1982

Progress Toward the Development of High Pressure Oil-Free Rotary Air Compressors

H. J. Skruch

E. T. Camponeschi

T. W. Bein

PROGRESS TOWARD THE DEVELOPMENT OF HIGH PRESSURE OIL-FREE ROTARY AIR COMPRESSORS

H.J. Skruch, E.T. Camponeschi, T.W. Bein

David Taylor Naval Ship Research and Development Center

Annapolis, Maryland

ABSTRACT

Cylindrical/planar-type single-screw compressor mechanisms were operated for approximately 8800 hours investigating materials and bearing technology required for oil-free, water-flooded operation. Carbon/graphite bearings located inside the water-flooded compressor zone provided excellent performance. Gaterotor materials investigated included both a filled nylon and a fiberglass/epoxy laminate. Compressor design philosophy is described with respect to developing both low pressure (125 lb/in^2) and high pressure (3000 lb/in^2) shipboard, water-flooded single screw compressors.

BACKGROUND

Low and high pressure (125 and 3000 lb/in^2) compressed air on most U.S. Navy ships is provided by oil-free reciprocating piston units. These machines are relatively heavy (up to 7000 lb) and generate relatively high vibration levels due to their large number of reciprocating and impacting parts.

A rotary, water-flooded, twin-helical-screw low pressure (125 lb/in^2) air compressor has recently been successfully evaluated aboard ship where it demonstrated substantial advantages in reliability, maintainability, size, weight, noise, and vibration, compared to existing reciprocating units for the same service. Based on this successful evaluation, water-flooded twin-screw-type compressors have been installed aboard some ships.

The apparent advantages of the rotary low pressure compressors compared to equivalent reciprocating units prompted a search for a rotary mechanism that provided similar gains over the piston-type high pressure units. Unfortunately, the twin-helical-screw compressor was not considered to be a feasible candidate for 3000 lb/in^2. However, a review of available rotary engine and compressor mechanisms determined that the Zimmern single-screw, globoid-worm-compressor mechanism was an attractive candidate for the intended service. This conclusion was based on its pressure balanced geometry which results in low bearing loads; reduced number of sealing parts; attractive size, weight, volumetric and mechanical efficiencies; and a relatively favorable developmental risk and cost. Three versions of the single-screw machinery existed at that time, none of which developed more than 250 lb/in^2. The cylindrical mainrotor, planar gaterotor (C/P) configuration, is shown in Figure (1). The cylindrical mainrotor, cylindrical gaterotor (C/C) configuration is shown in Figure (2). Also available for larger capacities was a configuration that utilized two back-to-back conical shaped planar mainrotors with four planar gaterotors.

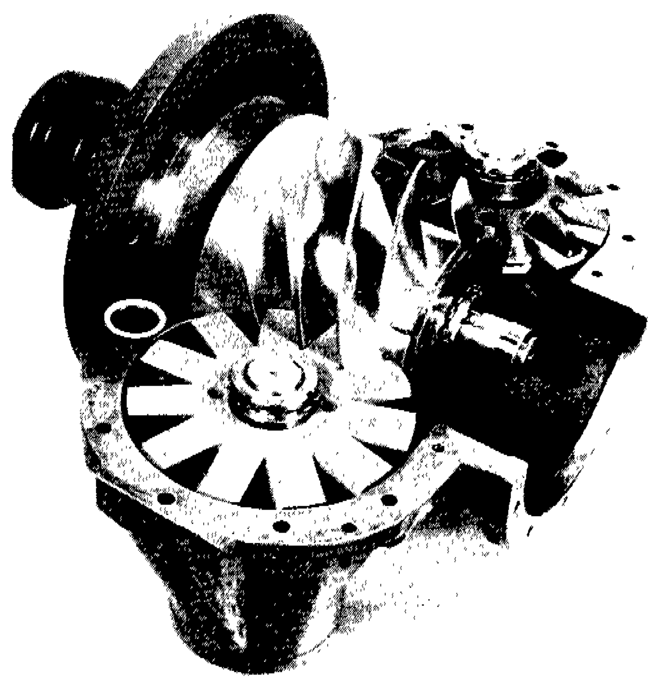

Figure 1 - Single-Screw Compressor with Cylindrical Mainrotor/Planar Gaterotors

The C/C version shown in Figure (2) was of particular interest to the Navy because it was being developed for capacities between 10 and 110 ft^3/min, and this arrangement is highly efficient from a size and weight standpoint. The C/C configuration is also able to handle higher pressure ratios up to 20:1, and has provisions for axial adjustment of the gaterotor to mainrotor clearance. These two features made this version highly desirable for a high pressure 3000 lb/in^2 stage.

