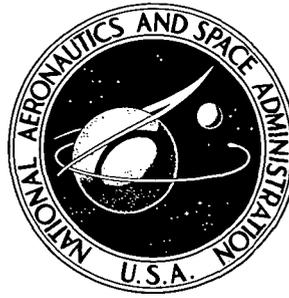


**APPLICATIONS OF
AEROSPACE
TECHNOLOGY**



NASA CR-2506

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BRUSHLESS DC MOTORS

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BRUSHLESS DC MOTORS

TABLE OF CONTENTS

	<u>Page</u>
Introduction	1
Knowledge Contribution Previously Identified	2
I. What They Are.	2
II. Development History.	3
A. Brush Failure	5
B. Low Cost Control.	8
C. Low-Speed, Direct Drive	9
D. Fast Response	10
III. Space Requirements and Contributions	13
IV. Significance and Impact.	16
Chronology	25

INTRODUCTION

How does new knowledge, acquired for one purpose, develop into useful technology having significant impact and benefits to society? This is one case study in a series of detailed investigations tracing the origins of new knowledge developed to solve specific problems of manned space exploration, and its subsequent modification and application to commercial needs.

What differences exist between the technology required for space exploration, and the requirements for application to earthly problems? What factors determine the time required to convert new knowledge into viable economic benefits? Various case examples disclose differing patterns of technological development. By comparing the common and contrasting findings, it may be possible to understand better how new knowledge generates real benefits.

Starting from a specific "knowledge contribution" previously identified from an analysis of Astronaut life support requirements, the origins, adaptations, and eventual significance of the new technology is presented.

BRUSHLESS DC MOTORS

Knowledge Contribution Previously Identified

Brushless DC motors were intensively developed and tested over several years before qualification as the prime movers for Apollo spacecraft life support blowers, and for circulating oxygen in the Lunar Portable Life Support System. Requirements of the manned space program for motors having nonsparking characteristics for use in pure oxygen, together with high efficiency, high starting torque, long life and good speed regulation markedly accelerated technical development of these motors. Photodiode controlled designs were developed by NASA in the early 1960's. Subsequently, motors utilizing Hall effect devices have been more widely used. Stringent aerospace requirements for brushless DC motors have resulted in new and improved drive systems, torque motors and servomotors, and a variety of motor control units.

Knowledge gained through prototype development and critical testing has significantly influenced the technology employed, broadened markets and applications, and reduced the cost of present day motors. Manufacturers and aerospace engineers believed that highly reliable and efficient brushless drives would find wide use in computers, battery powered tape recorders and eventually in a variety of consumer products. Windshield wipers on several German automobiles are currently powered by adjustable speed brushless DC motors.

I. What They Are

Brushless direct current motors are a versatile class of electric motor drives, created and developed over the last 12 years. Their most important characteristic is the elimination of carbon brushes--such as those found in a vacuum cleaner motor or an electric hand drill. Solid state sequencing of motor current is employed instead of brushes. Originally, it was necessary to get rid of these brushes to permit motor operation

in the vacuum of space. Subsequent development and use of brushless motors has shown that they possess many other more valuable advantages, and that a growing variety of motor applications are well served by the brushless DC motor.

II. Development History

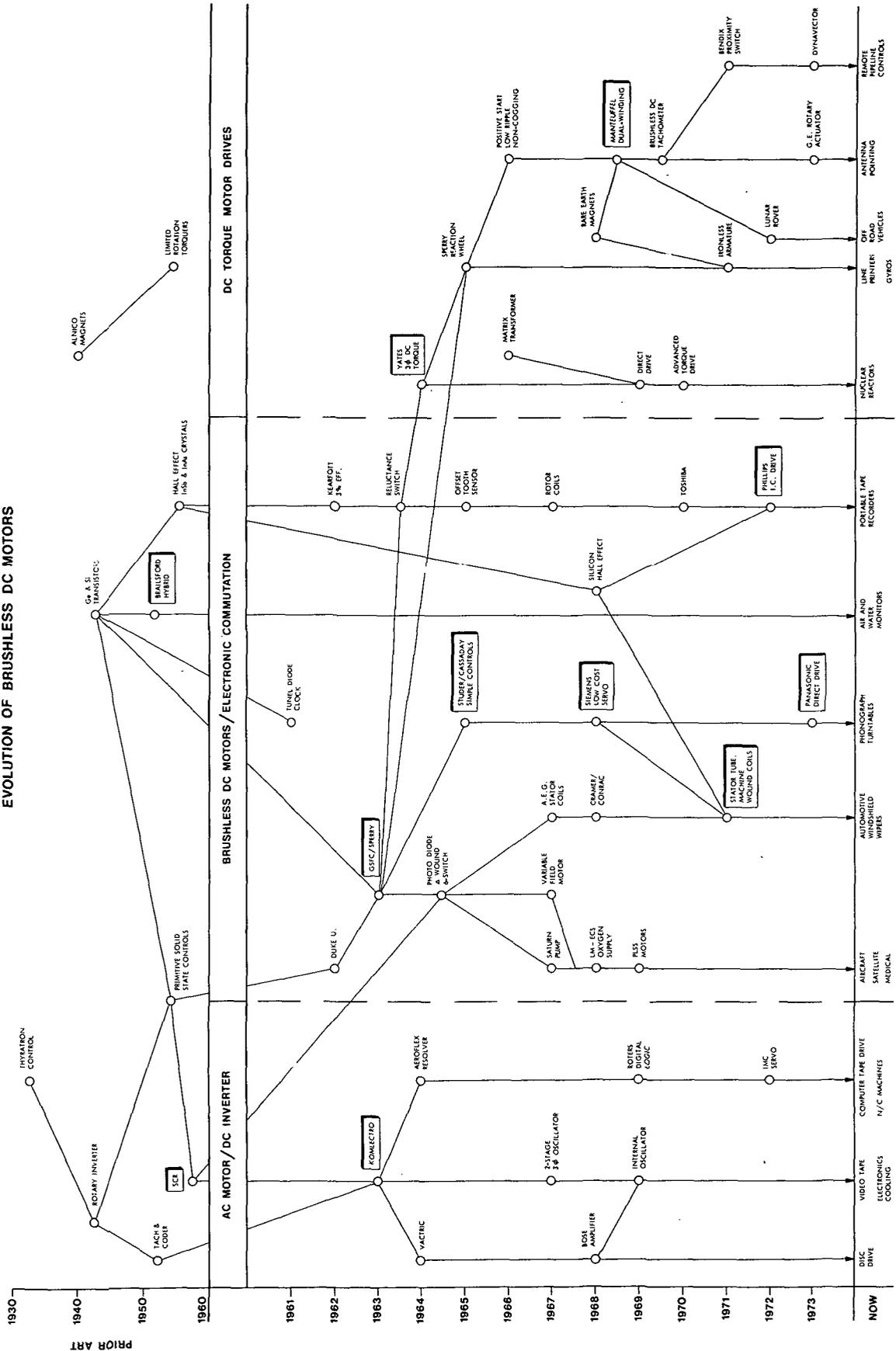
More intriguing than the series of technical innovations that trace the evolution of brushless DC motors are two secondary themes. First, the powerful influence of technical developments in fields not directly related to motor design, such as integrated circuits, lubricants, and permanent magnet alloys. Second is the aspect of serendipity which characterizes the applications and markets that were created for this new class of electric motors. Most of today's varied uses are based on secondary and less obvious characteristics of brushless motors in addition to the main advantages for which they were initially devised.

The actual invention of brushless DC motors took less than 5 years-- from the original definition of the problem, advancement through design, development, improvement, production and regular use occurred between 1963 and 1968. A broader appreciation of the motor situation before space needs arose and the trends of developments subsequent to the aerospace innovations is helpful in understanding the rapidity with which technical advances were achieved. This perspective also explains why considerable time elapsed before commercial applications of brushless motors became important. Some of the key events and major lines of development that led to the creation of brushless DC motors and their subsequent applications are shown in Figure 1. A more comprehensive technical history with substantial detail and documentation will be found in the chronology sections. However, neither the development chart nor the technical chronology explains adequately the motivations and the interactions that form important parts of this case study.

Direct-current motors are superior to AC motors in many important characteristics:

- . High efficiency;
- . High starting torque;
- . Ease of speed control and reversing; and
- . Small size and weight for a given power rating.

EVOLUTION OF BRUSHLESS DC MOTORS



Key Event

Despite these advantages, DC motors were for the most part limited to industrial applications and portable or mobile battery-operated equipment. Decisions reached many years ago relegated DC motors to obscurity. All electric motors, until 1980, were permanent magnet or direct current. The first electric power used in American homes was the C & C Motor introduced in 1886 to operate sewing machines from 6-volt batteries. Thomas Edison started the first (direct current) central power station in the United States in 1892. George Westinghouse championed AC, inaugurating the generating station at Niagara Falls in 1896. (See chronology sections). For a decade the advantages of DC power seemed to outweigh the efficiency with which AC could be distributed over long distances. By 1903, the difficulty of synchronizing widely separated AC generators had been solved so that interconnection became possible. Thus, the power grid of the U.S. was established and AC became the universal form of electric energy. This resulted in a motor industry overwhelmingly dominated by AC machinery, with DC motors finding more specialized and limited uses.

