are reviewed.

Also presented is a comparison of Shell 405 catalyst and a European spontaneous hydrazine catalyst called CNESRO I. Finally, conclusions are drawn regarding future trends in European auxiliary propulsion technology development.

I. INTRODUCTION

Although low-thrust propulsion technology has been studied for years in Europe, only during the last half decade has low-thrust auxiliary propulsion technology experienced rapid growth there. This growth is due to the development of new and more complex satellites. Firms formerly engaged in the development of European launch vehicles and aircraft are beginning to diversify into the field of low-thrust propulsion.

The first generation of European satellites requiring propulsion systems were European Space Research Organization (ESRO) satellites, such as the ESRO-II, HEOS-A1, and HEOS-A2, all of which used inert gas systems that were manufactured in the United States and integrated into the spacecraft in Europe. More recent ESRO satellites, such as the TD-1A satellite (launched in March 1972), have used inert gas systems with primarily European components. The French D-2A satellite, launched in April 1971 by the French Diamant B launcher, flew with an inert gas system comprised of mostly European components.

A second generation of satellites requiring auxiliary propulsion systems includes synchronous altitude, meteorology, and communication satellites. These satellites have been funded by ESRO, by individual national programs, or as part of programs also funded by the United States.

In 1968, studies of communication satellites at ESRO indicated the need for hydrazine auxiliary propulsion systems. At that time, a European hydrazine technology development program was initiated with ESRO funding of $500,000 through 1972. The program included a hydrazine compatibility program, the development of a spontaneous catalyst for hydrazine (CNESRO I),[1] the development of hydrazine plenum systems by Messerschmidt-Bölekow-Blohm (MBB) and ERNO, the development of a dual-seat solenoid valve, and the testing of the spontaneous catalyst at Société Européene de Propulsion (SEP)[1] and ERNO. The hydrazine

[1] Jointly funded by ESRO and the Centre National d'Études Spatiales (CNES); CNES funding for this effort has been about $700,000.

technology program has been aimed at future applications spacecraft. The ESRO budget approved for 1972 to 1977 includes at least $380,000,000 for applications spacecraft (Ref. 1). This budget is primarily for the GEOS Synchronous Meteorology Satellite, the Air Traffic Control Satellite (AeroSat), and an ESRO Communication Satellite, all of which will require hydrazine auxiliary propulsion.

The United Kingdom, France, and West Germany have had continuing national auxiliary propulsion technology development programs for many years. These national programs were primarily directed toward the propulsion requirements of the first generation of European spacecraft, which required inert gas or vaporizing liquid systems.

Spacecraft payloads have been small because of the limited launch capability of present European launchers. The French have been able to launch some of their systems on the Diamant launcher, while the United Kingdom has used the Skylark rocket to test its auxiliary propulsion systems. The combined funding levels of the national programs exceed the ESRO funding level for auxiliary propulsion system development. These national programs are presently being directed toward developing sufficient auxiliary propulsion experience for national participation in future communication satellite programs. Toward this goal, for example, the CNES is funding the development of a hydrazine auxiliary propulsion system to be tested as a payload of the D-5A satellite.

Nationally funded communications satellites have provided incentives for the development of auxiliary propulsion systems. The jointly funded French-German Symphonie communication satellite has spurred the development of a low-thrust bipropellant propulsion system at MBB and a low-thrust monopropellant hydrazine system at SEP. The Italian SIRIO communication satellite has led to the development of a low-thrust monopropellant hydrazine system at OTO Melara. The United Kingdom Geostationary Technology Satellite (referred to as UKAT), if funded, should lead to the development of a monopropellant hydrazine system in England. The interest in the Indian National Satellite (Insat) has led to the development of a hydrazine propulsion system at the Space Science and Technology Centre, India.

Because of European interest in the International Telecommunications Satellite Consortium, some of the Intelsat III hydrazine systems (designed by

TRW Systems Group, Redondo Beach, Calif.) were manufactured, tested, and qualified by ERNO. Similarly, several of the hydrazine propulsion systems on the Intelsat IV spacecraft were assembled at the British Aircraft Corporation (BAC). As part of the Skynet II program, which was funded by the United Kingdom, a hydrazine propulsion system designed by Philco Aeronutronics was assembled and tested by Marconi Space and Defense Systems (MSDS).

Auxiliary electric propulsion in Europe, as well as in the United States, is still in the development stage, with very few systems being developed with a specific mission in mind. Two systems that are planned for integration into specific spacecraft are a cesium bombardment thruster under development at SEP for use on the Intelsat V spacecraft and a 10-cm mercury bombardment thruster of the Culham Laboratory, which is slated for a second- or third-generation UKAT satellite. The ESRO Communication Satellite is presently being designed for the possible incorporation of an electron-bombardment thruster system. The French and German national auxiliary electric propulsion programs have provided several possible future flight systems that, at present, have no definite flight applications.

From current auxiliary propulsion flight programs in Europe, along with recent technical publications and advertisements in United States magazines, it is apparent that European auxiliary propulsion technology is approaching that of the United States. To gain further insight into the auxiliary propulsion technology state-of-the-art in Europe, this survey was undertaken. Several European government agencies and propulsion companies were visited. These visits included tours of test facilities and manufacturing shops.

The propulsion systems discussed here were funded, manufactured, or developed by the following companies or government agencies:[2]

<u>United Kingdom (England)</u>

BAC	British Aircraft Corporation, Filton House, Bristol
—	Culham Laboratory (United Kingdom Atomic Energy Authority), Abingdon, Berks.

[2]Acronyms will be used throughout the remainder of the text.

United Kingdom (England) (contd)

HSD	Hawker Siddeley Dynamics, Ltd., Hatfield, Herts
MSDS	Marconi Space and Defense Systems, Ltd., Frimley
RAE	Royal Aircraft Establishment, Farnborough, Hants
RPE	Rocket Propulsion Establishment, Aylesbury, Bucks

France

——	Aerospatiale
CNES	Centre National d'Études Spatiales, Toulouse
LEP	Laboratoires d'Electronique et de Physique Applique, Limeil Brevannes
ONERA	Office National d'Études et de Recherches Aérospatiales, Chatillon
SEP	Société Européenne de Propulsion, Puteaux, Villaroche, and Blanquefort

West Germany

DFVLR	Deutsche Forschungs und Versuchsanstalt für Luft und Raumfahrt, e. v., Trauen, Lampoldshausen, Stuttgart-Vainingen, and Braunschweig
ERNO	ERNO Raumfahrttechnik, Bremen
GfW	Gesselschaft für Weltraumforschung, Bad Godesberg
——	Giessen University
MBB	Messerschmidt-Bölkow-Blohm, Ottobrunn and Lampoldshausen
——	Technogieforchung, Stuttgart

Italy

——	OTO Melara, La Spezia

Holland

ESRO	European Space Research Organization, European Space Research and Technology Centre (ESTEC), Noordwijk

II. SYSTEMS UNDER DEVELOPMENT IN THE UNITED KINGDOM

A. Inert Gas Systems

In the 1950s, several inert gas systems were developed for United Kingdom sounding rockets. Only recently have spacecraft inert gas systems been developed. BAC, as part of a European consortium, has been delegated the task of fabricating an inert gas system for the ESRO COS-B satellite. The system, a Sterrer design, will be purchased from the United States, with system qualification and integration performed at BAC.

Inert gas system components have also been developed in the United Kingdom. Elliott Brothers, Ltd., now MSDS, developed a solenoid valve for use on the TD-1A inert gas system. As the launch date approached, the Elliott Brothers valve could not meet system requirements, and a Sterrer valve was chosen. Inert gas solenoid valves are continuing to be developed in the United Kingdom by Normal Air Garrett.

B. Vaporizing Liquid/Electrothermal Systems

The United Kingdom, unlike the United States, selected propane as the best possible vaporizing liquid for use in auxiliary propulsion systems (Ref. 2). This selection led to the development of a vaporizing propane system by the RAE. The first flight system was successfully tested in 1966 on the Skylark sounding rocket. This system was modified and is presently being developed for the X-4 satellite by HSD. The X-series satellites were to be launched by the Black Arrow launcher. However, the development of this launcher was canceled. Therefore, the X-4 payload will be launched by the Scout. Similarly, BAC is developing a vaporizing propane system for the U.K.-5 satellite. This system is to provide precession control.

Research at the RAE has been directed toward vaporizing ammonia systems (Ref. 3). An ammonia resistojet is presently under development. It requires only 5 W to heat the propellant to 1,000°C and create a 1470-N-s/kg specific impulse. Each thruster has dual heaters and two independent solenoid valves to provide redundancy. The two solenoid valves in parallel indicate that closed failure is the predominant failure mode. The RAE testing includes the use of vacuum tanks and pressure and temperature transducers, as well as an interesting method of flow measurement that utilizes a capacitive probe and a gaseous flow orifice. The capacitive probe measures orifice displacement, which is correlated with flow rate.