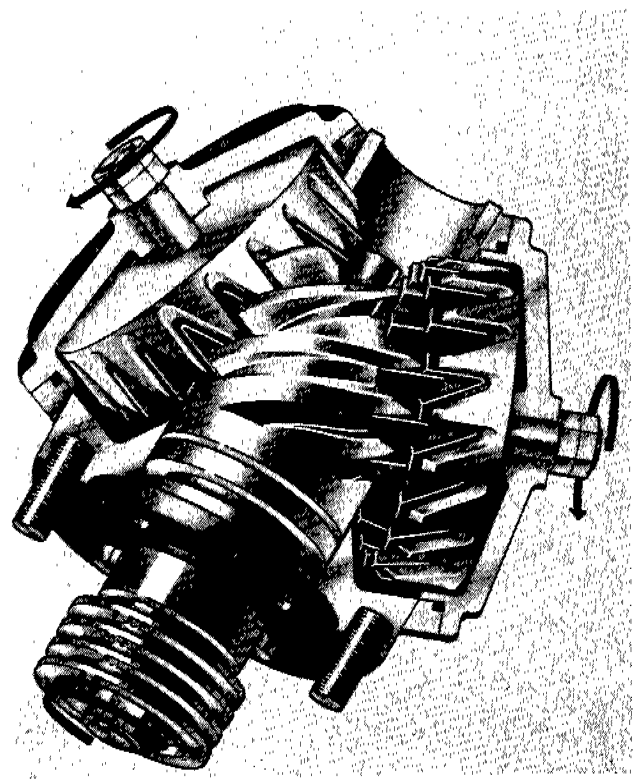

Figure 2 -Single-Screw Compressor with Cylindrical Mainrotor/Cylindrical Gaterotors

The review also determined that no oil-free high or low pressure single-screw air compressor existed, nor did any manufacturers express plans to market any in the foreseeable future. It therefore remained for the Navy to develop the technology that would make a high pressure, single-screw air compressor a reality.

A feasibility study indicated that there should be no insurmountable technical problem in designing a 3000 lb/in^2 stage using the C/C design. The next step was to conduct some hardware investigations to get an insight into the wear which occurs between the gaterotors and the mainrotor in the presence of water and to measure some of the thermodynamic characteristics. It was desired to work with C/C-configuration hardware because it was the design believed essential for a high pressure stage. Unfortunately, the only manufacturers of C/C - design compressors at that time were in Japan and they were not interested or willing to make any nonstandard parts for use in a development program. The C/P design, on the other hand, was being built in the U.S. by Chicago Pneumatics who expressed an interest in working with the Navy, and a willingness to make nonstandard housings, rotors and other parts of materials which were compatible with water.

As it turned out the C/P-design is inherently easier to use as a development tool insofar as fabrication and development of water flooded bearings and gaterotor materials are concerned. Also, although either the C/P or C/C design could be appropriately sized to meet the 60-70 ft^3/min capacity requirements of the first stage of a multistage rotary high pressure air compressor; the C/P configuration is best suited for the 100 and 200 ft^3/min capacities of present low pressure ships service air compressors. Therefore, a by-product of the high pressure development could be a new generation of rotary shipboard low pressure compressors.

Two bearing configurations were considered for achieving a water-flooded compressor design. One was to utilize grease lubricated bearings located outside the compression housing. A test compressor configured with external grease-lubricated bearings operated very successfully for 5176 hours substantiating the feasibility of such an alternative.

A more desirable alternative was to develop bearings which could operate in the water environment of the compression process. Water-lubricated bearings would greatly reduce the size and complexity of the compressor as well as contribute to lower maintenance requirements.

TEST COMPRESSOR

The bearing investigations were conducted in test compressors assembled with both commercial and special parts obtained from Chicago Pneumatics Tool Company.