Disadvantages of the usual DC motor seem to center around their brushes. They spark. They wear, and thus, require periodic replacement. The brushes generate radio noise and interfere with TV pictures. Sparking brushes can cause explosions in mines or refineries. Brushes also wear the commutator, which needs occasional cleaning and remachining. And, in the vacuum of outer space, they just do not work.

Since both the advantages and disadvantages of DC motors were well recognized, it had long been a goal to create a drive motor capable of providing the advantages of DC motors without the problems caused by brushes. Until about 1950, motor designs did not change much. The main emphasis was on devising better ways to convert AC into DC for easier motor control, as well as developing better methods for operating AC equipment from battery power and other DC sources. During the 1930's, the thyatron motor controller, ignitrons, and various rectifiers were used for DC motor control. During the war years, rotary convertors were widely used in military equipment, and earned a reputation as one of the least reliable elements in electrical systems.

A. Brush Failure

The key problem which ultimately culminated in the development of brushless DC motors was first reported during high-altitude strategic bombing in World War II. Rapid brush wear and the failure of rotating equipment occurred above 30,000 feet--foreshadowing the problems to be encountered in the hard vacuum of space. The U.S. Air Force and aircraft manufacturers have been working on reliable high-altitude electric brushes from 1943 to the present time.

Technical advances in other fields had the next decisive impact on motor development. The introduction of solid state transistor switches in the early 1950's made it theoretically possible to switch motor currents without the use of brushes. Early transistors, however, lacked the power capacity to handle motor currents. The second key development was the introduction of vastly improved magnetic materials, which made possible permanent magnet motors that were more than toys.

By the mid-1950's, H. D. Brailsford introduced the first DC motors to be called "brushless." This pioneering development greatly influenced later work because it demonstrated that once the brushes were eliminated, DC motors could operate for surprisingly long periods with exceptional reliability. The Brailsford motor was actually a "hybrid," utilizing spring contacts to trigger transistors so that the motor would start; once the motor was rotating, these contacts flew out, permitting true brushless operation. Motors utilizing this ingenious compromise design have been continuously manufactured for over 15 years, and are today proving their value in the operation of remote and unattended equipment, such as portable air and water pollution monitors.

With the start of space exploration, the brush problem became crucial. Only battery power or solar cell sources were available on early sounding rockets and satellites; and it was quickly learned that the operating life of conventional brush-type DC motors in the vacuum of space was limited to a few minutes. Sometimes this problem had to be solved by enclosing the tape recorder or camera drive in a pressurized container; but doing so increased weight and complexity. Other satellites used exotic lubricants that were supposed to prevent brush and bearing seizure. TIROS-M, an advanced weather satellite, experienced brush failure 1 month after launch. The later weather satellite, called ITOS-D, completely avoided similar brush problems by employing a total of seven brushless motors in the attitude control system, scanners, recorders, and other applications.

It appeared highly desirable to eliminate all types of failure-prone sliding contacts--slip-rings, bearings and gear drives, as well as electrical brushes. In support of future space missions, Goddard Space Flight Center established such a program in 1962. The Mechanical Systems Branch surveyed the various approaches available and found that only one U.S. manufacturer had a working breadboard model of an electronically commutated DC motor. Under contract to NASA, Sperry-Farragut developed the first in a series of brushless DC motors that would see use in many parts of the space program. The principle of photoelectric sensing of rotor position and electronic commutation of the motor was proved feasible. These DC motors were the first to demonstrate self-starting capability, had efficiencies more than twice as high as comparable AC motors, and were

qualified for year-long space missions. The operating life of these motors was limited only by bearing failure. Test specimens have been run for nearly 7 years before the bearings eventually failed and had to be replaced. The considerable publicity given to this motor development undoubtedly influenced later motor developments by other organizations.

Eliminating the brushes in a conventional DC motor was not the only way to achieve reliable operation at low pressure. Alternating current induction motors could also be used with the addition of a DC inverter. The introduction in 1957 of the silicon controlled rectifier (SCR) made solid state convertors practical for motor operation. Lamb Electric Company, in 1963, developed the Komlectro motor for use by the U.S. Air Force to monitor airborne radioactivity by means of high-altitude air sampling balloons.

Although AC motors operated from DC power through a converter are less efficient and considerably heavier than corresponding DC motors, this system does provide long life, high reliability, and no sparking to interfere with radio telemetry from the balloons. With various improvements over the years, specialized AC motors using increasingly sophisticated solid state pulsed DC controls have found important uses in applications where reliability, fast response and digital motor control are important. The lineal descendant of the Komlectro motors are today's Wind-Jammer blowers used by most computer manufacturers.

The introduction in 1958 of Hall effect crystals, which generate a voltage proportional to the strength of a magnetic field, provided a simpler way to sense motor position. In 1962, Kearfott Products constructed an experimental brushless DC motor using 12 Hall effect devices, along with transistor switches and power amplifiers. This experiment quickly showed the limitations of the existing Hall effect sensors. The breadboard model device produced 1-inch ounce of torque at a maximum electrical efficiency of less than 3 percent. Although the Hall effect sensors permitted the motors to be self-starting, the size, complexity and low output of these magnetic sensing devices seemed to rule them out for use in practical commutators for DC motors.

Brushless DC space-qualified motors, ranging from 1 watt up to 1/2 horsepower were in use by 1965 for applications such as circulating oxygen in the Apollo Lunar Module and driving the coolant pump on the Saturn I-B and Saturn V launch vehicles. These are basically free-running applications which do not require speed control or special torque regulation. NASA engineers at Goddard also supported the development of torque motors suitable for accurately pointing antennas, or controlling spacecraft attitude. Between 1964 and 1966, Yates and co-workers at Westinghouse developed brushless DC torque motors having characteristics similar to those

of a conventional torque drive, but designed for vacuum operation using a reluctance switch to control commutation. In a parallel development, Cassaday at Sperry modernized the "ironless armature" concept to develop torque motor drives having improved servo characteristics, smoother performance, and even lower electrical losses. (The so-called ironless motor construction technique was employed about the turn of the century before it was learned that conductors placed in slots are as effective as if they were actually in the air gap itself.) This concept returned to vogue in recent years primarily for high acceleration motors such as those used in incremental tape drives.

The brushless torque motor developed for Goddard by Sperry used a stationary wire-wound ironless armature and a multipole permanent magnet rotor. A much faster response rate is achieved due to the fact that the conductors are not surrounded with highly permeable iron laminations. Cogging and ripple are greatly reduced, and hysteresis and eddy current losses found in the normal laminated armature are eliminated, giving improved efficiency. Innovations such as a built-in current limitation, regenerative braking, and bi-directional motor control were incorporated in torque wheels that were considerably more efficient and lighter in weight than previous designs.

B. Low Cost Control

A highly significant technical paper was presented by Studer and Cassaday at the 1965 WESCON. This paper called attention to many of the less obvious characteristics and advantages of brushless drive systems. Circuit modifications were described which permitted constant torque operation and linear speed control in both directions.

More importantly, analysis of the drive system showed that greatly simplified servo control could be achieved by more fully utilizing the electronic commutator. Servo-controlled drives in the mid-1960's required a position sensor, pre-amplifier, power amplifier, current regulating section, reversing bridge, tachometer, and some form of speed reducer (gears, belts, etc.) on the motor output. NASA's analysis pointed out that most of the expensive electronics used in DC servo drives could be eliminated if brushless commutation was employed. No power amplifier is needed; speed reducers or gear trains can be eliminated, using the motor to provide direct controlled speed drive; and motor control can be obtained by suitable use of the electronic logic already present in the commutation circuits. Eliminating complexity and many of the parts would make precision servomotors more reliable--and also much less costly.

Within 3 years, Siemens Electric Company in Germany used precisely this approach to develop a low-cost, direct-drive system for battery powered tape recorders. In addition they offered the basic motor and electronic control system to U.S. manufacturers at the then unheard of price of \$25.

C. Low-Speed, Direct Drive

To satisfy NASA requirements for automatic tracking and pointing of solar arrays, Westinghouse improved the brushless direct-drive system by using the offset tooth sensor and careful field and pole shaping to achieve very low torque ripple. Similar innovations by Manteuffel at General Electric and Nola at Marshall Space Flight Center, resulted in larger, more powerful brushless power motors having split-windings capable of providing full torque at low speed, as well as higher speed at low torque. Compared to conventional high performance brush-type motors of the same weight and power, these new drives offered the following advantages: indefinite operating life, ten-fold improvement in reliability, motor friction reduced by 75 percent, improved heat dissipation, and uniform torque regulation (low ripple).

Carrying the brushless drive concept to larger power ratings began to influence builders of electric powered machinery. Thus, by 1970, William Lear announced the first 1/2-horsepower brushless motor available at a cost less than that of a conventional brush-type DC motor. For industrial applications and off-road vehicles, Lear believed that brushless motor designs in sizes up to 200 horsepower would be practical and economical. The U.S. Army built and tested 90-horsepower brushless drive motors for heavy duty vehicles.

The Lunar Roving Vehicle for traversing the moon, required four DC motors; one was used to drive each wheel. To insure that qualified motors could be provided, Marshall Space Flight Center specified parallel development of both brush-type motors and brushless motors. General Electric Company constructed brushless 1/4-horsepower motors utilizing Hall generators and the dual-winding concept. The brushless motor design for the Rover weighed 4.5 pounds compared with 6.5 pounds for the conventional motor. The brushless drive, as a consequence of its higher efficiency, also provided 40 percent greater travel distance from the batteries of the Rover. However, to shorten the development time and testing, it was finally decided to accept the weight penalty and additional complexity of using brush-type motors, hermetically sealed in nitrogen, and driving the wheels through a special harmonic drive system. The same type of brushless motor developed for the Lunar Roving Vehicle is now being tested by Lockheed for use in advanced electric vehicles and off-road emergency equipment.