High-power resistojets are presently being developed at the RPE for orbit raising. This class of propulsion system is somewhat higher in thrust than the auxiliary propulsion systems discussed here, but was included in this survey. The thruster can operate over a wide thrust range, but is planned to deliver 0.65-N thrust with a specific impulse of 8090 N-s/kg. The resistojet is designed by Advanced Rocket Technology, Irvine, California. The first thrusters were fabricated in the United States; however, recent fabrication has been performed in England. A thruster without its insulation package is shown in Fig. 1. Preliminary tests of the 3-kW resistojet with hydrogen propellant are discussed in Ref. 4. The RPE test facilities include vacuum tanks, pressure and temperature transducers, and thrust and flow measurement devices.

C. Monopropellant Hydrazine Systems

BAC, under contract to ESRO, has completed an in-depth hydrazine compatibility program. This work was performed at the RPE for BAC. The results of the first phase of this work are reported in Ref. 5. In addition, the RPE, which has been involved in the development of monopropellant hydrogen peroxide auxiliary propulsion systems since 1956 (then part of the RAE), is presently developing a 4.5-N monopropellant hydrazine thruster. This thruster differs from those developed in the United States, since its thrust chamber is lined with Rokide to reduce heat loss. The strength, durability, and effect on catalyst retention of the ceramic chamber have yet to be fully demonstrated.

In cooperation with Hughes Aircraft Corporation, BAC is fabricating several of the Intelsat IV hydrazine systems. This effort includes the development of the proper clean room and welding techniques to fabricate the all-titanium system. The components, including the thruster/valve assemblies, are supplied to BAC already fabricated. The system compatibility was verified at the RPE by partially filling the hydrazine tank and observing any associated pressure rise.

The United Kingdom program for communication satellites has included the Skynet I and II defense communication satellites. Skynet I was designed, fabricated, and launched by the United States; Skynet II, however, was designed by a United Kingdom contractor, assisted by an American associate, with a substantial percentage (about 50%) of the manufacturing performed in the United Kingdom. The auxiliary propulsion system, designed by Philco Aeronutronics, Newport Beach, California, was fabricated by MSDS from United States components. The thruster/valve subsystem was supplied by Hamilton Standard. The thruster has undergone limited testing by MSDS, including monitoring of tank and chamber pressures as well as system temperatures.

D. Electron-Bombardment Systems

Electron-bombardment thrusters have been studied in the United Kingdom for more than 10 yr, notably at Elliott Brothers, now part of MSDS (Ref. 6). Interest in ion propulsion at the RAE and Culham Laboratory began to increase in the period 1968-1970. The Culham Laboratory began detailed, diagnostic studies of a 10-cm mercury bombardment thruster with a hollow cathode, similar to the SERT II thruster in the United States. The RAE and Culham Laboratory are presently jointly developing this 10-cm thruster (Ref. 7). Recent performance data are given in Table 1. These data do not include neutralizer losses; however, they do indicate a high efficiency. This highly efficient thruster is presently being modified for use on a synchronous satellite (UKAT) to provide north-south stationkeeping. The system is being designed to reach full thrust in less than 5 min.

E. Colloid Systems

In 1968, the University of South Hampton was funded by ESRO ($70,000) to perform research on colloid systems. More recently, the Culham Laboratory has been funded by ESRO ($112,000) to develop an annular slit colloid thruster (Ref. 8). Present efforts are directed toward parametric studies of annular slit geometries and material durabilities. Tips of platinum-iridium are presently being used. The propellant is NaI in glyceral. The present thrust of the CTE 2 annular slit is 0.4 mN at a specific impulse of 13,000 N-s/kg and a 50% efficiency.

III. SYSTEMS UNDER DEVELOPMENT IN FRANCE

A. Inert Gas Systems

In the early 1960s, an inert gas system was developed for the Diamant A launcher (Ref. 9). The first spacecraft inert gas system was developed for the D-2A satellite. The system, developed by Aerospatiale, uses several United States components, including a regulator. French solenoid valves are used, along with several other European components (Ref. 10). The nitrogen gas leakage rate of the French solenoid valves (Aerospatiale design) is very low (3600 STP cm^3/s of nitrogen).[3] The development cost of this system (including $700,000 of company funding) was $1,200,000. The system was successfully launched onboard the D-2A in April 1971. Aerospatiale is presently developing a similar system for the Symphonie satellite. Characteristics of the D-2A and Symphonie inert gas systems are given in Table 2.

B. Vaporizing Liquid/Electrothermal Systems

An ammonia resistojet system has been developed by SEP (Fig. 2) (Refs. 9 and 10). Characteristics of this system are presented in Table 3. At present, CNES is not continuing the development of this thruster.

C. Monopropellant Hydrazine Systems

Under funding from CNES, SEP has developed a 2.5-N-thrust monopropellant hydrazine thruster (Refs. 9 and 10). This thruster, shown in Fig. 3, has been flight-acceptance-tested with both Shell-405 and CNESRO I catalysts. (A detailed discussion of these catalysts is présented in Section VI.) Characteristics of this thruster are presented in Table 4. Two of its interesting features are a dual-series hard-seat solenoid valve (SEP design; nitrogen gas leakage rate, 1800 STP cm^3/s) and three small-diameter (<0.25-mm) capillary tubes that supply the propellant to the catalyst. The SEP 2.5-N thruster is similar in design to the Hamilton Standard 2.5-N thruster of 1969 vintage. The Hamilton Standard, TRW Systems, and Rocket Research 2.5-N thrusters presently employ a single capillary feed tube of a larger diameter (0.25 mm) in their thrust chambers. The three small-diameter capillary tubes on the SEP thruster will be susceptible to possible clogging or damage due to handling. In addition, the high injection velocity

[3] Standard temperature and pressure.

of the SEP capillary tubes may lead to somewhat shorter catalyst life due to catalyst bed mechanical failure.

As compared to United States catalyst bed designs, the SEP loading techniques and retention methods are similar, the bed diameter is similar to that in our 2.5-N thrusters, but the bed length is somewhat less than that in our comparable multi-purpose thrusters. The SEP bed length is closer to United States thruster bed dimensions for thrusters designed for purely pulse mode operation. When testing the TRW Pioneer F and G thruster, "washout" was observed during long (>1000-s) steady-state tests when bed lengths similar to those of the SEP thruster were used. SEP has reported some observed "washout" after several minutes of operation. In addition, the bed length may affect thruster durability to ambient starts. Endurance testing of this thruster with Shell 405 catalyst exceeded 2 h of steady-state thrusting, 4600 hot starts, and 80 ambient (21°C) starts. The SEP test facilities included vacuum tanks, sight gauges for flow measurement, and pressure and temperature transducers.

CNES is presently funding ($500,000) SEP to develop this thruster into a complete hydrazine auxiliary propulsion system. The system will include a tank with a surface tension device (slow spin rate sufficient for propellant feed), 7 kg of hydrazine, hard seat valves, CNESRO I catalyst, and pressure and temperature transducers. The system will fly as the payload of the D-5A satellite in early 1973. The propulsion system will be tested at four duty cycles: continuous, 0.5-s-on/0.5-s-off, 0.9s-on/0.1-s-off, and 0.1-s-on/0.9-s-off. In space, these duty cycles will be repeated for 4500 hot starts, 60 ambient starts, and 6000-s total "on time."

D. Contact-Ion Systems

Under funding from CNES ($450,000), LEP and ONERA are jointly developing a linear strip cesium contact-ion thruster system for north-south stationkeeping of a geosynchronous satellite. ONERA has developed "linear strip" and "button" ionizers and is presently providing these ionizers for use in the LEP linear strip contact-ion thruster. In addition, ONERA has performed supporting research on contact-ion thrusters (Ref. 11), including analysis of ion flow boundaries, experimental tests of ionizer efficiency, and sputtering tests. LEP is presently developing (Ref. 12) a contact-ion thruster system with the general characteristics given in Table 5.

E. Electron-Bombardment Systems

ONERA has studied a 5-cm mercury bombardment thruster. Tests with the 5-cm discharge chamber utilizing a tantalum wire cathode indicated high power requirements. The thruster was redesigned, and preliminary tests at 2.5-mN thrust and 61,740-N-s/kg specific impulse required 270 W of power (Ref. 6). Work on this thruster was suspended in 1968 when CNES directed all of its related funding to contact-ion thrusters.