The C/P compressor configuration shown in Figure (1) consists of one cylindrical mainrotor with two planar rotating seal rotors known as gaterotors enclosed in a split case. During operation, power is applied to the main rotor shaft which in turn drives the gaterotors. The single screw mainrotor has six grooves, each of which, with the case, serves to confine a volume of air. Air enters through the suction cavity into the grooves and is discharged radially through ports at the opposite end of the case. The gaterotors function similarly to the pistons of a reciprocating compressor in that the teeth reduce the volume of the air confined in the grooves as they move through the grooves. Two compression processes are carried out simultaneously and symmetrically opposite on the top and bottom of the mainrotor. Therefore, no appreciable net axial or radial forces act on the mainrotor. Water is injected into the thread at selected locations to seal and lubricate the gaterotor tooth and mainrotor. The water mixes with the air during the compression process and absorbs some heat of compression before being discharged. The water is separated from the air, cooled, and recirculated to the compressor. The compressor housing and mainrotor were fabricated from SAE 64 bronze while the gaterotor supports, gaterotor shafts and main rotor shaft were fabricated from Nitronic 60, Type 17-4 PH and type 316 stainless steels, respectively. The motor end of the mainrotor is supported by two grease-lubricated antifriction bearings located outside the pressure housing. These bearings carry all of the thrust loading which acts on the mainrotor as well as most of the radial load. A face-type shaft seal prevents water loss from the pressure housing. Vents are located between this seal and the grease-lubricated bearings so that minor shaft seal leakage cannot intrude into the bearings.

WATER-FLOODED BEARINGS PROVISION

The gaterotor-shaft bearings and the mainrotor suction-end bearing for this unit were designed to operate in a water-flooded environment. Water for injection into the bearings was tapped off of the recirculating water loop and cleaned by a 30-micrometer nominal-rated filter, and three injection lines were used to supply water to the five water-flooded bearings. One line supplied water to the mainrotor shaft suction-end bearing, one supplied water to the left gaterotor shaft bearings, and the third line supplied water to the right gaterotor shaft bearings. The water for the suction-end shaft bearing was injected axially at the flanged end of the bearing. Water for the gaterotor-shaft bearings was injected between the upper and lower bearing as shown in Figure (3).

All bearing water, after being discharged from the bearings, entered the suction cavity and mixed with the inlet air. The compressor assembly was mounted in a fabricated steel frame and direct driven by a 25-horsepower 1800 rpm electric motor. The unit discharged air into a stainless steel combination air/water separator and accumulator. Appropriate instrumentation and monitors permitted completely unattended operation under a variety of conditions.

BEARING CONFIGURATION

The predicted loads and velocities, dimensional constraints, and suggested materials and configuration for the water-flooded bearings were prepared and reviewed by several bearing fabricators. The design selected consisted of a rotating chromium-plated inner race and a stationary carbon/graphite outer race. In this unit, the resulting bearings would operate at a PV (pressure x velocity) ranging from 27,000 lb/in^2-ft/min to 59,000 lb/in^2- ft/min. These PVs are well within the predicted capability of the materials combination selected for this service. These bearings were designed to operate as water-cooled, self-lubricating bearings rather than as hydrodynamic bearings since at that time it was believed that excessively large clearances were required for full-film lubrication.