In the small motor field, cost was the major barrier to the wider use of brushless motors. Several technical developments outside the motor field helped make lower cost motors practical. By 1967, thin film silicon Hall effect devices replaced the larger and more expensive earlier Hall bulk generators, but the silicon sensors had even lower sensitivity and output, thus needing amplification. Improved ceramic magnets and the introduction

of high performance rare-earth magnets made possible smaller, cheaper, and more powerful permanent magnet motors of all types. Typical commercial brushless motors are shown in Figure 2, together with variable speed controls.

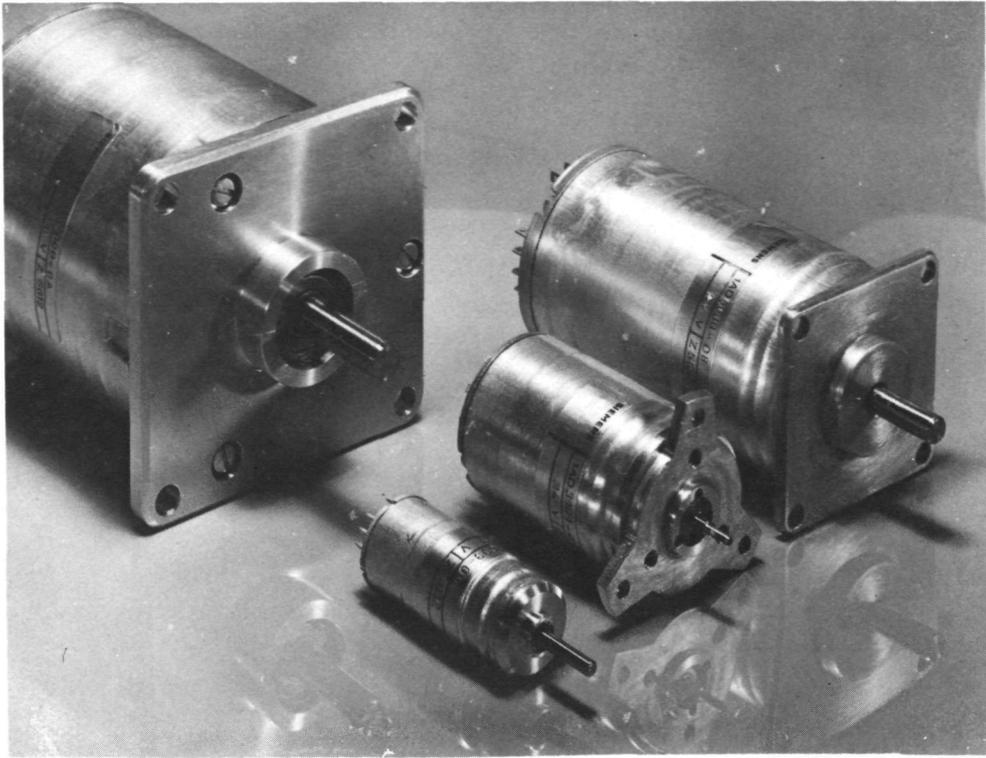
Widespread use of integrated circuits drastically reduced the cost of the circuitry used for amplification, commutation, and control logic. Phillips Electronics in Holland brought all of these diverse technologies together in 1972 with the introduction of tiny circuit chips containing the silicon Hall sensor and the associated transistorized amplifier and control logic. These chips are mounted directly inside the motor case for portable, low-cost, battery-operated tape recorders. For this type of application, these motors provide constant-speed, positive high-torque tape drive, substantially increased battery operating time, and three electrically-switchable tape speeds.

D. Fast Response

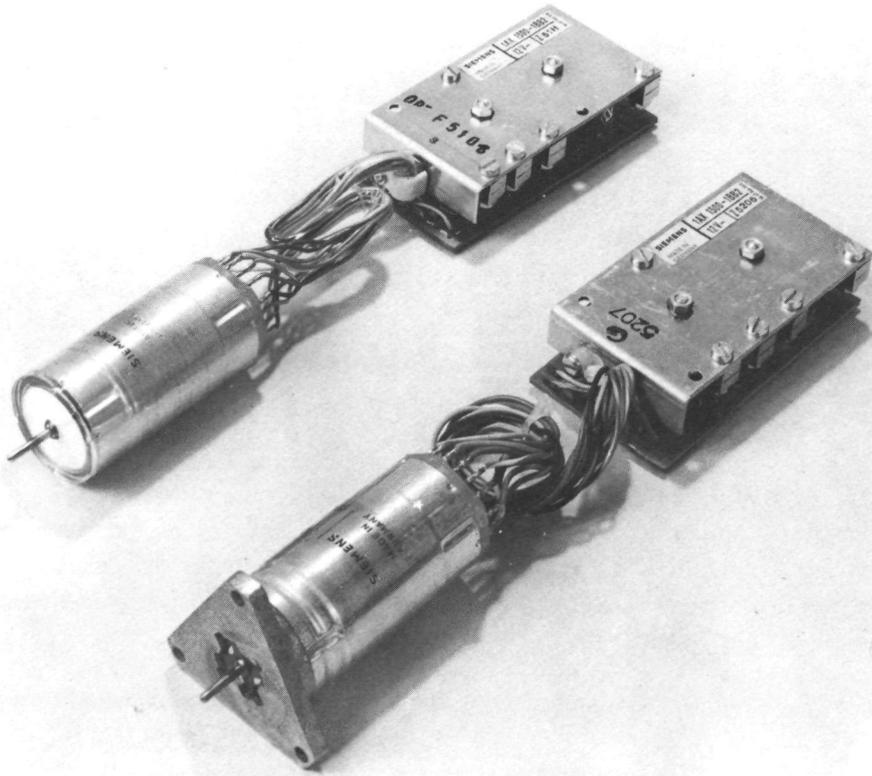
One of the less obvious advantages of brushless motor design is exceedingly fast motor response. Reducing the inertia of the armature by using small-diameter, high-performance magnetic rotors permits high acceleration rates. Employing the stationary "ironless armature" concept provides even faster response, smooth servo characteristics, and a 10-fold reduction in rotational losses. The need for just these characteristics in computer peripherals such as tape drives, disc-packs, and line printers, has largely been responsible for the revival of interest in the ironless motor concept.

New phonograph turntables powered with brushless direct-drive motors, have been recently introduced by several manufacturers. The requirements for phonograph motors provides an illustration of the indirect and not always obvious advantages that frequently determine success in bringing new technology into the commercial marketplace. For many years, the finest transcription turntables used a constant-speed synchronous motor with a belt speed reducer to rotate the turntable. Over the past 5 years, brushless DC motor drives were introduced by European and Japanese producers of portable tape recorders which had to operate from battery power. Figure 3 shows a typical turntable motor and speed control. More recently, the advantages provided by DC servo control drives have become important in high quality audio equipment operated from line power. This type of drive motor permitted precise speed regulation independent of variations in the local line frequency or voltage.

Continued refinement and use of these phonograph drives soon disclosed even greater advantages. First, the speed constancy was substantially better than could be obtained with the finest synchronous motor. The DC