SEP, in cooperation with Lockheed, Sunnyvale, California, is developing a cesium electron-bombardment thruster for use on its concept of the Intelsat-V spacecraft. This thruster is shown in Fig. 4. A cathode has been tested separately, but the complete thruster system has not yet been demonstrated.

IV. SYSTEMS UNDER DEVELOPMENT IN WEST GERMANY

A. Inert Gas Systems

ERNO was contracted by ESRO to integrate Sterrer-design inert gas systems into several early ESRO satellites. More recently, ERNO was contracted ($1,100,000) to supply the TD-1A inert gas system (Ref. 13). Tanks, nozzles, and various other components were developed at ERNO; the regulator and solenoid valves were supplied by Sterrer; originally, a solenoid valve was supplied by Elliott Brothers, Ltd., England. ERNO fabricated the system, performed qualification testing, and integrated the system into the TD-1A satellite. This satellite was successfully launched in March 1972. Characteristics of this thruster are presented in Table 6.

The GfW funded ERNO ($130,000) to develop a solenoid valve for use in future inert gas systems. The in-line solenoid, using EPT-10 soft seats, is shown in Fig. 5. This thruster/valve system is capable of a wide range of thrust levels and has been tested for over a million cycles with 1080 STP cm^3/s of nitrogen gas leakage.

B. Vaporizing Liquid/Electrothermal Systems

At the DFVLR in Trauen, the preliminary design of an 80-mN-thrust ammonia resistojet has begun. The resistojet will be a "fast heat-up" design.

C. Monopropellant Hydrazine Systems

In 1965, MBB began studies of monopropellant hydrazine thrusters. A 9.9-N-thrust monopropellant hydrazine system was tested for use in the West German national space program. MBB developed a solenoid valve and a flight-weight thruster in 1968 (Fig. 6). Typical performance data (obtained from development thrusters) are given in Table 7. This thruster was not tested extensively. Also, the bed contained three, homogeneously distributed, sizes of Shell 405 catalyst. In addition, the bed was not vibration-packed. A decision to develop a bipropellant thruster at 9.9-N thrust for the Symphonie satellite caused work on this monopropellant system to be terminated in 1969.

Jointly with TRW Systems, Redondo Beach, California, ERNO fabricated, flight-qualified, and integrated several hydrazine auxiliary propulsion systems for the Intelsat III spacecraft. The thruster (a TRW design) was fabricated, loaded, and tested at ERNO. The characteristics of this thruster are similar to TRW design data. A facility was developed at the DFVLR in Trauen to test these thrusters. The test system included load cells for measurement of thrust, sight gauges and turbine meters for flow measurement, and temperature and pressure transducers. All measurements checked with those determined at TRW. A solenoid valve (Fairchild Hiller, Stratos), pressure transducers, and a few other components were purchased from the United States. The titanium propellant tank was fabricated by ERNO.

Recently, in support of the West German national space program, ERNO was contracted ($1,100,000) to supply a hydrazine monopropellant system for the AEROS spacecraft. This system consisted of several components fabricated in the United States, including a propellant tank with an EPT-10 diaphragm (PSI), solenoid valves (Fairchild Hiller, Stratos), and filters (Wintec); however, the thrusters were manufactured by ERNO. The system, which was fabricated, tested, and integrated by ERNO, is scheduled to be launched in the fall of 1972.

ERNO is presently developing the 0.5- to 2-N catalytic monopropellant hydrazine thruster depicted in Fig. 7. The thrust chamber is lined with ceramic material to reduce heat loss. The bed dimensions are on the order of those of the SEP thruster. Also, the length of this thruster is considerably smaller than that of similar United States thrusters. Thus, the general comments made about the SEP thruster also apply to this thruster. No performance data for this thruster are yet available.

In addition, the development of a spontaneous catalyst is under way at the DFVLR in Trauen. Catalysts from a number of manufacturers in West Germany have been evaluated, and a catalyst produced by Kali-Chemie A. G., Hannover, is being tested presently. Different percentages of iridium on alumina are being prepared for test. The alumina is attrited before the iridium is placed on the substrate.

Monopropellant hydrazine plenum systems have been developed in West Germany at MBB and ERNO. Under contract to ESRO, MBB has developed an "active" plenum system that uses a solenoid control valve and a pressure switch. ERNO is presently developing a similar system.

D. Bipropellant Systems

A number of low-thrust bipropellant systems have been developed. A small company — Technologieforschung — has developed a 0.8- to 2.5-N-thrust bipropellant monomethylhydrazine/nitrogen tetroxide (MMH/NTO) thruster (Ref. 14). Performance of this thruster is given in Table 8. Recent tests have indicated a higher specific impulse of 2250 N-s/kg. The solenoid valve for this system is extremely impressive, since it can operate at a pulsewidth as low as 5 ms. At the present time, the Air Force Rocket Propulsion Laboratory, Edwards, California, is testing this thruster. In addition, the solenoid valve is being tested by the ESRO European Space and Research Technology Centre for possible use in an inert gas system.

MBB has been developing bipropellant thrusters for many years. It manufactures the bipropellant thrusters for the third-stage of the Europa II launcher. In the low-thrust range, MMB was funded ($2,300,000) to develop a 9.9-N-thrust bipropellant system for the Symphonie satellite. This MMH/NTO thruster is shown in Fig. 8, and its characteristics are given in Table 9. The thruster configuration was selected in 1968, and the thruster was fully qualified in 1971. MBB will fabricate, qualify, and integrate this bipropellant system into the Symphonie satellite. System features include 2-μm (nominal) filters and thrust chamber throat cooling (chamber temperature, <300°C). The MBB test facilities include a high-vacuum tank, load cells for thrust measurement, turbine meters for flow measurement, and pressure and temperature transducers.

Gaseous-hydrogen/oxygen bipropellant thrusters are also being studied at the DFVLR in Trauen. Original work was performed at 10-N thrust. The injector was optimized to achieve 90% characteristic velocity (c*) efficiency. A flight-weight 0.5-N thruster, with a Teflon soft-seat valve developed at the DFVLR, is presently being fabricated. These thrusters are similar to those which the Marquart Corporation is presently developing for the Air Force "water rocket" program. DFVLR at Trauen has developed a rather sophisticated test facility for these thrusters. It includes vacuum facilities, hot-wire anemometers for measurement of flow rate, load cells for thrust measurement, and pressure and temperature transducers. Data are received and processed by computer.

E. <u>Electron-Bombardment Systems</u>

At the DFVLR, Braunschweig, several mercury electron-bombardment thrusters have been developed (Refs. 15 and 16). The lowest-thrust propulsion system — the ESKA 18P — operates at >20-mN thrust. Although this is above the thrust level of auxiliary electric propulsion systems and is intended for primary electric propulsion, the ESKA 18P is included in this survey because it represents a rather advanced design of the mercury-bombardment thruster. In addition, ERNO has been contracted to develop a control logic and power conditioning module for the ESKA 18 thruster.

F. <u>Radio-Frequency Ion Propulsion Systems</u>

Since 1962, H. Loeb of Giessen University has been studying an ion thruster wherein the ions are produced by a high-frequency electrodeless discharge (Ref. 17). More recently, a 4-cm-diameter thruster, RIT-4, has been developed (Ref. 18). MBB has worked with Giessen University to develop a mercury feed system and a power conditioning module for this thruster. Performance characteristics of the RIT-4 thruster are given in Table 10.

G. <u>Pulsed-Plasma Systems</u>

The DFVLR in Stuttgart-Vaihingen is developing a low-thrust pulsed-plasma thruster. Solid Pb-I is fed between two magnets. The device is about 2% efficient with a 50-N-s impulse bit. The mass utilization is not known; however, assuming a reasonable value for mass utilization, the specific impulse is about 2940 N-s/kg.

V. SYSTEMS UNDER DEVELOPMENT IN ITALY, INDIA, JAPAN, AND RUSSIA

A. Italy: Monopropellant Hydrazine Systems

In support of the SIRIO Communication Satellite Program, OTO Melara has developed a monopropellant hydrazine thruster with a thrust level of approximately 20 N. This thruster has a penetrant injector and uses Shell 405 catalyst. It operates with a nominal 2250-N-s/kg specific impulse. Test facilities include thrust and pressure measurement devices supplied by SEP; at present, no vacuum facilities are being used. Detailed performance and endurance data were not available at the time this survey was made.

B. India: Monopropellant Hydrazine Systems

In support of the Indian National Satellite (Insat) Program, the Space Science and Technology Center, Trivandrum, has begun to study monopropellant hydrazine systems. Dr. A. E. Muthunayagan of the Center has visited several people in the United States to gather knowledge related to monopropellant hydrazine systems. In addition, several pounds of Shell 405 catalyst have been purchased.