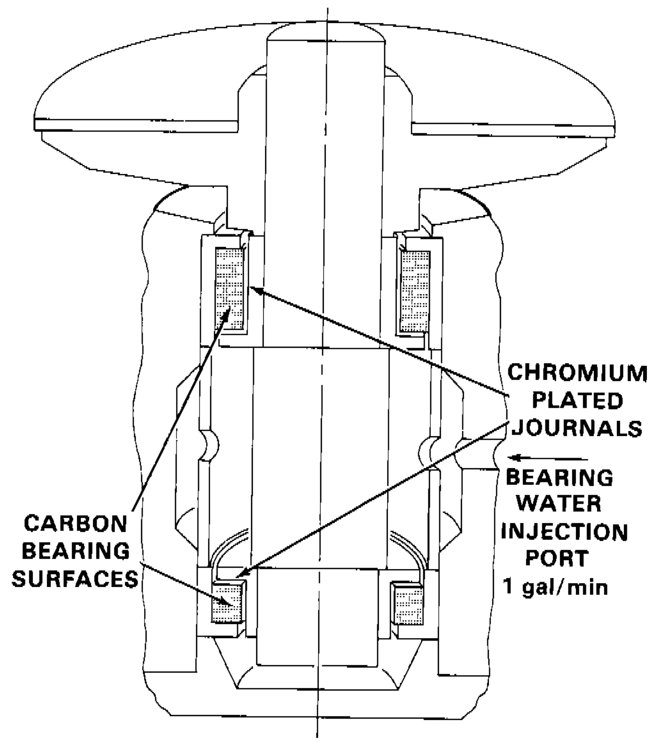

Figure 3 - Illustrated Gaterotor Shaft Assembly with Water-Flooded Bearings

Results from preliminary testing of the carbon/bearings indicated that they were overheating due to inadequate water flow through the bearing. Grooving as shown in Figures (4) was incorporated to permit additional cooling waterflow through the bearings. An annular recess and radial grooves were machined into the thrust portion, and longitudinal grooves cut at 10° to the bearings center axis were machined into the journal portion of the carbon/graphite to facilitate the water flow.

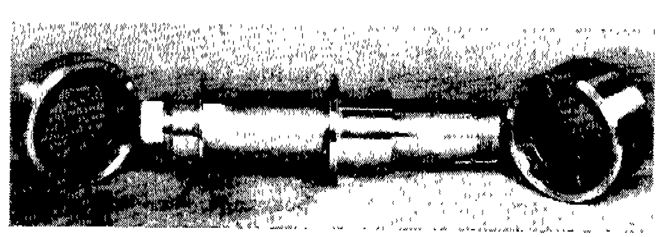

Figure 4 - Grooved Carbon/Graphite Bearing and Gaterotor Shaft Assembly

Subsequently, inner races with chromium oxide and chromium carbide plasma sprayed coatings, applied to a 15-7 PH stainless steel substrate, were evaluated against the same carbon/graphite bearings. The notation used to identify the four gaterotor bearings is illustrated in Figure (5).

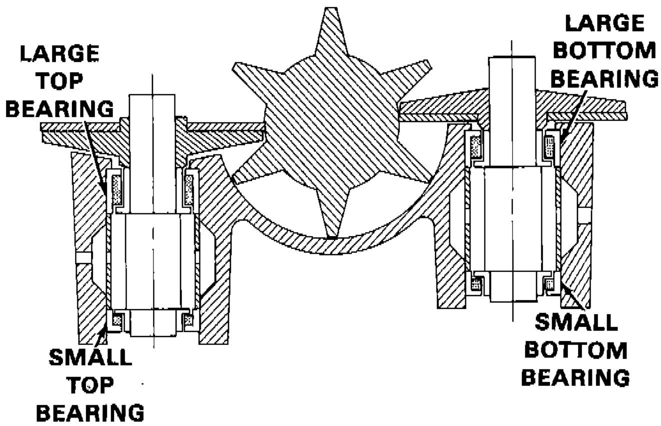

Figure 5 - Cross Section of Compressor with Water-Flooded Bearings

TEST PROCEDURE

This investigation was to establish the feasibility of using water-flooded bearings in a C/P design single-screw compressor and to determine the upper load (PV) limit of the various bearing configurations. This information would then be used to predict water-flooded bearing designs for the higher loads and speeds anticipated in the high pressure portion of the rotary single-screw compressor program.

Satisfactory bearing operation was judged by two critical performance elements. The first element was the basic performance capabilities of the grooved carbon configuration. The second element was the wear characteristics of the materials combination.

The technique used to vary the PV values while operating at a constant 1800-rpm motor speed was to reduce the bearing surface width. The procedure was to obtain wear rates at a given PV level, then machine away a predetermined amount of the carbon wearing surface and then operate the compressor and obtain another wear rate at the higher PV value.

The first bearings to be investigated were the carbon bearings with hard chromium plated inner races. The second materials combination was the plasma sprayed chromium carbide inner races and the third series used chromium oxide plasma sprayed coating; both against the carbon counterface.

Each of the three sets of bearings were evaluated with the compressor operating 24 hours a day, 125 lb/in^2 discharge air pressure, 98°F - 102°F discharge air temperature, 19.5 - 23.5 gal/min total recirculating water flowrate and 1 gal/min injection flowrate for each gaterotor bearing set. During operation on a continuous basis the unit was shutdown for two hours at least once a week.

Compressor performance was continuously monitored and one or more inspections were made during the first 100 hours of testing for each of the three bearing sets. Compressor performance along with bearing dimensions, wear characteristics, and appearance at inspections were analyzed for indication of compatible performance with the grooved-carbon configuration. Bearing inspections were scheduled after the first 100 and 500 hours of operation,and thereafter at 1000 hour intervals unless otherwise necessary.