Hall Effect Brushless DC Motors - Size 5 to Size 35



Brushless DC Servo Control Motors and Control Units

Figure 2

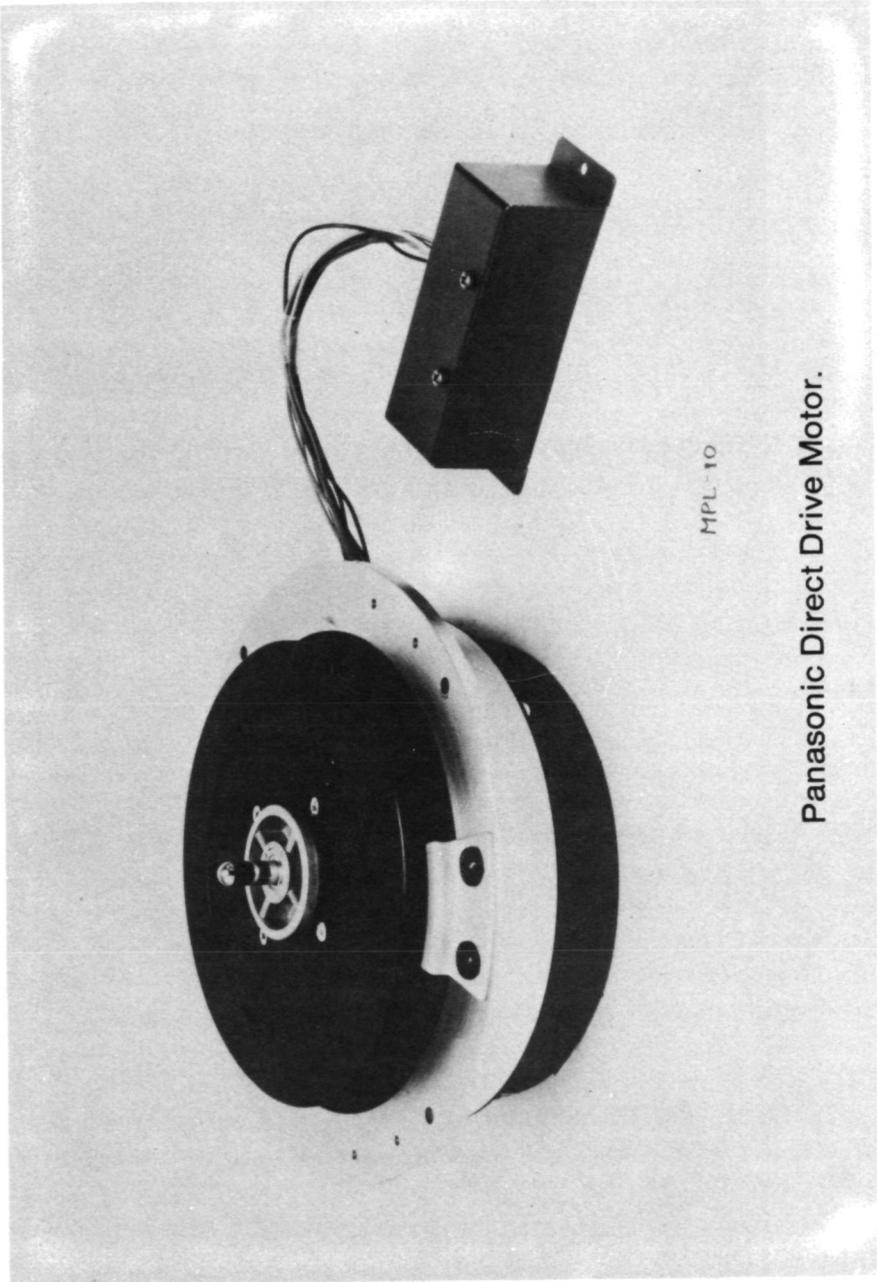


Figure 3

motor provides continuous instantaneous speed regulation, whereas the synchronous motor provides constant average speed but is subject to momentary speed variations called "flutter." Second, the DC motor made direct low-speed drive practical. Troublesome and noisy speed reducers could be completely eliminated, and the motor shaft could become the phonograph spindle driving the turntable directly at the required record speed. Typically, no part of the motor or the driven mechanism turns faster than 1/2 revolution per second, so that virtually all vibrations are confined to sub-audible frequencies. The net result is that DC phonograph drives provide accurate reproduction with less unwanted noise and distortion. New standards of performance have been set by these drive systems that provide significant reductions in rumble, flutter, and wow, while delivering unmatched speed regulation and long-term reliability.

III. Space Requirements and Contributions

Motor requirements for any space application are stringent, frequently straining the known limits of performance. When the first portable life support system was designed for the Apollo astronauts, small extremely efficient fan and pump motors were needed to circulate oxygen and cooling water through the space suits. During the 4 years before the first lunar landing, three times as much equipment would somehow have to be fitted into the backpack without increasing its dimensions. The brushless motors used on the lunar surface provided the same performance, but were reduced to half of the original size and weight. Planetary probes required motors that would keep antennas accurately pointed for several years, draw minimum power, and respond to tiny command signals.

Table 1 summarizes major performance requirements for brushless motors used in space. Certain parameters were more critical for manned missions, while other requirements were essential for satellites.

Contributions to motor design and drive system technology stemming from various NASA programs have taken three main forms:

- . Demonstration of the capabilities and advantages of improved DC motor drives at an early date--about 5 or 6 years before commercial grade motors with similar characteristics were needed.
- . Numerous technical advances were developed and thoroughly evaluated. Significant innovations were achieved in key areas of motor efficiency, simplified servo control, fast response rate, and direct, low-speed drive systems. The range of technical contributions is indicated in Table 2.

TABLE 1

BRUSHLESS DC MOTORS

MANNED SPACECRAFT ECS AND PLS MOTORS

- RELIABILITY
- NON-SPARKING
- HIGH STARTING TORQUE
- NO RFI
- HIGH EFFICIENCY (55 - 75%)/LIGHT WEIGHT
- SMALL SIZE

OTHER SPACE SYSTEMS (REACTION WHEELS, ANTENNA POINTING OTHER
ON-BOARD DRIVES, AND LUNAR ROVER)

- LONG LIFE
- NO BRUSH SEIZURE OR WEAR
- REMOTE POSITION OR SPEED SENSING AND CONTROL
- DIRECT (LOW SPEED) DRIVE
- HIGH EFFICIENCY
- SMALL CONTROL SIGNAL
- HIGH POWER/WEIGHT
- THERMAL RESISTANCE
- FAST RESPONSE RATE/ACCELERATION

TABLE 2

BRUSHLESS DC MOTORS

<u>REQUIREMENTS</u>	<u>SPACE PROGRAM CONTRIBUTIONS</u>	<u>ADVANCES</u>
COMMUTATION	● SATELLITE PLSS/ECS	PHOTO-DIODE MAGNETORESISTOR RELUCTANCE SWITCH OFFSET TOOTH LOGIC CONTROL
SIZE/WEIGHT	● PLSS	40% REDUCTION
SPEED/POSITION TORQUE CONTROL	● ORBITING SATELLITES	BRUSHLESS TACH DUAL RANGE TORQUE SIMPLIFIED SERVO LOW CONTROL INPUT ϕ LOCK OSCILLATORS
ENVIRONMENTAL RESISTANCE	● PLANETARY PROBES	SEALED MOTORS HEAT STERILIZABLE RADIATION RESISTANT
RELIABILITY LIFE	● ALL	FAILURE MODE ANALYSIS BEARINGS, LUBRICATION TEST & DEMONSTRATION 95% +, GUARANTEED 10,000 HOURS
EFFICIENCY	● SATELLITES PLSS/ECS	FIELD WINDINGS POLE SHAPING MAGNETIC MATERIALS 45% UP TO 80%
LOW RFI LOW NOISE		LOW RIPPLE MAGNETIC BEARINGS SOLID STATE SWITCHING
HIGH HORSEPOWER	● ROVER, SATELLITES	Δ -WOUND, 6-SWITCH DIRECT DRIVE DYNAMIC BRAKING
HIGH ACCELERATION FAST RESPONSE RATE	● STABLE PLATFORMS	LOW INERTIA ROTOR IRONLESS MOTORS

- . Disseminating the technology. Widespread and prompt publication of the accumulated aerospace experience influenced later technical trends. Performance advantages that could be attained became recognized. Techniques and designs that provided predictable performance were available. Many of the engineers and contractors active in space programs throughout the 1960's would also design and produce commercial motor systems needed in the 1970's.

IV. Significance and Impact

As a result of the momentum provided by motor developments to meet space requirements, brushless drive technology was remarkably developed by 1968. However, commercial markets of consequence were not available. Over the next 5 years, there would be major changes in the requirements for commercial grade precision motors.

Before new knowledge can have significant economic and social impact, three things are essential:

- . The required technology must be available.
- . Market needs must be accurately perceived.
- . The technology must be adapted to suit individual applications.

Quite typically, the first nonspace uses for brushless DC motors were rather sophisticated, and primarily limited to critical applications where relatively costly drive systems could be justified. Among early uses were:

- . Numeric Control Milling Machines. High-power, high-speed drive (120 inches per minute), with accurate tool positioning in point-to-point N/C machine tools.
- . Control actuators in Direct Digital Control systems for chemical plants and refineries.
- . Pump drives and fast-acting controls for nuclear power reactor systems.
- . High voltage DC torpedo drives.
- . N/C contouring machines. Low speed during machining, with fast traverse, and high rate stop-start cycles.

The process of engineering high-performance, high-reliability motor controls inevitably created diversity--different varieties of motor designs, many types of electronic control circuits, different modes of operation--with each system adapted to fit the special requirements for each particular application. Specialization also made it practical to produce motors providing one or more of the performance advantages of earlier brushless drive systems, without all of the features that increased cost. In the special purpose motors that evolved, many of the former distinctions among DC and AC, or brushless, permanent magnet or induction motors became obscured. This growing ambiguity is typical as new technology diffuses into new forms and novel applications.

The development and use of brushless drive equipment entered a tumultuous phase about 1967. Two factors are responsible for the confusion that exists in related fields since that time: (1) an enormous increase in the extent of digital control in all fields, and (2) the almost spontaneous emergence of magnetic stepping motors as versatile, low-cost drive and positioning motors. Some of the confusion derives from the terminology used. Magnetic steppers are true motors that provide discrete, incremental rotation in response to DC pulses--one pulse advances the rotor exactly one step. These stepper motors are known by a variety of names. They are called step servomotors since they are generally used in servomechanisms; brushless DC motors since they are constructed without brushes and driven by pulsed DC; incremental step motors since the shaft increments through some discrete angle for each pulse.

The technology of magnetic stepper motor design and use evolved quite differently from that of brushless DC motors. The basic elements had been developed years before--during World War II and the mid-1950's. But, applications for stepping motors were relatively few and the available steppers were chiefly regarded as drives for rotary switches, rather than as true motors. Without much fanfare, during the 1960's, the stepping motor was radically improved, and emerged as whole families of drive system components--competing in many cases with the brushless DC motor. Today it is difficult to draw clear distinctions between the permanent magnet or variable reluctance types of stepper motors and electronically commutated DC motors.

The history of magnetic stepping motors was neglected and obscured in the furor of commercial activity in the mid-1960's. A skeleton bibliography tracing the major trends of theoretical development and application is presented in the chronology sections. Primarily, these references show the slow development of basic devices prior to 1962, followed by frantic exploration of applications from the mid-1960's through 1970, and more orderly and solid growth since that time.