C. Japan: Monopropellant Hydrazine Systems

The Japanese have begun to study monopropellant hydrazine systems. Several people have visited manufacturers in the United States to gather information on monopropellant hydrazine systems. Both Ishikawajima-Harima and Mitsubishi Heavy Industries of Japan have purchased large quantities of Shell-405 catalyst. From these purchases of catalyst, it can be concluded that Japan is very active in this field.

D. Russia: Inert Gas Systems

Very little is known about specific Russian propulsion hardware. From discussions with Russian scientists and engineers at international meetings or during tours of the United States, specific questions about propulsion system hardware are asked, but little information is released. In technical papers, the existence of certain types of propellant systems is discussed; however, only hardware developments in the United States are referenced. In one paper (Ref. 19), the Russians acknowledge the existence of inert gas systems on their spacecraft: "Gas power plants, or pneumatic systems, are widely utilized in space vehicles. Thus, they controlled the Soviet probes Venera, Mars-1, Zond-3, Luna, the spacecraft Vostok." In photographs of Russian propulsion systems taken at the LeBourget Exhibition in June 1971 (Ref. 20), certain components that resemble inert gas nozzles can be seen. Figure 9 shows two very small inert gas (or plenum) nozzles on the Soyuz spacecraft. The nozzle assemblage and welding appear substandard to United States quality requirements. Figure 10 shows three small inert gas nozzle/solenoid valve modules on the Luna-16 spacecraft. The very large solenoid valves imply a much more massive inert gas system that those used in United States technology.

E. Russia: Monopropellant Systems

As with the inert gas systems, very little is known about Russian monopropellant system development. The Russians refer to two possible monopropellant fuels; however, this does not mean that they use both. Reference 19 infers this with the statement "Hydrogen peroxide or hydrazine can be the single-component fuel."

Monopropellant systems on the Soyuz spacecraft can be seen in Fig. 9 (Ref. 20). These thrusters were located externally, with no thermal protection for the feed lines. From flight data on the Surveyor spacecraft, unprotected bipropellant lines experience flight temperatures as low as -7°C, with an allowable lower temperature of -17°C. Due to its similarity to the Surveyor spacecraft, Soyuz line temperatures as low as -7°C could be possible. Since hydrazine freezes around 1°C, while hydrogen peroxide has a freezing point as low as -17°C, it can be assumed that hydrogen peroxide is the monopropellant. Also, the development of a spontaneous catalyst for hydrazine in Russia has not been reported. Finally, the massive valves, thick electrical wiring, low nozzle expansion ratio, and heavy propellant lines imply a very low incentive for mass optimization. The shiny valve and decomposition chamber surface suggest some form of plating, such as gold.

F. Russia: Bipropellant Systems

During a recent visit to JPL by several Russian scientists to discuss lunar spacecraft, very little was learned about the Russian low-thrust bipropellant systems on Luna spacecraft. In the photograph from the Luna-16 spacecraft (Ref. 20) given in Fig. 10, a bipropellant thruster is shown.

Nozzle and thrust chamber machining quality control appears to be less rigorous than that for similar United States thrusters. The most likely low-thrust bipropellants utilized for low-thrust systems in Russia are nitrogen tetroxide oxidizer and monomethylhydrazine or Aerozine-50 fuels, which are discussed in Ref. 19.

VI. COMPARISON OF SHELL 405 AND CNESRO I CATALYSTS

In 1962, the Shell Development Co., Emeryville, California, was awarded a NASA contract, technically managed by JPL, to develop a spontaneous catalyst for hydrazine. The result of this work was the development of Shell 405 catalyst (Ref. 21). Although the preparation method for this catalyst is classified, the following characteristics can be reported:

Carrier:	Reynolds RA-1 (γ-alumina)
Iridium content:	31-33% by weight
Catalyst surface area:	100 m^2/g (minimum)
Cost:	\$5950/kg

Professor Pannetier of the Faculte de Sciences de Paris, Paris University, has been funded by CNES since the late 1960s to develop a spontaneous catalyst for hydrazine, similar to Shell 405. Preliminary papers (Ref. 22) reported a co-precipitation method of producing the catalyst. In 1968, Cie des Métaux Precieux (CMP), a French chemical company, developed a method for making pure (< 5 ppm of sodium) chloroiridic acid with a solubility for iridium of up to 500 g/liter. In March 1969, the preparation of a catalyst by impregnation of alumina began. "Two impregnations with a solution of 300 g/liter of iridium each followed by a drying and reduction in hydrogen at 300°C were enough to obtain a catalyst with 36-37%" ... iridium (Ref. 10). The carrier was γ-alumina supplied by Péchiney-Saint-Gobain, Meuilly, France, with an overall surface area of 410 m^2/g. After impregnation, the total surface area dropped to 135-145 m^2/g. The general characteristics of this catalyst, CNESRO I, are:

Carrier:	French alumina (γ-alumina)
Iridium content:	30-40% by weight
Catalyst surface area:	135-145 m^2/g
Cost:	More than \$5950/kg when for sale (due to development costs)

Two interesting points of comparison on the alumina carrier can be made. Reynolds RA-1 alumina is partially attrited prior to impregnation. From discussions at CNES and ESRO, it was learned that the French alumina now also is partially attrited prior to impregnation. From magnified photographs of both CNESRO I and Shell 405 catalysts, it can be seen that the French alumina has a much finer crystalline structure. Both the Reynolds RA-1 alumina and French alumina are designated as γ-aluminas; however, the French alumina is prepared from aluminum monohydrate gell (boehmite) found in France, while the Reynolds RA-1 alumina is prepared from alpha aluminum trihydrate (gibbsite) obtained from bauxites found in the United States, as well as other parts of the world.

Durability comparisons of Shell 405 and CNESRO I have been performed by SEP and ERNO. The tests at SEP were done with a 2.5-N thruster, while those at ERNO were performed on the 15.6-N Intelsat III thruster. The results of the tests are given in Table 11. At the termination of the SEP tests, both the CNESRO I and Shell 405 catalyst beds had experienced mass loss, with the CNESRO I bed experiencing the greater loss. Once a catalyst bed experiences a significant mass loss (>5%), thruster performance comparisons become difficult. At the termination of the ERNO tests, Shell-405 had not lost much mass, but CNESRO I had lost approximately 15%. However, Shell-405 showed signs of agglomeration. CNESRO I catalyst tests at ERNO ended with the thruster exhibiting large pressure spikes immediately after thruster ignition. For both the SEP and ERNO tests, the chamber pressure response times with the Shell 405 catalyst were generally somewhat slower than those with the CNESRO I catalyst. Experimental test catalysts that are more active than Shell 405 have been found to exhibit less durability. From the European test data presented in Table 11, CNESRO I has 50-75% of the durability of Shell 405.

Comparisons of the durability tests at ERNO and SEP with similar tests in the United States are difficult. The Shell 405 catalyst at SEP was purchased before 1968, the year when Shell modified its production process to the use of attrited carrier; therefore, the catalyst may not have been a good example of the present product. In similar tests of 2.5-N thrusters in the United States, the number of ambient starts reported by SEP was greatly exceeded, with less loss of catalyst. In tests at TRW Systems on the

Intelsat III thruster for an Air Force program, the cold and ambient start durabilities exceeded the ERNO results by a factor of 2 to 5. Similar tests at the Rocket Propulsion Laboratory, Edwards, California, demonstrated a cold start durability that is at least a factor of 2 greater than the ERNO value. The experience in the United States has thus demonstrated significantly greater cold and ambient start capabilities for Shell 405 than were demonstrated in European tests.

VII. OBSERVATIONS

A. National Development Trends

The trend in the United Kingdom space program is toward funding satellites as opposed to launch vehicles. With the cancellation of the Black Arrow launcher program, the small scientific satellites of the United Kingdom will now be launched by the Scout (Ref. 23). These small scientific satellites use vaporizing propane systems. Although funding of scientific satellites of this class is decreasing, the United Kingdom is developing vaporizing ammonia propulsion systems for future low-mass satellites.

The emphasis of the funding is presently directed toward communication satellites, which require the higher performance of monopropellant hydrazine systems. With the progression from Skynet I to Skynet II, the emphasis toward more involvement of United Kingdom contractors was evident. When the proposed United Kingdom Geostationary Technology Satellite (UKAT) is approved, the development of a monopropellant hydrazine system can be expected, since government and industrial interest is shifting in this direction.