RESULTS

The compressor with water-flooded bearings was operated a total of 3604 hours over 11 months in evaluating the three bearing materials combinations.

Wear was characterized by changes in four dimensional parameters; carbon/grahite thrust face wear and bore wear, and chromium thrust flange wear and journal wear. There were no signs of erosion, corrosion, or biological growth during the evaluation period.

CHROMIUM PLATING BEARING RACES

Wear results for the bearing set of chromium plated 17-4 PH stainless steel and carbon/graphite are shown in Figures (6) and (7).

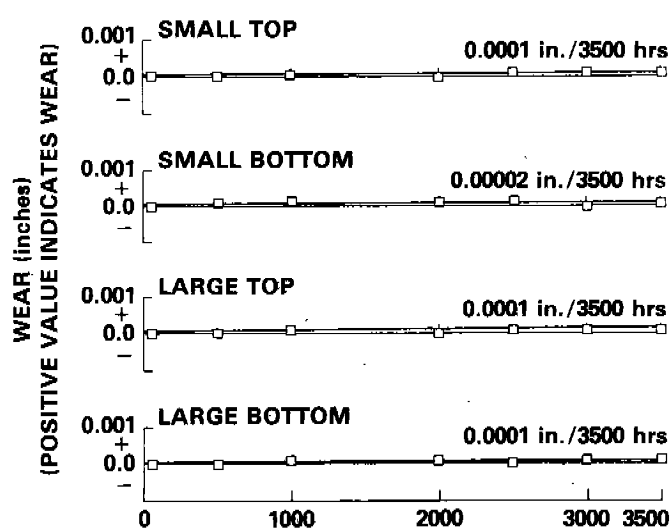

Figure 6 - Carbon/Graphite Bore Wear Against Chromium

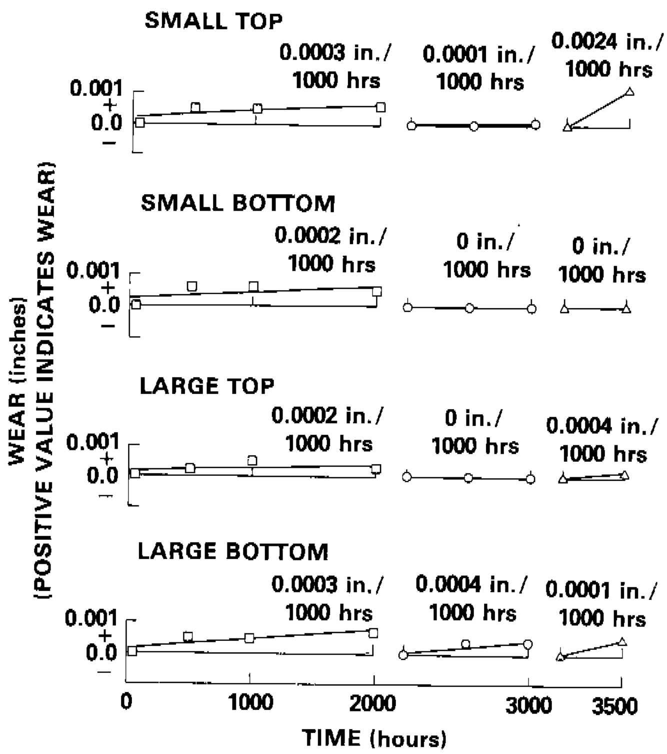

Figure 7 - Carbon/Graphite Thrust Face Wear Against Chromium

Figure (8) shows the carbon/graphite thrust face and journal wear rates for the various PV's over its particular test interval.