The spectacular growth of computer peripheral equipment began about 1968. These data storage units, and input-output devices make the data processing world go around. Floppy-disckey registers are rapidly displacing card punch for data entry. Disc-packs, line printers, optical character readers, and tape cassettes are linked to every large central data processing unit. Since 1970, these computer accessories--each requiring one or more precision motors--have been increasing at 25 percent per year. Peripherals shipped separately totaled \$4.6 billion in 1973, up from \$800 million in 1967.

Small, fast-responding, and above all, reliable motors must be used to power computer accessories. Constant speed regulation is a requirement for disc and drum data storage units, while high-starting torque and fast start-stop action is needed for line printers. Key-to-disc registers need motors capable of scanning the entire disc in 30 milliseconds. Because electronically controlled brushless motors provide the entire range of features needed, about half of all brushless torque motors, servomotors, timing motors, and stepping motors produced today are used in computer peripherals.

Medical equipment requiring special motor characteristics is becoming a significant market for brushless motors. Power actuated artificial limbs need quiet, powerful, small motors that operate from compact battery packs. Blood pumps used in surgery, or for artificial kidney machines, need accurate flow control with pump rates that can be continuously adjusted over a 20-fold range. The inherent capability of brushless motors to provide slow speed, direct drive, and logic or computer controlled pumping speed, dictated their use. Brushless motor control also eliminates sparking.

The introduction of textured and patterned double-knit fabrics greatly stimulated the market for precision, pulse-controlled motors in textile machinery. The fast response of permanent magnet DC logic-controlled motors made brushless stepper motors a logical choice for intricate textile processing machines.

Modern cameras now use DC motors to drive the film transport and synchronize shutter motion, as well as automatically setting the iris and providing power zoom-lens drive. The Maurer camera used on the lunar surface was virtually designed around the capabilities of size 8 brushless permanent magnet motors. A similar model is currently in production for use by the serious amateur movie maker.

In fact, many of today's fastest growing applications for small motors turn out to have performance and reliability requirements similar in many respects to those for space systems. Figure 4 shows major current uses, and indicates the primary characteristics that must be satisfied.

REQUIREMENTS	APPLICATIONS											
	COMPUTER PERIPHERALS	MEDICAL EQUIPMENT	PHONOGRAPH TURNTABLES	AUTOMOTIVE WINDSHIELD WIPERS	ELECTRONICS-COOLING FANS & BLOWERS	VACUUM OR HIGH ALTITUDE AIR & WATER POLLUTION SAMPLING	PIPELINE CONTROLS	TAPE RECORDER DRIVES	NUCLEAR REACTOR CONTROLS			
RELIABILITY, LONG LIFE	•	•		•	•	•	•	•	•			
NO MAINTENANCE	•											
HIGH STARTING TORQUE	•											
CONSTANT SPEED/TORQUE DIRECT (LOW SPEED) DRIVE	•	•	•						•	•		
ADJUSTABLE SPEED, WIDE SPEED RANGE		•	•	•					•	•		
NON-SPARKING		•										
SMALL SIZE/LIGHT WEIGHT					•	•	•					
HIGH EFFICIENCY				•	•				•	•		
LOW RFI	•											
REMOTE SPEED & POSITION SENSING & CONTROL	•									•		
RESIST EXTREMES OF TEMPERATURE, RADIATION											•	•
FAST RESPONSE TIME	•											•
LOW VIBRATION & NOISE												•

Figure 4 - Brushless DC Motor Applications/Requirements

Increased use of integrated circuits reduced the cost of solid state motor control to a fraction of the previous price. Control units that were formerly separate, could be built directly into the motor. Feedback control of speed or position, once restricted to aircraft and special industrial drives, could be widely used. Progress in electronics and control logic has drastically reduced the cost of brushless DC motors. Today, brushless drives range in cost from several hundred dollars for more powerful motors with sophisticated controls, down to \$8 for a basic model. Innovations in design and motor manufacturing have made possible increasing use of brushless drives in less critical applications.

The automotive market is a growing user of long-lasting, maintenance-free brushless motors. Several European auto makers use \$10 brushless motors to drive windshield wipers because they permit full power, continuously adjustable speed control, and have a life expectancy of 20 years. Quiet operation, high torque and reliability makes the brushless motor ideally suited for power windows.

The motor and generator industry is experiencing the impact of changing demand for DC motors. The number of small DC motors made in the U.S. has increased sixfold since 1963. Motor cost has been cut in half. Despite reduced prices, total sales have been growing at 13 percent annually. Shipments of all DC motors in 1972 were up 28 percent over sales the previous year. Figure 5 shows the rapid increase in motor demand over the past few years.

Domestic producers of precision motors compete with a number of foreign manufacturers who have been especially adept at devising lower-priced brushless DC motors. Perhaps even more important than technical development, West German and Japanese firms have exploited large volume applications that need the very features provided by brushless operation--constant speed, quiet running, direct low-speed drive, long-life, and precise variable speed control. Imports of fractional horsepower motors by the U.S., has for several years exceeded exports. In 1972, U.S. imports for consumption were \$40.5 million versus \$25 million in exports. Japan, West Germany and the United Kingdom are the principle foreign suppliers.

The ultimate impact of the development of high performance brushless motor drives cannot yet be predicted. Since brushless DC motors and several types of magnetic stepping motors can be used for the same general applications, it is difficult to separately define the various markets for each class of actuators and drives. Worldwide, over 50 firms manufacture brushless devices, with some 30 suppliers in the United States.

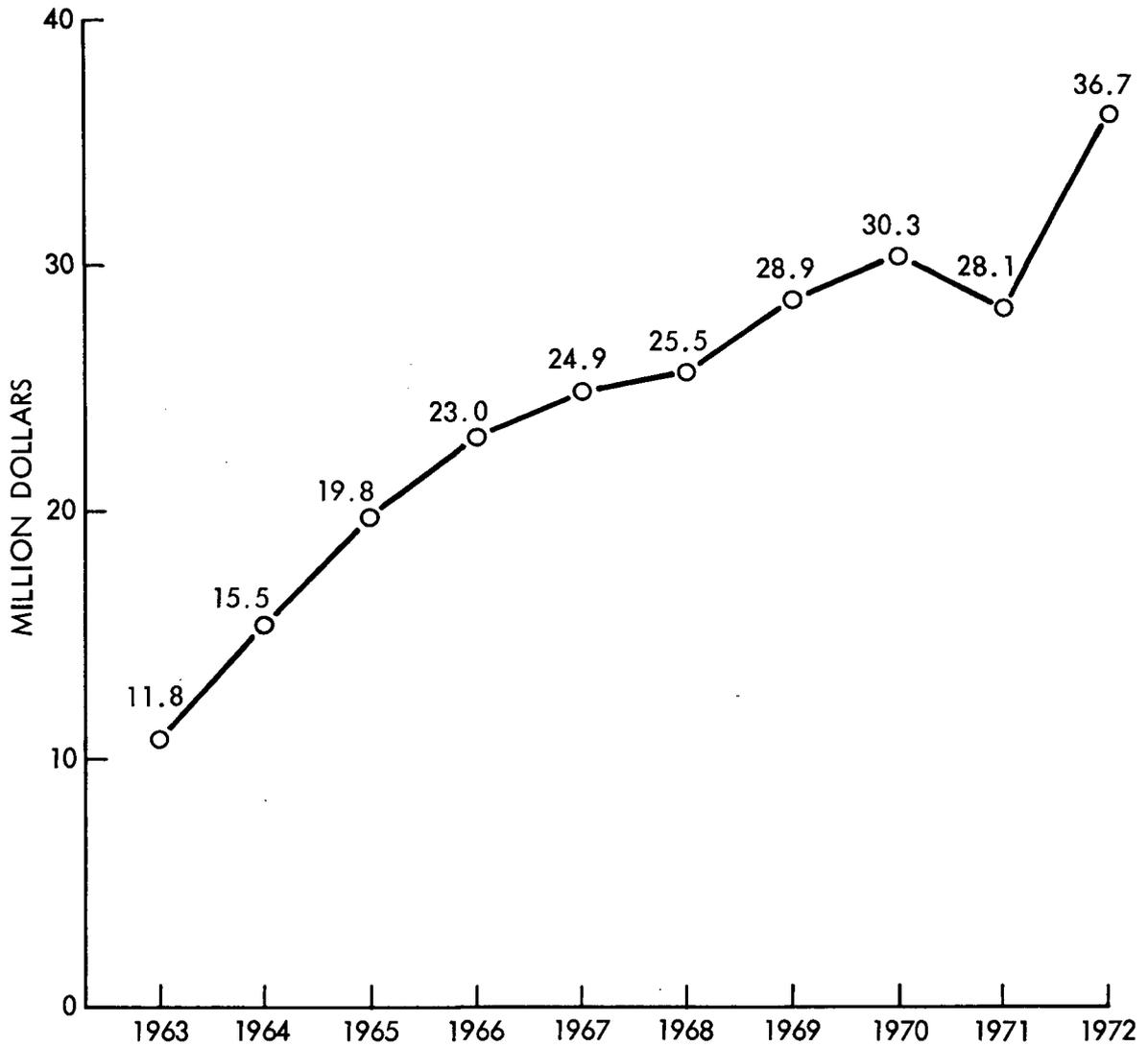


Figure 5 - Value of Shipments - Direct Current Motors Less Than 1/20 H.P.