The joint development of a 10-cm mercury electron-bombardment thruster at the RAE and Culham Laboratory is continuing, with the present system planned to provide north-south stationkeeping of a European synchronous satellite for the UKAT satellite.

The development of inert gas systems in France is continuing. These systems are planned for use on future French satellites launched by the Diamant launcher, as well as other satellites such as Symphonie. In addition, the French will continue to fund needed component developments. The decision of CNES to develop a spontaneous hydrazine catalyst (jointly funded by ESRO) as well as hydrazine thrusters signifies a desire of the French to develop a strong hydrazine propulsion technology base. With the launch of the D5-A spacecraft next year, the French will have demonstrated their catalyst and hardware in space. Even with a slightly decreasing national space budget, the continued development of spontaneous hydrazine catalyst and hydrazine auxiliary propulsion systems can be expected, with possible use of the Intelsat V or future ESRO spacecraft.

The development of a contact-ion thruster in France is continuing; however, in light of the cancellation of similar developmental work in the United States, French development efforts may shift to the development of an electron-bombardment thruster.

The West German development of inert gas systems for use on ESRO satellites is continuing. The government is continuing to fund necessary component development programs. The decision to fund ERNO to develop a hydrazine system for AEROS can clearly be interpreted as an effort to continue development of monopropellant hydrazine technology in West Germany. With the possibility of future ESRO and West German synchronous spacecraft, along with an increasing West German national space budget, the continued development of monopropellant hydrazine systems there can be expected. The development of low-thrust, bipropellant auxiliary propulsion systems in West Germany is impressive. The use of such systems in the United States has been limited; for similar functions, United States spacecraft have used monopropellant systems due to their lower cost and higher reliability. The use of bipropellant attitude propulsion systems on United States (or ESRO) spacecraft is not expected (except for very-high-total-impulse missions). Their use on future West German spacecraft is possible. The development of the Symphonie bipropellant auxiliary propulsion system will be completed.

While auxiliary chemical propulsion systems have had an ever-increasing importance in the West German national program, electric propulsion has seen a reverse trend. This is due to the absence of a clearly defined requirement for primary electric propulsion spacecraft. In 1963, the development program was directed toward a 100-kW electric propulsion spacecraft. Each year has brought about a decrease in the expected power level. With the recent cancellation of the SELAM program, the emphasis has shifted toward low-thrust auxiliary propulsion systems for stationkeeping propulsion. The development of low-thrust systems is being accomplished by scaling down high-thrust systems, such as the Giessen University RIT thruster and the DFVLR, Braunschweig, ESKA thruster. A low-thrust pulsed-plasma thruster is also being funded. The funding for these systems will continue, with the hope for their integration into future West German or ESRO synchronous spacecraft.

B. General Conclusions

The state-of-the-art of European inert gas systems (ERNO and Aerospatiale) can be considered equal to that in the United States. Many components (e.g., regulators and pressure transducers) are still purchased from the United States, but propellant tanks, solenoid valves, and other critical components are manufactured in Europe. From economic considerations, it is doubtful that United States spacecraft will use European inert gas systems in the foreseeable future, since the cost of European systems is about twice that of similar systems manufactured here. The high cost is associated with the initial component development and the need for specialized manufacturing equipment. With continued development and additional European flight experience, the cost of these systems should decrease. Also, there exist several European solenoid valves (ERNO, Aerospatiale, and Technogieforchung) that are definitely worthy of consideration for use in future United States spacecraft.

The state-of-the-art of European hydrazine auxiliary propulsion (ERNO and SEP) can be considered about 2 yr behind that of the United States. This is not surprising, since we have spent more than $40,000,000 developing this technology, while the total European expenditure is surely less than $5,000,000. Specific technical areas requiring additional advancement include catalyst bed sizing for specific duty cycles and additional thruster testing to characterize thruster durability in increased duty cycles. The present high cost of European hydrazine auxiliary propulsion systems is associated with the initial component development and the need for specialized manufacturing equipment. With continued national development programs and additional flight experience (GEOS, AeroSat, and future joint NASA/European satellites), the cost of these systems will decrease.

The CNESRO I catalyst development program has provided a spontaneous catalyst with 50-75% of the durability of Shell-405. In addition, this development program has made possible a less restricted sale of Shell-405 catalyst to Western Europe.

The electron-bombardment thruster of the RAE and Culham Laboratory is, at present, the most efficient European auxiliary electric thruster. Due to the developmental status of most of the European systems, it is too early for general conclusions regarding possible uses of European auxiliary electric propulsion systems. In the next few years, integrated thruster and power conditioning systems can be expected from the current development programs at the RAE, Culham Laboratory, SEP, LEP, Giessen University, and the DFVLR at Braunschweig.

From available photographs of Russian spacecraft and from the success of Russian space ventures, it can be assumed that Russian auxiliary propulsion technology is quite advanced. Much could be learned from a Soviet-American auxiliary propulsion technology exchange. Perhaps the recently signed Soviet-American space technology agreement will open the door to such an exchange.

REFERENCES

1. "ESRO Adopts 6-Year Finance Plan," Aviat. Week, p. 17, Dec. 20, 1971.

2. Briscoe, H. M., "The Choice of Propellant for a Cold Gas Propulsion System for a Satellite," J. Brit. Interplan. Soc., Vol. 20, pp. 72-78, 1965.

3. Earl, A. G., "Proposals for Hydrazine and Ammonia Resisto Jet Orbit and Attitude Control Systems for Satellites," J. Brit. Interplan. Soc., Vol. 25, pp. 31-41, 1972.

4. Donovan, J. A., Lord, W. T., and Sherwood, P. J., "Fabrication and Preliminary Testing of a 3 kW Hydrogen Resistojet," AIAA Paper 72-449, presented at the AIAA Ninth Electric Propulsion Conference, Bethesda, Md., Apr. 1972.

5. Berry, W., et al., A Study of Materials Compatibility with Hydrazine, ESRO CR-34. British Aircraft Corporation, Bristol, England, Mar. 1971.

6. "Survey of Electric Propulsion System for Space Application in Europe," Eurospace, Memorandum 7, 8-10, rue Cognacq-Jay, Paris, France, July 1970.

7. Day, B. P., and Hastings, R., The RAE 10-cm Hollow Cathode Mercury Thruster, Technical Report 71135. Royal Aircraft Establishment, Farnborough, Hants., England, June 1971.

8. Bracher, J. E., "ESRO's Work on Electric Propulsion," AIAA Paper 72-478, presented at the AIAA Ninth Electric Propulsion Conference, Bethesda, Md., Apr. 1972.

9. Pujes, J.-P., "Microthruster Development in France under Direction of the Centre National d'Étutes Spatiales (CNES)," J. Spacecraft Rockets, Vol. 8, No. 2, pp. 140-150, Feb. 1971.

10. "La Technologie Spatiale Francaise," IPF Éditeur, 12, rue des Fassés-Saint-Marcel, France, 1971.

11. LeGrives, E., and Labbe, J., "Research on Cesium Contact Mirothrusters at ONERA," AIAA Paper 72-495, presented at the AIAA Ninth Electric Propulsion Conference, Bethesda, Md., Apr. 1972.

12. Eschard, G., Loty, C., Pélissier, A., and Bonnal, J. F., "Basic Studies of Cesium Contact-Ion Thruster," AIAA Paper 72-440, presented at the AIAA Ninth Electric Propulsion Conference, Bethesda, Md., Apr. 1972.

13. Inden, W., "Development Results of the ESRO TD Satellite Pneumatic System," AGARD Lecture Series 45. 7, rue Ancelle 92 Neuilly-Sur-Seine, France.

14. "Measurement of Steady State Specific Impulse of Tiroc-Rocket Engine under Vacuum Conditions," ESTEC Contract 1394/71 HP, Technologieforshung, am Bismarckturm 10, 7 Stuttgart 1, West Germany.

15. Junge, H. J., and Sprengel, U. W., "Direct Thrust Measurements and Beam Diagnostics on the Ion Thruster ESKA 18-P," AIAA Paper 72-433, presented at the AIAA Ninth Electric Propulsion Conference, Bethesda, Md., Apr. 1972.

16. Arlt, H.-J., and Au, G. F., "Electrostatic Ion Thruster ESKA 28 for Interplanetary Missions," AIAA Paper 72-434, presented at the AIAA Ninth Electric Propulsion Conference, Bethesda, Md., Apr. 1972.

17. Loeb, H. W., "Recent Work on Radio Frequency Ion Thrusters," J. Spacecraft Rockets, Vol. 8, No. 5, pp. 494-500, May 1971.