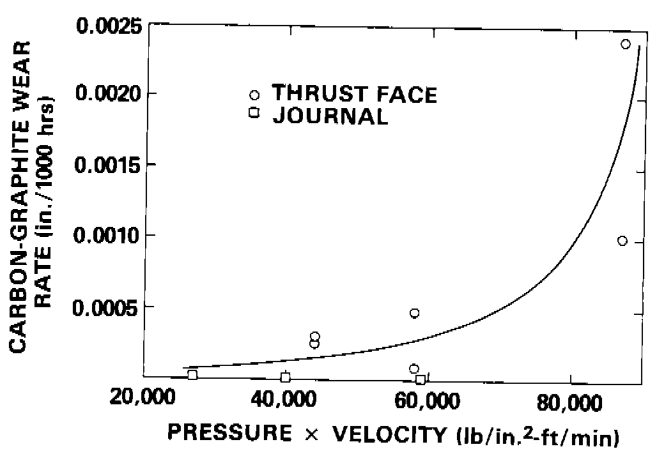

Figure 8 - Carbon/Graphite Wear Rate vs Pressure x Velocity

Wear of the carbon/graphite bearing bore wear and the respective chromium plated journal wear is negligible. Figure (9) shows the appearance of a typical loaded thrust bearing (small top) after 2000 hours of operation. The unloaded thrust bearings and journals were in a "like-new" condition at that time.

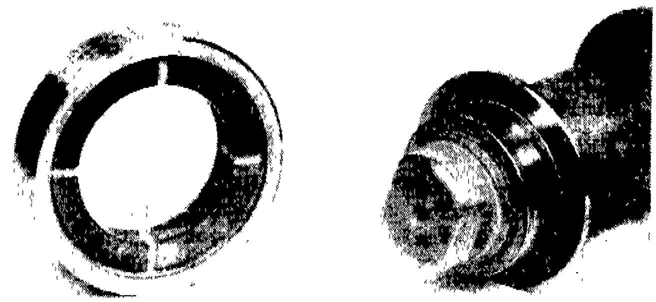

Figure 9 - Small Top Bearing After 2000 Hours Operation

Inspection and measurements of this bearing set at 10 hours and 60 hours indicated essentially no wear of either the carbon surfaces or the chromium-plated surfaces. There was evidence of sliding contact on all four of the carbon bores and on the small top carbon thrust face and the large bottom carbon thrust face. The inspections, at 500, 1000 and 2000 hours, also indicated good wear resistance for this material combination. The most wear after 2000 hours of service was on the large bottom carbon/graphite thrust face which showed 0.0006 inch maximum wear. This rate was considered acceptable so the operating PV (pressure x velocity) for the thrust faces was increased at the 2000 hour mark.

The PV for the thrust faces was controlled by the width of the annular recess on the thrust face. The recess was 0.062 inch wide for the first 2000 hours, providing a PV of 44,000 lb/in^2-ft/min. This dimension was increased to 0.125 inch for the next 1000 hours which yielded a PV of 58000 lb/in^2-ft/min. The loaded carbon thrust faces showed about the same amount of wear at the higher PV and this wear rate was considered acceptable.

The thrust face PV was again increased by increasing the width of the annular recess to 0.292 inch yielding a PV of 87000 lb/in ft^2/min. The carbon/graphite thrust face wear after 500 hours of operation at this PV was 0.0012 inch for the small top carbon thrust face, and 0.0005 inch for the large bottom carbon thrust face. This amount of wear was considered unacceptable, so the testing with the chromium plated bearings was stopped at that point.

CHROMIUM CARBIDE BEARING RACES

The second set of bearings evaluated consisted of the chromium carbide plasma sprayed onto 15-7 PH stainless steel inner races and carbon/graphite outer races. The first inspection for this material combination was conducted after 100 hours of operation. Measurements indicated excessive wear on the loaded carbon/graphite thrust faces and the small bores. The wear rate of these elements ranged from 0.0012 inch/100 hours to 0.0023 inch/100 hours. The dimensions of the chromium carbide plated surfaces remained the same after 100 hours.

CHROMIUM OXIDE BEARING RACES

The third set of bearings evaluated consisted of the chromium oxide plasma sprayed 15-7 PH stainless steel inner races and carbon/graphite outer races. Evaluation of this bearing set was stopped after 4 hours of operation when air capacity and discharge pressure decreased and unusual compressor noise developed. Bearing measurements revealed excessive wear on the carbon/graphite components with no dimensional changes found on the chromium-oxide coated elements. The wear rate of the carbon/graphite components ranged from 0.0006 inch/4 hours to 0.0081 inch/4 hours.

GATEROTOR MATERIALS

Materials for gaterotors must be able to sustain stresses imposed by the air loadings and be compatible with the mainrotor material so that both surfaces experience very low wear rates. In this development program where water is to be the lubricating fluid and the mainrotor has to be made of metal for strength reasons, the choice of gaterotor materials seemed to be directed toward plastics.