Source: Current Industrial Reports, "Motors and Generators," MA-36H.

The U.S. market currently requires over 100,000 units of continuous rotation brushless DC motors. Shipments are estimated to have a value of \$1.8 to \$2.5 million in 1973; and growth rate exceeds 25 percent annually. In addition, more than 65,000 units are used as brushless DC torque motors, limited rotation torque devices, servo units, timers and brushless tachometer generators. The market for small magnetic stepper motors has now grown to be much larger than that for position sensing brushless DC motors. Table 3 presents an approximation of the share of markets for several types of brushless motors and related brushless devices, including the necessary logic and control units. Permanent magnet stepper motors regulated by pulsed DC logic drives now represent over 70 percent of the magnetic stepper market in the United States. Variable reluctance type stepper motors have a smaller market, but are expected to post more rapid growth over the next few years.

An application survey conducted by the world's largest producer of true brushless DC motors (Hall effect position sensor type), forecasts a total world market of \$50 million for all types of brushless motors by 1978. The market in the United States by then, will probably range from \$12 to \$15 million.

At present, brushless DC motors and precision brushless stepper motors represent the most dynamic segment of the motor industry. A little over 10 years ago, brushless DC motors didn't exist in a practical form. Continued stimulus to solve space problems and extend motor capabilities has made available a new range of motors and related devices that are proving their value in both industrial and consumer products.

TABLE 3

DOMESTIC MARKET DEMAND FOR BRUSHLESS DEVICES
ESTIMATED VALUE OF SHIPMENTS
(Millions of dollars)

	<u>1973</u>	<u>1978</u>
Brushless DC Motors, 360°, position sensing	\$2.5	\$6.3
Brushless DC Torque Motors	0.7	3.7
Brushless Torquers, Limited rotation	0.5	2.5
Brushless Tachometers	0.3	1.5
Permanent Magnet Stepper Motors	26.0	45.0
Variable Reluctance Stepper Motors	<u>6.0</u>	<u>14.0</u>
Total	\$36.0	\$73.0

Principal Suppliers of Brushless DC Motors

AEG-Telefunken
Aeroflex Laboratories, Inc.
Astro Dynamics, Inc.
Barber-Colman Co.
Brailsford and Co., Inc.
Computer Devices Corp.
Cramer Division, Conrac Corp.
Fujitsu, Ltd.
Globe Industries Division, TRW Inc.
Haydon Switch and Instruments, Inc.
Hitachi America Ltd.
IMC Magnetics Corp.
Inland Motor Co.
Kearfott Products Division,
 General Precision, Inc.
 Singer Co.
Lamb Electric Division, Ametek, Inc.
Lear Siegler, Inc.
Magnedyne Corp.
Magnetic Technology, Inc.
Philips (Netherlands)
Siemens Corp.
Sigma Instruments
Sperry Marine Systems Division
 Sperry Rand Corp.
Toshiba America, Inc.
Varo, Inc.
Vernitron Corp.
Wright Division, Sperry Rand Corp.

CHRONOLOGY

EARLY DC AND AC GENERATORS AND MOTORS

- 1878: Thomas A. Edison invented the bi-polar DC generator which raised generator efficiency from 50 percent to the then unheard of 90 percent.
- 1882: First central station power generation in the U.S. Edison's Pearl Street Station initiated service to 59 customers.
- 1883: Edison 3-wire 240 volt DC distribution system adopted. Early generators used brushes of strap copper and copper mesh; sufficient sparking occurred to burn commutator bars and brushes badly.
- 1885: William Stanley, Westinghouse engineer, developed the first commercial AC generator design.
- 1886: George Westinghouse obtained U.S. patent rights to the induction transformer developed in Europe by Gaulard and Gibbs. Stanley modified the design creating the first practical transformer.
- 1886: First laboratory demonstration of AC generating system using transformers. Stanley built six transformers and used Siemens generator imported from Europe to light offices in Great Barrington, Mass. Line length was 4,000 feet.
- 1886: First commercial AC generating station in the U.S., Niagara generators built by Westinghouse started operation November 30, 1886.
- 1888: The carbon brush introduced by Depole greatly reduced sparking and commutator wear.
- 1888: AC induction motor invented by Nikola Tesla. Only DC motors were previously available.
- 1896: Internal equalizer developed by Lamme made very large AC generators possible.
- 1898: As transmission distances increased, direct current was largely displaced by AC, except for large traction motors, for which DC motor characteristics are more favorable.
- 1900: First turbine alternator in U.S. at Hartford, Connecticut. World-wide attention given to this plant influenced subsequent designs.

- 1903: The first large steam turbine driven AC generator in U.S. was installed in Chicago.
- 1926: The Chicago system had an interconnected capacity of 1 million kilowatts, and extended over an area of 10,000 square miles.

CHRONOLOGY

EVOLUTION OF BRUSHLESS DC MOTORS

- 1940's: Rapid brush wear and failure of rotating equipment was first observed during high level bombing of Japan. U.S.A.F. worked on reliable brushes from 1947 to 1958.
- 1950's: Alnico V magnet alloys; Alnico VI and others followed.
- 1954-
1956: H. D. Brailsford, developed "hybrid" DC motor; P.M. rotor with spring contacts which trigger transistors for starting, then fly out and permit true brushless running.
- 1958-
■ 1959: Early sounding rockets and missile development showed that operating life of DC brush motors in vacuum was limited to a few minutes.
- 1959: Adams and Chilton (NASA/Langley), "Attitude Controls for Satellites, A Weight Comparison of Several Methods." Analysis concluded that a brushless motor drive was most suitable. NASA Memorandum 12-30-58L, Langley Research Center, February (1959).
- 1960: M. B. Pickover, "Transistorized Motor Speed Control for Satellite Tape Recorders," Proc. IRE, 48, 725-8 (April 1960).
- 1961: H. E. Stockman (Lowell Technical Institute). Tunnel diode motor patented for use as clock drive for educational purposes.
- 1961: Ratajski (Kearfott), "Brushless and Windingless Components." Discussion of recent advances in Hall effect sensors and magnetoresistive devices for possible use in brushless rotating machinery. Two laboratory model motors were built and tested, but power handling capacity was limited by the available Hall generators. The author commented: "For several years, the development of reliable and small brushless DC motors, with true DC motor characteristics, has been a goal of many motor manufacturers. It is also a top requirement for military systems, where noiseless operation with long life is a necessity. A brushless DC motor is the drive most suitable for inertial wheel systems to control satellites in space since they are supplied directly from solar batteries." Military System Design 4-9 (November-December 1961).

- 1962: P. H. Trickey, et al. (Duke University). Developed a solid state commutator for DC motor. Trickey joined Wright Machinery Division of Sperry Rand. Much of the work at Duke was performed under grants from NASA/GSFC.

- 1962: Phillip Studer (Goddard). In a program started to eliminate unreliable sliding electronic contacts, extensive search for brushless motors was conducted. Only one U.S. manufacturer had an operating experimental "breadboard" model.

- 1962: G. Bauerlein (Kearfott). Used 12 Hall effect diodes in an experimental brushless DC motor having transistor switches and power amplifier. Gave 2 in-oz torque and 3 percent efficiency. IRE conference, 1962.

- 1963: Lamb Electric (Division of Ametek). Developed "Komlectro" for air sampling balloons used by U.S.A.F. to monitor airborne radiation.

- 1963-
- 1964: R. D. Kincer, Roy Hill and R. C. Rakes (Sperry-Farragut/G.S.F.C.). Initial development of flight-grade brushless DC motor using photo sensor commutation. Had six sensors and six coil windings. Advantages: self-starting; lamp life more than 40 years; rugged, vibration resistant; 95 percent reliable for more than 1 year in vacuum. NASA TND-2108, 1964.

- 1963: Goddard Space Flight Center. Goddard sought source for motor for satellite array drive. Received four or five serious responses. Aeroflex, Sperry, Westinghouse, etc. Westinghouse contract started.

- 1964-
- 1966: W. W. Yates (Westinghouse). Brushless DC torque motor having characteristics similar to a conventional PM torque motor, but designed for vacuum operation. Used three-phase windings and a reluctance switch. Torque ripple and cogging problems. NASA-CR-374.

- 1964: J. M. Welch and W. M. Cassaday (Sperry). Development of Reaction Wheel brushless DC motor drive. The old "ironless motor" concept was applied to create a 7-pole pair torque wheel drive in which the armature rotor contributes an insignificant portion of the required inertia. Extra windings were included for higher efficiency. The electronic commutation circuit was modified to perform current limiting without requiring a series limiter. Regenerative braking was incorporated to conserve power. Bi-directional control requires only a few milliwatts of power. NASA-CR-388 and NASA-CR-58775. WESCON Technical Papers 1965 session 5.