18. Trowan, F. M., Lang H., and Loeb, H. W., "Development of the Radio Frequency Microthruster RIT 4," AIAA Paper 72-473, presented at the AIAA Electric Propulsion Conference, Bethesda, Md., Apr. 1972.

19. Pavlov, I., "Low Thrust Engines," Aviatsiia i Kosmonavtika, No. 8, pp. 38-39, 1970, National Translation Center, NASA Document 71-10928.

20. Pfeffer, H. A., "Some Photographs of Russian Spacecraft Propulsion Systems (Soyuz, Luna 16) Taken at the LeBourget Exhibition, June 1971," Internal Working Paper No. 618. European Space Research & Technology Centre, Control and Stabilization Division, Noordwijk, Holland, Oct. 1971.

21. Vogue, H. H., "Development of Catalyst for Monopropellant Decomposition of Hydrazine," Final Report, Contract NAS 7-97, Report No. S-13947. Shell Development Co., Emeryville, Calif., Apr.-Dec. 1964 (Confidential).

22. Contour, J.-P., and Pannetier, G., "No 560-Etude des Proprietés Catalytiques de l'Iridium Supporté par l'Alumine," Bulletin de la Societe Chimique de France, No. 9, 1968 (in French).

23. Simmons, N., "The United Kingdom Program of Communication Satellites," AIAA Paper 72-548, presented at the AIAA 4th Communications Conference, Washington, D.C., Apr. 1972.

Table 1. RAE and Culham Laboratory 10-cm mercury electron-bombardment thruster characteristics

Thrust, mN	10
Specific impulse, N-s/kg	24,500
Thruster power, W	300
Propellant utilization efficiency, %	90
Power conditioning efficiency, %	85

Table 2. D-2A and Symphonie inert gas system characteristics

	D-2A	Symphonie
Propellant	nitrogen	nitrogen
System mass, kg	8	8.15
Storage pressure, kN/m^2	23,300	25,000
Thrust, mN	28	1000
Specific impulse, N-s/kg	706	706
Total impulse, N-s	1300	1430

Table 3. SEP ammonia resistojet characteristics

Thrust, mN	5
Specific impulse, N-s/kg	1690
Thruster power, W	20
Average propellant temperature, K	1100

Table 4. SEP catalytic monopropellant hydrazine thruster characteristics

Thrust, N	1.6 to 2.8
Specific impulse, N-s/kg	2100 to 2250
Feed pressure, kN/m^2	1370 to 2250
Catalyst	Shell 405 or CNESRO I
Valve and thruster mass, g	180
Durability (Shell 405 catalyst)	
Hot starts (>120°C)	4600
Ambient starts (21°C)	80
Total burn time, h	2

Table 5. Estimated LEP cesium contact-ion thruster characteristics

Thrust, mN	0.53
Specific impulse, N-s/kg	49,000
Engine efficiency[a], %	35
Life, h	18,000

[a]Including neutralizer.

Table 6. ERNO TD-1A inert gas system characteristics

Propellant	argon
System mass, kg	24.3
Storage pressure, kN/m^2	15,200
Thrust, mN	20 and 60
Specific impulse, N-s/kg	510
Total impulse, N-s	5500

Table 7. MBB catalytic monopropellant hydrazine thruster characteristics

Thrust, N	9.8 to 14.7
Specific impulse, N-s/kg	2240
Chamber pressure, kN/m^2	1034
Catalyst	Shell 405

Table 8. Technologieforschung MMH/NTO bipropellant thruster (TIROC) characteristics

Thrust, N	0.7 to 2.15
Specific impulse, N-s/kg	2450
Chamber pressure, kN/m^2	645 to 2120
Mixture ratio	1.65

Table 9. MBB Symphonie MMH/NTO bipropellant thruster characteristics

Thrust, N	7.8 to 12.2
Specific impulse, N-s/kg	2790
Chamber pressure, kN/m^2	650 to 1060
Mixture ratio	1.64
Total efficiency, %	88

Table 10. Giessen University RIT-4 thruster characteristics

Thrust, mN	1.4	3.9
Specific impulse, N-s/kg	13,700	38,200
Beam power, W	60	120
Thruster power[a], W	118	180
Power conditioning efficiency, %	90	90

[a]Including neutralizer.

Table 11. Comparison of Shell-405 and CNESRO I catalysts

Parameter	Shell-405	CNESRO I
SEP tests		
Number of hot starts (>120°C)	6400	4900
Number of ambient starts[a] (21°C)	101	61
Total burn time, s	14,800	8000
ERNO tests		
Number of ambient starts (21°C)	20	10 to 15
Number of cold starts (4°C)	20	10 to 15
Total burn time, s	5000	3000

[a]The number of cold and ambient starts to catalyst failure is the main life determinant, not the total test burn time.

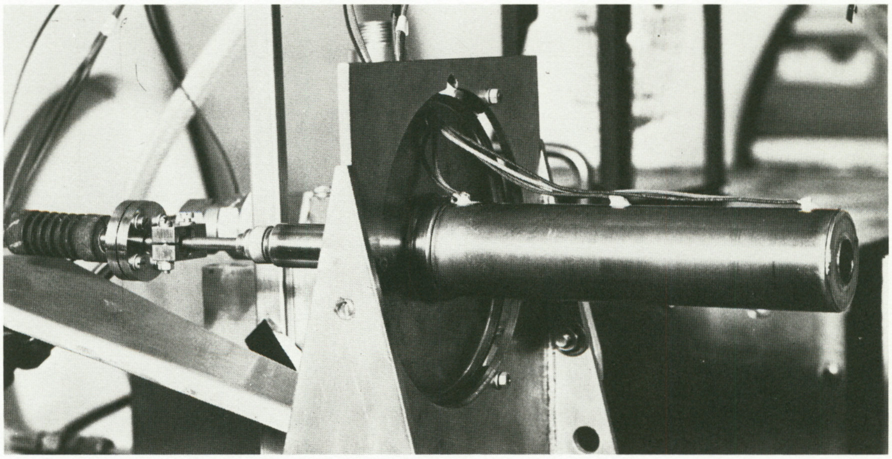

Fig. 1. RPE 3-kW resistojet (photograph courtesy of RPE)

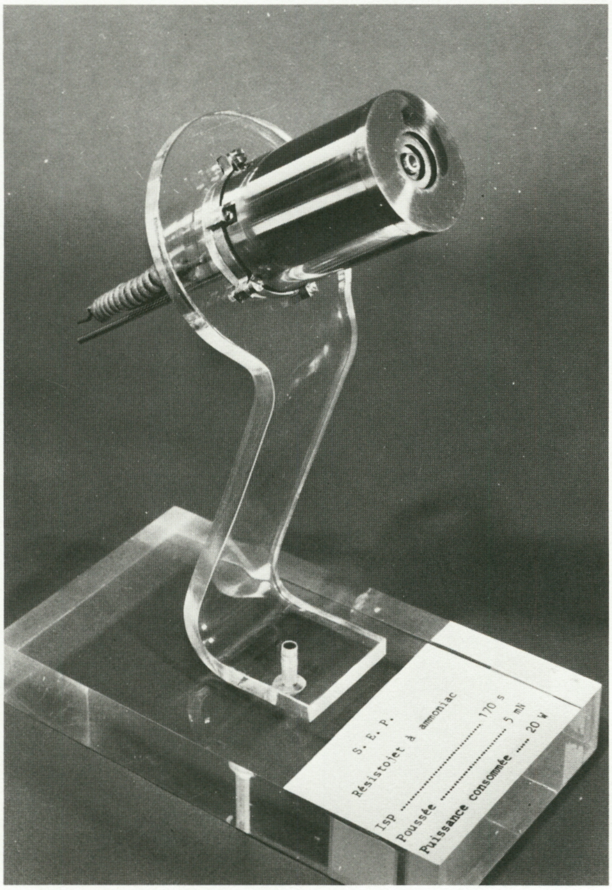

Fig. 2. SEP ammonia resistojet (photograph courtesy of SEP)

