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INSPECTION OF TWO BRAYTON ROTATING UNITS AFTER EXTENSIVE ENDURANCE TESTING

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16. Abstract

The NASA-Lewis Research Center has been engaged in a program to demonstrate the technology for closed Brayton cycle power conversion systems for space. A system was designed to produce 2-10 kW net continuous electric power for at least 5 years. The turbine-alternator-compressor power conversion unit in the system is designated "Brayton Rotating Unit" (BRU). Four BRU's have been fabricated and extensively tested. One BRU has accumulated 11 000 hours of operation and another has accumulated in excess of 21 000 hours. Testing has demonstrated that the BRU's have met or exceeded performance objectives. Two BRU's have been disassembled and given a thorough post-test inspection. The inspection results show that after 21 000 hours of operation there is no apparent wear or failure mode that will prevent the attainment of the 5-year life objective.

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INSPECTION OF TWO BRAYTON ROTATING UNITS AFTER EXTENSIVE ENDURANCE TESTING

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E-9013

SUMMARY

The NASA-Lewis Research Center has been engaged in a program to demonstrate the technology for closed Brayton cycle power conversion systems for space. A system was designed to produce 2-10 kW net continuous electric power for at least 5 years.

The turbine-alternator-compressor power conversion unit in the system is designated "Brayton Rotating Unit" (BRU). Four BRU's have been fabricated and have been extensively tested as a single component and in concert with the complete Brayton engine. One BRU has accumulated 11 000 hours of operation and another has accumulated in excess of 21 000 hours. These tests have demonstrated that the BRU satisfies the design performance objectives. The endurance tests and post-test inspections have verified the mechanical integrity of the design with the possible exception of the turbine scroll. This possibility, however, can be eliminated by redesigning the scroll to change the configuration from a torus to a plenum.

Coatings deposited on the turbine wheel did not affect performance. The loss of reflective coatings on the heat shield and seal housing at the turbine end did not result in an increase in alternator winding temperatures, demonstrating that the reflective coatings are not needed.

The alternator insulation system is apparently unaffected by 21 000 hours of operation. No change was detected in the exposed surfaces of the insulating materials.

The gas bearing system has been demonstrated to be extremely rugged and reliable. It has repeatedly demonstrated the ability to ingest hard particles larger than the film thickness and sustain shaft-to-pad high speed contacts without affecting performance or life.

The BRU tests that have been conducted and the results of the post-test inspections verify that a major portion of the NASA program objective has been achieved. The technology required to produce a power conversion unit for use in a Brayton closed cycle power conversion system has been demonstrated and there is no apparent wear or failure mode that will prevent attainment of the 5-year life objective.

STAR Category 37

INTRODUCTION

The NASA-Lewis Research Center has been engaged in a program to demonstrate the technology for closed Brayton cycle power conversion systems for space applications. As a part of this program, a power conversion system was designed to produce 2-10 kW net continuous electric power for at least five years. All required components and subsystems, except the heat source and a space radiator, have been fabricated and extensively tested. The test programs included individual component performance tests (refs. 1 to 4), subsystem performance and endurance tests (refs. 5 and 6), and complete flight-type engine performance and endurance tests (refs. 7 and 8). These tests have demonstrated that the system meets or exceeds design performance objectives.

The turbine-alternator-compressor power conversion unit in the system was designated the "Brayton Rotating Unit" (BRU). The operating conditions imposed on this component by the power conversion system requirements presented a difficult problem in the design of the rotor bearing system. A severe axial thermal gradient resulting from the turbine inlet temperature of 1600° F (1144 K) and the compressor inlet temperature of 80° F (300 K) had to be accommodated. The rotational speed of 36 000 rpm requires operation between the second and third system critical speeds. To prevent contamination of the working fluid by an organic lubricant, the bearings had to be lubricated by the working fluid, a mixture of helium and xenon (M.W. 83.8) or krypton (M.W. 83.8).

Four BRU's were fabricated utilizing gas bearings which consist of a double-acting Rayleigh-step thrust bearing and two tilting pad journal bearings with the pads pivoted on full conforming ball-and-socket pivots. Gas bearing technology at that time had not been demonstrated and they were thought to be extremely sensitive to the ingestion of particles and to any high speed shaft to pad contacts (rubs). Another area of concern, inherent in this design, was the reliability and life of the full conforming ball-and-socket pivot. These were the only metal to metal wear points in the BRU and there was no way of predicting potential life.

A major task in accomplishing the program objective was therefore to demonstrate potential reliability and show that the life expectancy of the bearing system can, with confidence, be projected to five years. To accomplish this, the motions of the pads, thrust bearing, and shaft were monitored by means of capacitance-type proximity probes throughout all of the component tests and during the early phases of the endurance tests.

This paper presents the operating history of two BRU's and the results of inspections conducted after 21 000 hours on BRU 2 and 11 000 hours on BRU 4. The results of these inspections will be compared with previous inspections to demonstrate that the BRU has the potential to meet the life and reliability design goals.

BRU DESCRIPTION

General Description

The BRU designed and fabricated by the AiResearch Manufacturing Company of Arizona is fully described in reference 9. Figure 1 presents cross-sectional views of the BRU showing the main components and thermal control features. Figure 2 displays the rotating assembly which consists of a radial outflow single-stage compressor, thrust bearing runner, a four-pole modified Lundell alternator rotor, and a radial in-flow turbine. Three curvic couplings and a through tie bolt provide for accurate assembly of the rotating assembly.