- 1964-
- 1970: P. Studer (G.S.F.C.). Brushless motor having 65 percent efficiency providing 0.25 in-oz at 3,000 rpm on 1 Watt, stall torque of 3.25 in-oz and fast time response. Reliability 94.4 percent for 1 year. Sealed design to protect windings. Ran 6 years, 7 months in hard vacuum. NASA-TND-2819.
 - 1965: Cassaday (Sperry) and Studer (G.S.F.C.). WESCON report of development of low-cost brushless motor with closed loop feedback speed control. Eliminates need for separate control pre-amp and power amplifier. (Similar to later Siemens motor.) Motor has now run 7 years in lab atmosphere.
 - 1965: Sperry Farragut. Final Report: Development of sealed brushless DC Motor. Five motors being readied for U.S.A.F. OV-113 to be launched March 1967. NASA-CR-231. May 1965.
- 1964-
- 1965: Marshall Space Flight Center/Saturns IV and V. Coolant pump on Saturn launch vehicle driven by 1/2-hp brushless motor using photo chopped commutation. 75 percent efficient. Motor ran with cavity flooded with alcohol-water coolant.
- 1965-
- 1966: Matrix Research and Development Corporation. G.S.F.C. contract to develop noncontacting rotary power transformer to replace slip rings in satellite electrical system. Needed as part of integrated peak-power transfer circuit. NASA-CR-76932.
- 1965-
- 1969: Hamilton-Standard/M.S.C. Oxygen circulating blower for lunar module life support system. Sperry medium-power brushless DC motor: 2 in-oz at 13,000 rpm; 65 percent efficiency. Reliability 99.9 percent for 100-hour mission.
- 1965-
- 1969: Westinghouse-G.S.F.C. Advanced Brushless DC Motor. Combined three components: pointing accuracy ± 1 degree.
 - Brushless DC torque motor
 - Rotary power transformer
 - Offset-tooth sensor
 Performance similar to Microsyn, but 360 degrees rotation.
- 1965-
- 1969: C. Lovell (Hamilton-Standard). Selection and testing of brushless DC motors for PLSS. Reliability, size, and efficiency required pushed the design art considerably.

- 1966: Honeywell. Patent on silicon Hall effect sensor plus amplifier on a single chip. Independent precursor of Phillips IC chip.
- 1966: Janonis (Lear Siegler). High Voltage DC Brushless Torpedo Propulsion Motor. Used 6 static switches and 3-phase thyrestor bridge to drive a 6,500-volt Lundell type brushless DC motor.
- 1967: Aeroflex/G.S.F.C. New "variable field" brushless DC motor developed by Aeroflex Laboratories.
- 1967: A.E.G. (West Germany). Introduced electronically controlled brushless DC motor using one diode per winding coil, and bridge balance principle.
- 1967: Ante Lujic (Cramer/Conrac). "Inside-out" brushless DC motor using solid state commutation holds set speed ± 0.5 percent for tape recorders and phonographs. (Similar to AEG motor for U.S. market.)
- 1967: G. E. Burton (Royal Aircraft Est.). Oscillator switch commutation converts commercial stepper motor to reliable bi-directional brushless DC motor.
- 1967: G.S.F.C. Studies on ripple reduction. Using photo-diodes and multiphase windings, Delta wound. Switching transistors are a problem. Goddard used fully saturated transistors, with magnet shaping to get constant, low ripple torque.
- 1967: Siemens Electric. Introduced servo controlled tape recorder sold in U.S. for \$100. Motor and speed control package available separately at \$25 O.E.M. Dittrick and Rainer in Siemens Review, 35, 97-99, March 1967.
- 1968-
- 1970: Cambridge Thermionic Corporation. NASA-CR-115793. Magnetically suspended rotor for 24-V brushless DC motor. Purpose to eliminate bearings. Cambion DC suspension system.
- 1968: S. Greenblatt (Bose Corp.). High Efficiency Induction Motor Amplifier. DC to AC inverters of three types.
- Base band inverter
 - Cycloconverter
 - Pulse modulator
- NASA-CR-86128.
- 1968-
- 1969: H.C. Rotors Associates, Inc. Logic controlled brushless DC motor for J.P.L. Closed loop control with 55 percent efficiency in a continual run or stepping mode from pulsed inputs. NASA-CR-104086.

- 1968-
- 1969: R.D. Jesse (Westinghouse). Brushless Direct-Drive System. Controller for Brushless Array Drive provides automatic control of array on command with automatic tracking. Solved problems of sensor output equality, pulse width and torque variations. NASA-CR-113909.
- 1969: Slabiak and Collins (U.S. Army/Delco). Brushless electric motor designed for heavy-duty vehicles. SAE Jour. 46-51, (May 1969).
- 1969: E. Bohm (J.P.L.). Simplified design of Brushless DC Motor without excessive electronic circuitry.
 - High efficiency
 - Lower temperature
 NASA-CR-106071
- 1969-
- 1970: Manteuffel and Hertzendorf (General Electric). Brushless motor having split windings which can be connected to give full windings or 1/4 windings for low torque, high speed; or high torque, low speed. NASA-CR-102675, NASA-CR-102942. Advantages compared to conventional high performance brush type motor of same weight and power:
 - infinite life
 - 10 to 1 reliability
 - 4 to 1 lower friction
 - 3 to 1 lower rotor inertia
 - fewer ripple cycles per revolution
 - improved heat removal from windings
- 1970: Toshiba (Japan). Low cost brushless DC tape recorder drive, constant speed over 8-V to 12-V range, speed selection over 10:1 range, guaranteed service life of 8,000 hours, inductive sense coils driven by oscillator, switched by three-sector metal disc on rotor.
- 1970: Wm. P. Lear (Lear Enterprises, Inc.). Announced availability of 1/2-hp; 120-V brushless motor lower in cost than a brush type DC motor. Foresees sizes up to 200 hp.
- 1970-
- 1972: Seminski, et al. (General Electric). Development of high torque rotary actuator with roller-gear drive. Used samarium-cobalt magnets
 - low backlash
 - low torque ripple
 - high stiffness
 NASA-CR-103057 (1971), NASA-CR-122458 (1974).

- 1970-
- 1972: R. L. Presley (Bendix). High reliability rotary actuator for space use. Space qualified 150-ft-lb torque actuator based on Bendix Dynavector drive. Innovations:
 - high ratio (818:1) actuator
 - reliable proximity switch to eliminate optics
 NASA-CR-122470.
 - 1971: P. Studer (G.S.F.C.). Magnetic bearing patent, stationary field, stationary armature windings, to drive rotor which is magnetically suspended. U.S. Pat. 3,694,041, September 26, 1972.
 - 1971: R. L. Fisher (Sperry Rand). Ironless Armature Torque Motor, used samarium-cobalt permanent magnets and three-phase winding in a stationary ironless armature, weight 1.5 lb., 4-in. diameter, developed 65 in-oz. Voltage waveform not as desired. NASA-CR-130224.
 - 1971: G. L. Ward (Washington Technological Associates). Motor control package for brushless DC motors. Used three-phase, Delta wound design with lamps and photocells. All electronics on hybrid flat packs, including the control amplifier and driver circuits. NASA-CR-121498.
 - 1971: Broadbent (Martin-Denver). "Survey of Electrical Motors Used In Space," T-71-48890-004, December 1971.
 - 1972: Phillips Electronics (Eindhoven). Hall Effect motor with 6 n-p-n transistors, 7 resistors in amplifier circuit on a single IC chip. For use in low cost tape recorders. Electronic Engineering, January 1972, pp. 20-21.
- 1971-
- 1973: F. Nola (MSFC/G.E.) Lunar Roving Vehicle drive motors specified. Brush type and brushless motors developed in parallel. General Electric built brushless 1/4-hp Hall effect motor using dual winding concept. Brushless design weighed 4.5 pounds compared with 6.5 pounds for brush type. Provided 40 percent greater mileage, and did not need sealed atmosphere. Prime contractors elected to use the brush motor, sealed in 7.5 psi nitrogen.
 - 1972: Panasonic (Japan). After 2 years of experimentation, Panasonic introduced 24-pole direct-drive servo-controlled BDCM Phonograph turntable SP-10. Significantly lower rumble, wow and flutter than other motor drives.

- 1972: P. Studer (G.S.F.C.). "An Ironless Armature Brushless Torque Motor" in Significant Accomplishments in Technology 1972.
- 1972: Lyman, "DC Torque Motors Take Control." Electronic Products Magazine, (February 21, 1972) 29-33.
- 1973: W. M. Peacock, "In-Orbit Performance of the ITOS Improved Attitude Control System with Hall Generator Brushless Motor and Earth Splitting Technique." NASA-TM-X-66267, March 1973.
- 1973: United Audio (Dual). Introduction of direct-drive BDCM having 16 coils offset in two-layer field winding of Dual 701 phonograph turntable. Electronic feedback speed control provides instantaneous regulation, reducing flutter and wow.

CHRONOLOGY

DEVELOPMENT AND APPLICATION OF MAGNETIC STEPPING MOTORS

1920-

1950: The idea of an incremental drive is at least as old as the escapement wheel--still used in chronometrically regulated DC timing motors. Crude electrical steppers, built as demonstration units led to the development of stepping switches and simple rotary solenoids which have been in use for decades.

1930's: The first practical modern application of a stepping motor as a servomechanism with electrical input and a torque output appeared in the early 1930's, when the British Navy developed a remote positioning system for transmitting shaft rotations with a bi-directional stepping motor operated in conjunction with a mechanically driven step transmitter.

1940-

1945: The British stepper system was adapted by the U.S. Navy and widely used during World War II in Naval instrumentation.

1943-

1948: Rotary solenoids were applied in stepping drives to steer torpedoes under commands from a series pulse train. These early types of drives antedate the familiar AC servo and synchro feedback systems.

1948-

1960: Closed-loop servomechanisms were developed, and quickly took over because they offered clear advantages over stepper motors in size, speed, accuracy and resolution. They were self-synchronous in analog drives and avoided the tricky analog-to-digital conversion. Existing stepper motors were quietly refined, but there were no major innovations.