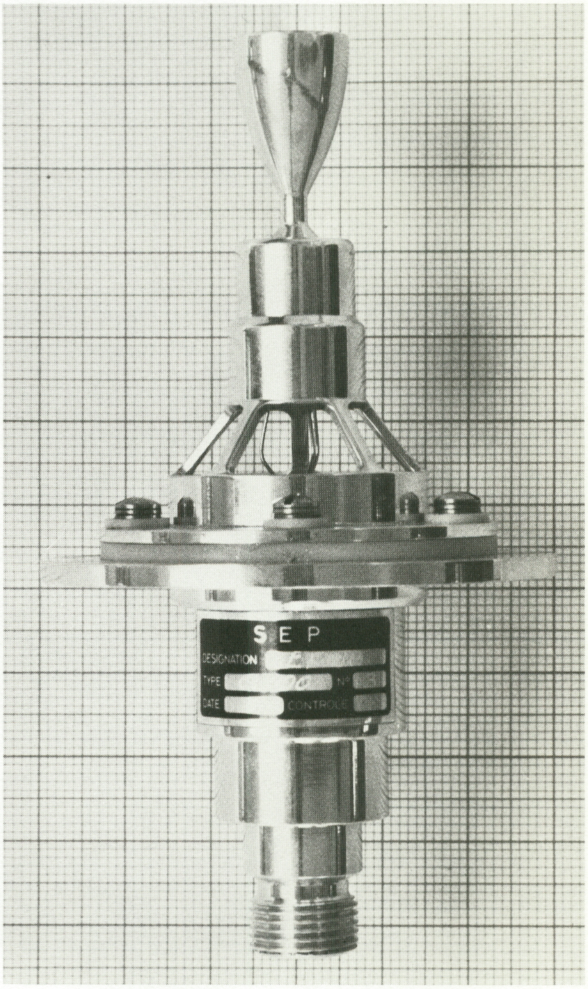

Fig. 3. SEP 1.6- to 2.8-N catalytic monopropellant hydrazine thruster (photograph courtesy of SEP)

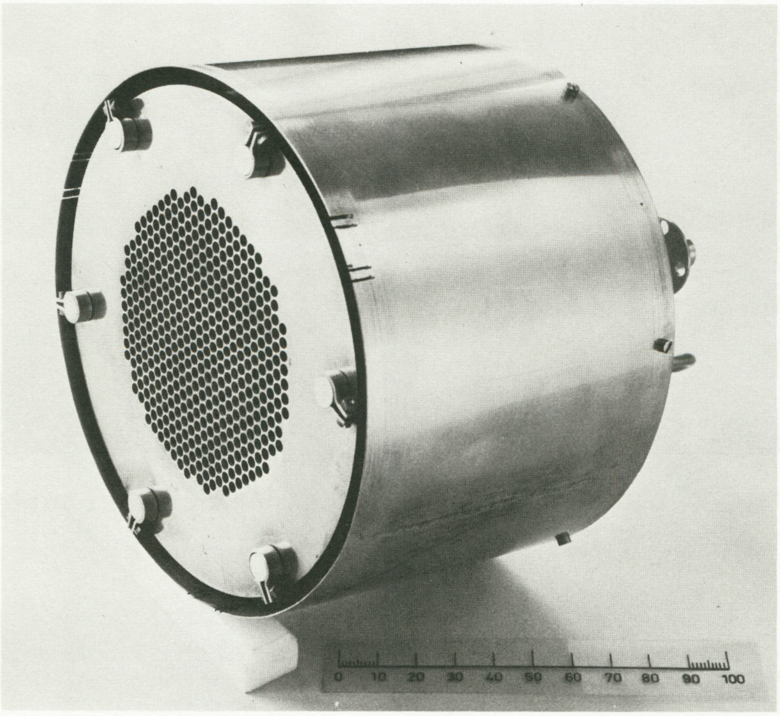

Fig. 4. SEP cesium electron-bombardment thruster (photograph courtesy of SEP)

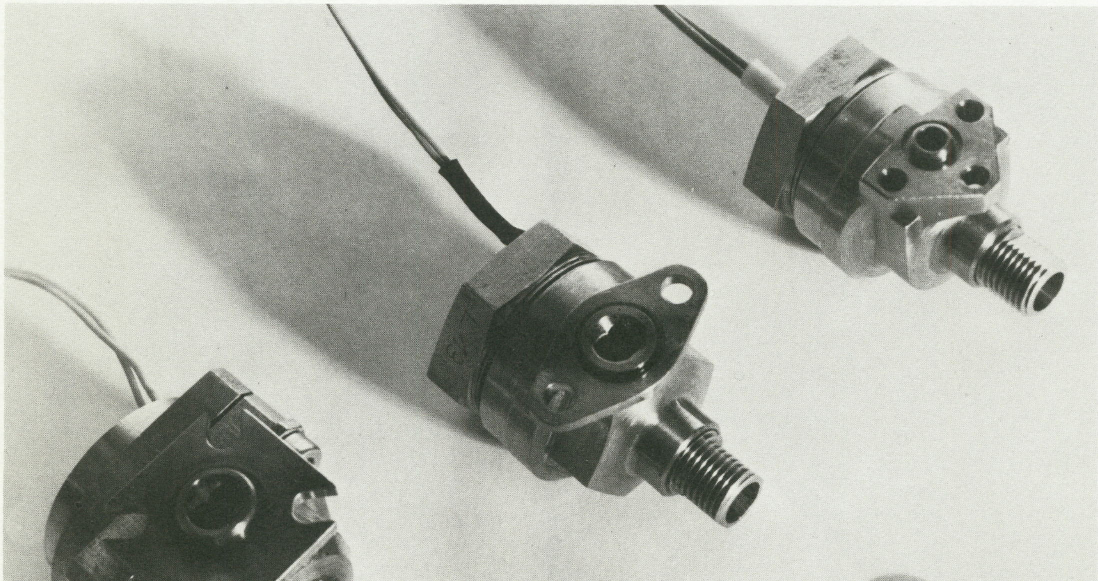

Fig. 5. ERNO inert gas solenoid valve/thruster modules (photograph courtesy of ERNO)

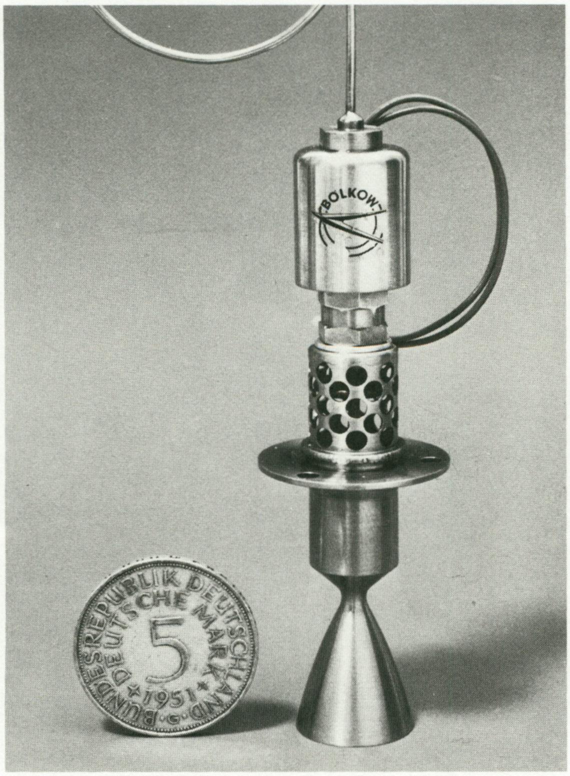

Fig. 6. MBB 9.8- to 14.7-N monopropellant hydrazine thruster (photograph courtesy of MBB)

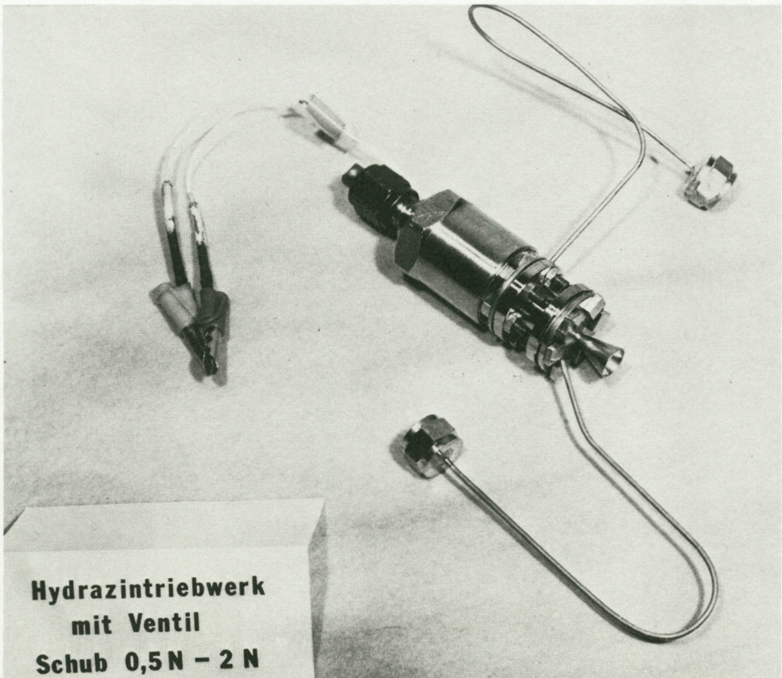

Fig. 7. ERNO 0.5- to 2-N catalytic monopropellant hydrazine thruster (photograph courtesy of ERNO)