In discussions with Chicago Pneumatics it was found that they had typically used a filled nylon material for gaterotors in their commercial line of oil-lubricated compressors. However, more recently they were experimenting with a fiberglass/epoxy laminated material. Both these materials were considered to be worthwhile candidates to be evaluated in the water-flooded compressor and both could be obtained from Chicago Pneumatics machined to fit the mainrotor in the laboratory C/P compressors.

Nylon-based gaterotors were used for approximately 2000 hours in a compressor operating with the external grease lubricated gaterotor bearings. Gaterotors made of the fiberglass/epoxy laminate were used for approximately 3600 hours in the compressor with the internal, water-flooded bearings.

GATEROTOR RESULTS

Nylon-based gaterotors were used for approximately 2000 hours. Figure (10) shows that two sets of the nylon-base gaterotors exhibited growth in the water environment. Measurement of gaterotor tooth tip to mainrotor clearance revealed a tendency of the material to grow at a rate of from 2 to 6/thousandths of an inch per 500 hours of operation. This caused the tips of the gaterotor teeth to bottom in the mainrotor grooves which

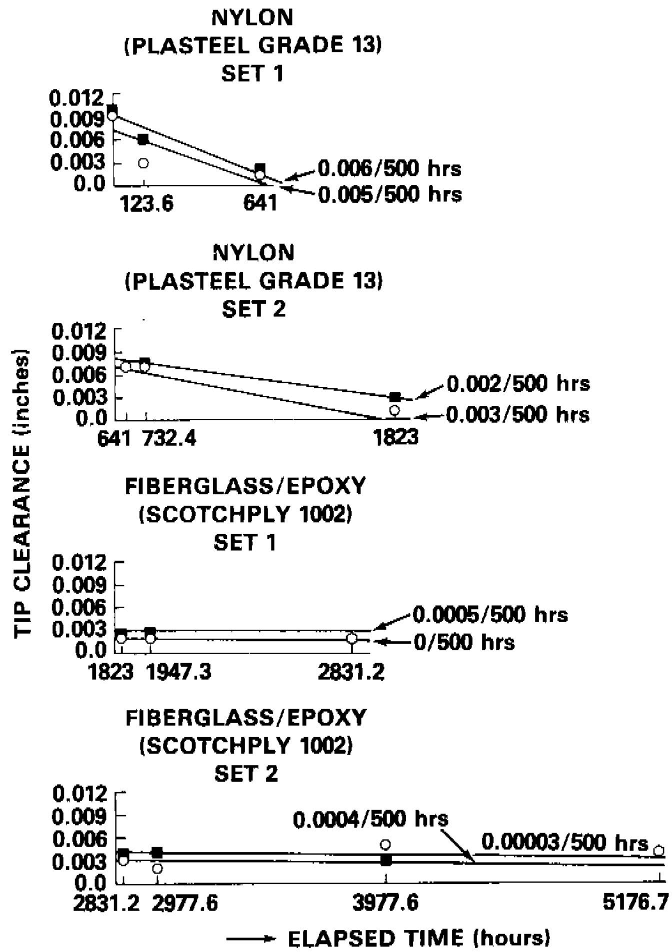

Figure 10 - Gaterotor Tip Clearance vs Time

could lead to catastrophic failure of the gaterotor.

Two sets of gaterotors made of the fiberglass/epoxy laminate were also evaluated. Figure (10) shows that this material exhibited excellent stability in nearly 3400 hours operation.

It is not possible to measure the gaterotor flanks because the surfaces consist of compound angles that are constantly changing. What can be measured using conventional techniques are clearances between the gaterotor flanks and the mainrotor grooves by means of feeler gauges. Measurements using that technique indicated no changes more than 0.001 inch in gaterotor to mainrotor clearances.

MAINROTOR PERFORMANCE

The mainrotors used in each bearing-development compressor were made of SAE 64 bronze and were manufactured by Chicago Pneumatics. Unfortunately, measurements of the tooth flanks of mainrotor are very difficult to obtain because, as described above for the gaterotors, the compound curvatures are continually changing and there is no way of establishing conventional referencing systems.