1950's: Ledex rotary solenoids, relatively slow (20-30 pulses per second) steppers for rotary switches and related applications. Output torques limited to a few inch-pounds.

1952: Sigma Instruments. Cyclonome introduced. Claimed to be the first practical two-wire stepping motor; this device anticipated by many years the time when integrated circuitry would permit application of equivalent devices to become widespread.

- 1958: Teller Company. "Digitork" stepping motor can operate at speeds up to 100,000 steps per minute at torques up to 3,000 inch-pounds. Motor was 14 inches in diameter by 28 inches long. Unit was pulsed by thyratrons and triggered by punched paper tape.
- 1959-
- 1963: With the space age, and the development of automatic digital techniques, the limitations of analog servo systems became apparent. Feedback became a burden. Stepping motors were developed primarily for the aerospace and military market. By 1965, "demilitarized" commercial models became available.
- 1963: Proctor, "Stepping Motors Move In." One of the earliest and most extensive reviews of new ways of using magnetic stepping motors. Emphasized the emerging applications for pulse driven motor speed and position control. Product Engineering, (February 4, 1963).
- 1964-
- 1968: More or less independently of the military and aerospace steppers, new classes of high speed, high-torque stepping motors were developed for the automation market. Some major innovations in stepper motor design and use were made as computer control and digital logic became more common.
- 1964: T. Goto (Japan), "Dynamic Characteristics of Three-Phase Step Motors"--used as digital control of machine tools. Electrical Engineering in Japan, 84, 81-92 (October 1964).
- 1964: Nishida and Mizuno (Fujitsu Ltd.), "Dynamic Performance of a Stepping Motor." The stepping motor had not been studied as a true motor, but primarily as an angular indexing device. Electrical Engineering in Japan, 84, 22-30 (September 1964).
- 1964: G.E. Burton (R.A.E./Farnborough), "Commutation Systems for Satellite Motors." Conference on Commutation in Rotating Machines. (London), (November 19-20, 1964).
- 1965: Baker (R.A.E./Farnborough), "A Velocity Controlled Servo System Using a Stepping Motor." Closed-loop servo applications are described.
- 1965: Kavanaugh and Perkins, "Timing and Stepping Motors." Machine Design, 102-105, (December 16, 1965).
- 1965: Fredriksen (IBM), "Closed-Loop Stepping Motor." Machine Design, 202, (September 16, 1965).

- 1966: Jirafe, "A Transistorized Pulsed Drive for a Stepping Motor." Bi-directional operation using bi-filiar windings and transistorized flip-flop drive. Electronic Engineering, (G.B.), 38, 316-21 (May 1966).
- 1966: IEEE Conference on Electrical Applications for Textile Machinery. (Atlanta), 87 pages, (April 14-15, 1966). Stepping motors for application in digital control of textile equipment.
- 1967: G.E. Burton (Royal Aircraft Establishment). Reported use of oscillator switch commutation to convert a commercial stepper motor to a reliable bi-directional brushless DC motor. The Engineer, (London), 224, 829-832 (December 22, 1967).
- 1967: Fredriksen (IBM), "Stepping Motors Come of Age." Electro Technology, 36-41 (November 1967).
- 1967: Hata and Takashima, "A Method of Positioning Using a DC Servomotor with Dual Mode Operation." Digital positioning system using high speed (slewing mode) advance, and slow-rate final positioning. J. Japan Assoc. Automation Control Engineers, 11, 485-92 (September 1967).
- 1968: Baty (Icon Corporation), "Open-Loop Numerical Control." ASTME Tech. Paper MS 68-166, "Recent Advances in Open-Loop Numerical Control." Also adapted in Instruments and Control Systems, 89-91 (August 1969).
- 1968: Janow (NASA), "Guidance and Control Components for Space Applications." National Electronics Conference, (December 1968). Described brushless DC motors, variable field brushless DC motors using optisyn position sensors.
- 1968: McNaught and Waloff (Sperry Gyroscope), "A Review of Stepper Motors and Recent Developments in High Response Units." Two developments have rekindled interest in stepper motors as drive units: (a) widespread adoption of digital control devices, (b) development of solid state logic circuits that provide higher switching rates and greater power. Recent development of small diameter multi-pole motors yield high performance. Instrument Practice, (G.B.), 315-22 (April 1968).
- 1968: Icon Corporation, "Guidelines for Specifying Stepping Positioning Systems."
- 1968: Singer Corporation (Kearfott Div.), "Technical Information for Engineers." Design guidelines for selection and application of magnetic stepper motors.

- 1968: S.S.L. Chang (University of New York/Stoney Brook), "An Analysis of the Stepping Motor--What It Can Do." Proceedings of National Electronics Conference, 36-41 (December 9-11, 1968).
- 1968: Robinson (NASA/Lewis) and Taft (University of New Hampshire), "A Dynamic Analysis of Magnetic Stepping Motors." IEEE Transaction on Industrial Electronics and Control Instrumentation. IECI-16(2): 111-125 (1969).
- 1969: Barlocher (Switzerland), "Drives With Stepping Motors: Applications, Properties and Operation." Introduction, review and discussions of stepper motor drives for the machine construction engineer. Schweiz. Tech. Z., 66, 457-76 (June 1969).
- 1970: IMC Magnetic Corporation, "Tormax Steppers and Controls."
- 1970: Superior Electric Company, "Slo-Syn Stepping Motors."
- 1970: Bianculli (RCA), "Stepper Motors Application and Selection." IEEE Spectrum, 25-29 (December 1970).
- 1970: Chiarella (A.W. Haydon), "Rotation By the Digits With Permanent-Magnet Stepper Motors." Machine Design, 84-87 (November 26, 1970).
- 1970: (Anon.) (England) "Uses of Stepper Motors." Description of available commercial types, drive systems and applications. Machine Design & Control, (G.B.), 8, 12-17 (September 1970).
- 1970: Noske and Croymans (Germany), "New Fast Stepping Motors." Fast response, low inertia, high-rate motors for machine drives. Steuerungstechnik, (Germany), 3, 328-31 (October 1970).
- 1971: Arthur D. Little, Inc. Reported sales of stepping motors in 1970 were about \$20 million, and growing 15 to 20 percent per year. Much of the increase will result from expansion into new areas, especially N/C tools. Over 90 percent of the Japanese N/C machinery being produced employs stepping motor drives.
- 1971: (Anon.) "Stepping Motor Survey." Instruments and Control Systems, 87-93 (September 1971).
- 1972: Sigma Instruments, "Products for the Digital Control of Position and Speed."
- 1973: Beling and Morin (Sigma), "Permanent Magnet Stepping Motors." Instruments and Control Systems, Part I, Performance Factors, 53-55 (January 1973); Part II, Drives, 60-65 (February 1973).

CHRONOLOGY

SEMICONDUCTORS, RECTIFIERS AND HALL GENERATORS

- 1879: E. H. Hall, discovery of Hall effect. American J. Math., 2, 287 (1879).
- 1948: Torrey and Whitmer, "Crystal Rectifiers," McGraw (1948).
- 1948: Bardeen and Bratain (BTL), Discovery of the point-contact transistor "The Transistor, a Semiconducting Triode," Phys. Rev., 74, 230-231 (1948).
- 1951: "Junction Transistor Developed by BTL," Tele-Tech., 10, 66 (August 1951).
- 1952: "G. E. Predicts That Germanium (transistors) will Miniaturize Electronic Components," Prod. Eng., 23, 179 (March 1952).
- 1953: First point-contact photo-transistors tested in long-distance dialing equipment (March).
- 1954: "Silicon Transistor Announced," Electronics, 27, 6 (1954).
- 1955: "New Transistor Radio Hits Market," Electronics, 28, 7-8 (June 1955).
- 1957: "The Fused Silicon Rectifier," Commun. and Electronics, 28, 733-46 (January 1957).
- 1957: Silicon rectifiers first used in brushless airborne alternators. Henkels, Commun. and Electronics, 33, 620-26 (November 1957).
- 1958: "New Varistor is Described," Electronics, 31, 14 (March 28, 1958).
- 1958: "The Controlled Rectifier Nears Production," Control Eng., 5, 32 (February 1958).
- 1959: Grubbs (Bell Telephone Labs). "Hall-Effect Devices." Bell System Tech. J., 853, (May 1959).
- 1960: Epitaxial Crystal Growth Process introduced.
- 1961: Motto, "Using the Hall Generator, A New Control and Instrumentation Component." Automatic Control, 48 (June 1961); 24 (July 1961).

- 1961-
- 1965: F. W. Bell, Sprague and other companies intensively develop and refine Hall device production and applications for both bulk and thin-film Hall effect sensors.
- 1963-
- 1965: Weib, Moczala, Kuhrt and others. Extensive metallurgical studies in Germany resulted in improved intermetallic crystals for bulk Hall generators.
- 1966: Kuhrt (Siemens), "New Hall Generator Applications," Solid State Electronics, 9, 567-70 (1966).
- 1967: Honeywell introduced the first U.S. integrated circuit chip containing silicon Hall sensor, amplifier and Schmitt trigger for use in contactless keyboard switch. Goddard Space Flight Center employed these IC devices in motors until 1970.
- 1972: Silicon Hall Effect Generator and Amplifier on a Single Integrated Circuit Chip, Electronic Engineering, 20-21 (January 1972).

- Activity linked to aerospace requirements

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