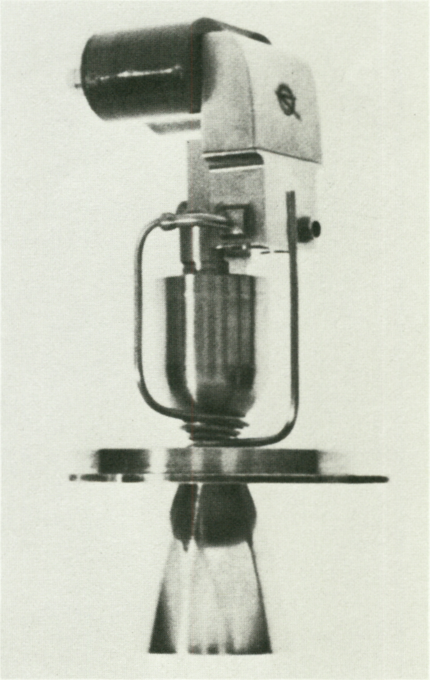

Fig. 8. MBB Symphonie MMH/NTO bipropellant thruster (photograph courtesy of MBB)

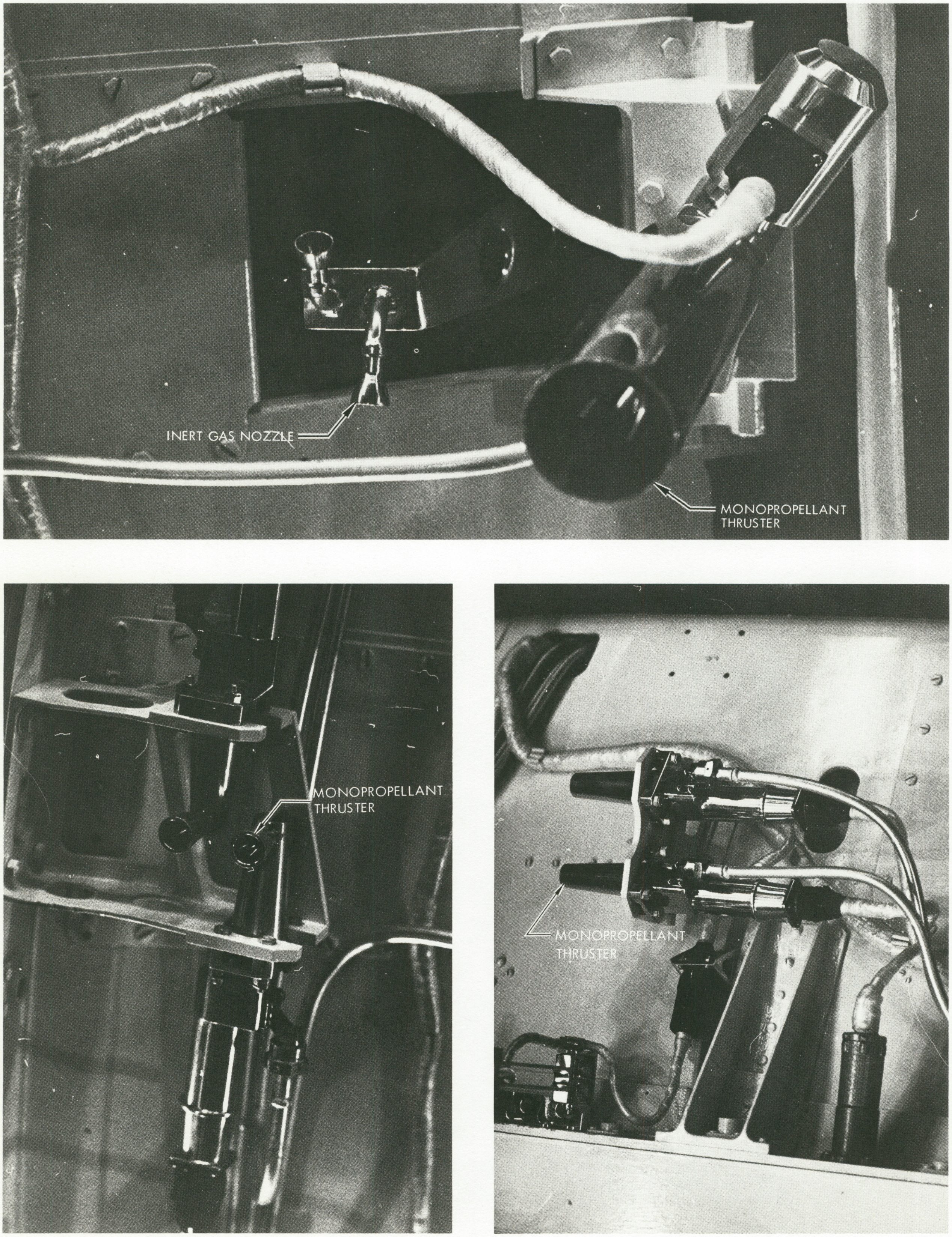

Fig. 9. Inert gas nozzles and monopropellant thrusters on the Soyuz spacecraft (photographs courtesy of H. Pfeffer)

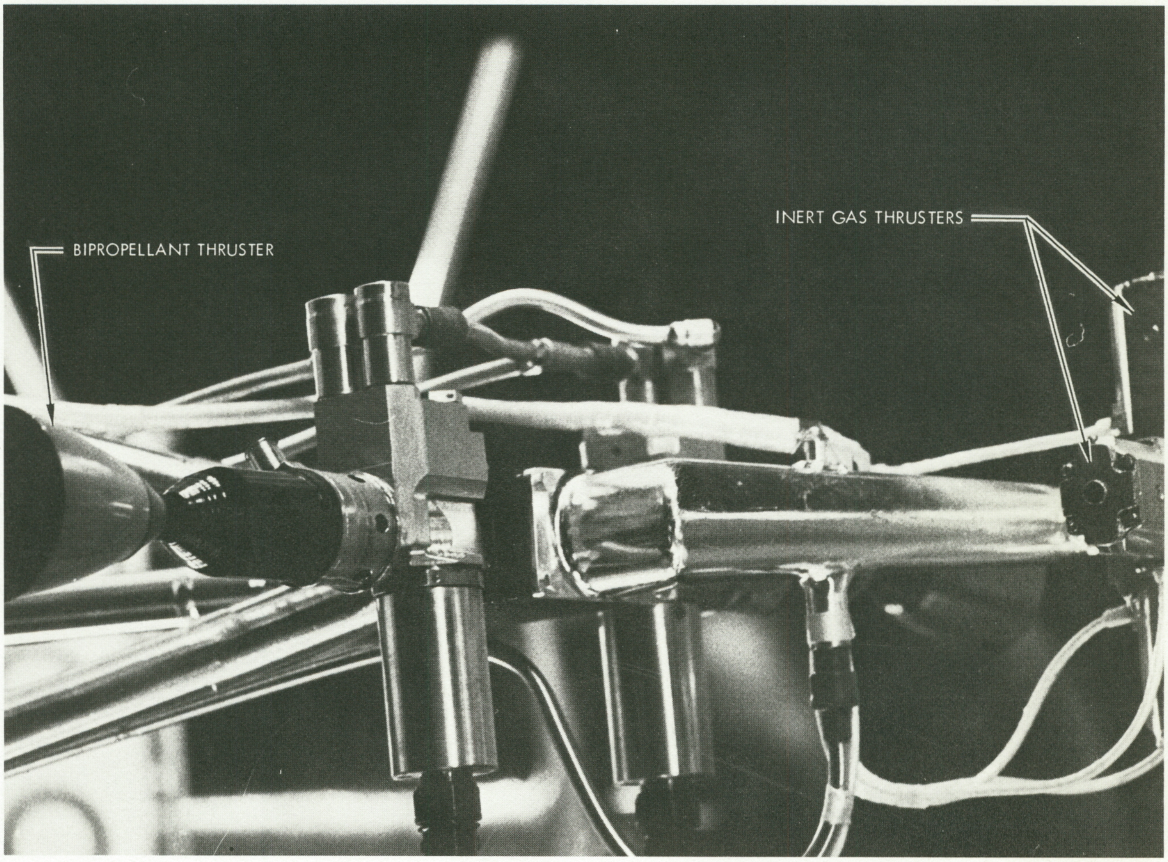

Fig. 10. Inert gas thrusters and bipropellant thruster on the Luna-16 spacecraft (photograph courtesy of H. Pfeffer)

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