Feeler gauge techniques are useful in establishing clearances between the mainrotors and gaterotors and between mainrotors and housings. Also surfaces can be observed for changes in appearance such as the wearing away of manufacturing tool marks. Using these direct and indirect measurement techniques, rotor wear over 8776 hours of operation in two compressors appears to be less than 0.001 inch on any of the rotors in that feeler gauge measurements have not changed and in most areas the original machining marks can still be seen below the polished surface. Therefore SAE 64 bronze is considered a satisfactory mainrotor material when used in conjunction with fiberglass/epoxy gaterotors for shipboard C/P - type low pressure, water flooded single screw compressors.

DISCUSSION

This investigation showed that it is very feasible to operate a water-flooded C/P-tye single-screw compressor with bearings located within the water environment. The grooved carbon/graphite bearing configuration performed successfully as a combination thrust bearing and journal bearing.

This material combination consisting of hard chromium plated 17-4 PH stainless steel and antimony filled carbon/graphite exhibited excellent wear resistance through 3000 hours of operation at PV's up to 58,000 lb/in^2-ft/min. Longer bearing life was possible but not demonstrated due to changes which were made to the bearing configuration. The accelerated wear tests indicated that this material combination could achieve acceptable low wear rates at PV levels below approximately 67000 lb/in^2-ft/min as shown in Figure (8). The particular plasma sprayed ceramic coatings tested caused excessively high wear of the carbon/graphite counterfaces although the ceramic coatings showed no evidence of degradation during testing. The porosity inherent in these plasma-sprayed ceramic coatings apparently produces an abrasive, incompatible surface for the carbon/graphite.

Alternate application and finishing techniques may be able to achieve smoother surface finishes which may result in a more compatible wearing surface.

The results from the tests performed with the plasma sprayed chromium carbide and chromium oxide coatings do not rule out the use of these materials, but does rule out the use of these materials when deposited on this bearing configuration by this particular plasma spraying process. Technical reports and information from suppliers and users indicates that a number of ceramic materials operating against carbon and other ceramics have the potential to carry much higher PV loadings than the chromium and carbon/graphite combination. High-load-carrying water-flooded bearings may be essential in the high pressure stages of a C/C-type compressor where the bearing size becomes relatively small and the bearing loads high.

The excellent stability and wear compatibility demonstrated by the fiberglass/epoxy laminate gaterotors mark this material as satisfying the requirements for gaterotors in low pressure water-flooded C/P type single screw compressors when operated against mainrotors made of SAE 64 bronze. Also, the relatively high strength which can be achieved with fiberglass reinforcement make this and similar materials particularly attractive for the gaterotors in high pressure stages.

CONCLUSIONS

The excellent compressor performance achieved with water-flooded carbon/graphite and chromium bearings configurations with fiberglass/epoxy gaterotors provides confidence that the Navy has sufficient technology to contract for water-flooded cylindrical/planar, single-screw compressors. Such compressors should be capable of performing in a reliable, trouble-free manner for thousands of hours. This compressor design which does not reqire gaterotor shaft seals and their attendant parts design should compare very favorably with water-flooded helical-twin-screw units which require 8 shaft seals, timing gears, and an oil lubrication system.

The effort reported herein represents the first steps of a program whose eventual goal is the development of high pressure single-screw compressor stages with the expected advantages inherent in rotary oil-free machinery.

Efforts are currently underway to demonstrate the low-pressure technology at higher speeds and to design, fabricate and evaluate high pressure single-screw compressor stages which will utilize the technology obtained in this phase.

ABBREVIATIONS

lb/in^2	- pounds per square inches
ft^3/min	- cubic feet per minute
ASME	- American Society of Mechanical Engineers
SAE	- Society of Automotive Engineers
PH	- Precipitation hardenable
rpm	- Revolutions per minute
PV	- Product of pressure times velocity
ETM	- Elapsed time meter reading
hr	- Hours
lb	- Pounds force
PTFE	- Polytetrafluoroethylene
C/P	- Refers to a single-screw compressor with a cylindrical mainrotor and planar gaterotors
C/C	- Refers to a single-screw compressor with a cylindrical mainrotor and cylindrical gaterotors
P/P	- Refers to a single-screw compressor with a planar mainrotor and gaterotors

REFERENCES

(1) Thelen, W.H., "Evaluation of Various Rotary Mechanisms for Potential as High-Pressure Shipboard Compressors," DTNSRDC PAS Report 76-34 of March 1977.

(2) Chicago Pneumatic Tool Company of Solon Ohio, "A Study of an Optimum 3000 PSIG Single Screw Compressor of November 1973.