The rotating assembly, with a design rotational speed of 36 000 rpm, is supported by a hydrodynamic double-acting gas-lubricated thrust bearing and two hydrodynamic gas-lubricated tilting pad journal bearings. External pressurization is supplied to both sides of the thrust bearing and to each pad of the journal bearings for hydrostatic operation below design speed (start-up and shutdown).

The alternator is cooled by means of a cooling fluid (dimethyl polysiloxane) circulated through a heat exchanger which is an integral part of the alternator frame.

Journal Bearing

Each journal bearing assembly (fig. 3) consists of three pads. Each pad is mounted on a lapped ball and socket pivot. The pivots have a 0.2500-inch (6.35 mm) radius and are fabricated from solid tungsten carbide. The hydrostatic gas supply is fed through the pivot joint to a single orifice and pocket located at the pivot point of the pad. One pad in each bearing is mounted on a flexible beam to accommodate thermal and centrifugal growth of the shaft and to lower the critical speed. The flexible beam has a nominal spring rate of 2000 pounds per inch (13.8×10^6 N/m). The remaining pads are mounted on rigid beams. The flexible beams are adjusted to provide an assembled preload of approximately eight pounds (35.6 newton) to assure adequate journal bearing loads at all operating conditions.

Thrust Bearing

The thrust bearing (fig. 4) is a Rayleigh step bearing with a single hydrostatic orifice in each sector. The bearing assembly with the stators mounted face-to-face separated by a gaged spacer provides a double-acting preloaded thrust bearing. The stator assembly is mounted on a flexure pivoted gimbal (fig. 5) to assure alinement of the runner and stator plates. Friction pads are installed on each gimbal axis to dampen the gimbal motions and thus assure dynamic stability of the assembly.

The flow of gas in the bearing during hydrostatic operation generates a small torque on the shaft which slowly accelerates the shaft in reverse rotation. This feature is utilized to assure complete freedom of rotation prior to starting the system. Motoring cannot start until reverse shaft rotation is indicated in the start-up circuitry.

The internal BRU instrumentation consists of 37 thermocouples and 22 capacitance proximity probes. The thermocouples were used to verify the predicted thermal map and to monitor the alternator winding hot-spot temperatures. The proximity probes were utilized to monitor the dynamic motions of the shaft and bearing components.

During the later phases of the endurance testing, after a high degree of confidence had been developed for the component, none of this instrumentation was maintained or monitored, with the exception of the alternator hot-spot temperatures.

HISTORY AND INSPECTION OF BRU-2

BRU-2 was first tested for 1000 hours in a test loop to evaluate its operation and overall performance as a component. This testing, in addition to covering the complete design operating range, also included off-design testing to determine its operational limitations. The results of this phase of testing, reported in references 1 and 2, have verified the mechanical integrity of the BRU and have demonstrated that it exceeds or meets all performance objectives.

After completing the component phase of testing, BRU-2 was installed in a flight-type system and tested for an additional 2000 hours as part of a complete Brayton engine. This phase of testing, described in reference 7, was conducted in a vacuum environment. After the scheduled completion of these tests, BRU-2 was disassembled and inspected. The results of this inspection were published in reference 10.

At this time the Brayton engine and its control system were modified to simplify the start procedure and to permit unattended operation of the facility. The engine was then operated at a 1600° F (1144 K) turbine inlet temperature with an electrical output of 7-8 kW for an additional 17 568 hours. During this period the engine was subjected to 64 stop-start cycles and 16 thermal cycles. The engine was stopped by dumping the working fluid into an evacuated storage tank. This reduced the system pressure to about 3 psia. The stop-start cycles were performed primarily to demonstrate to visitors the "single button" start-up and shutdown features of the engine. Duration of these shutdowns was less than 15 mintues and the components and ducting remained at temperature. The thermal cycles resulted from shutdowns that were of sufficient duration to permit the engine to cool to room temperature. These shutdowns were caused by instrumentation failures, test support equipment failures or gas leaks to the atmosphere from the engine heat exchanger/recuperator.

After removal from the Brayton engine (21 000 hrs operation) and prior to disassembly, BRU-2 was helium leak checked. This check revealed a crack that had developed in the turbine scroll along one of the welds (see fig. 7). No other leaks were detected.

After removal of the turbine and compressor scrolls, the shaft was floated by means of the jacking gas system. An electrical shaft-to-frame continuity check was made using a volt-ohm meter. The meter will indicate an open circuit or infinite resistance when the shaft is freely supported on the gas film. A closed circuit or low resistance is indicated if any part of the rotating assembly touches any part of the stationary assembly; that is, shaft-to-pad or thrust-runner-to-stator. A low resistance will also be indicated if a conducting particle bridges any part of the air gap between shaft and ground. The continuity check indicated a normal open circuit from shaft to ground. This check was repeated several times with the same results; that is, an open circuit indication and free reverse rotation of the shaft.

BRU-2 was then completely disassembled and the following visual observations were noted:

(1) The backswept portion of the turbine blades and the hub were coated with a fine black powder that had the appearance and characteristics of lamp black.

(2) The turbine seal holder was originally plated with nickel and polished to produce a highly reflective surface. The outside surface down to the demarcation line shown in figure 8 and the entire inside surface (fig. 9) had a thin coating that had the rust-colored appearance of iron oxide. The lower outside portion of the holder material was discolored a dark blue. No evidence of the original nickel plating was found.

(3) The copper heat shunt (fig. 9) was plated with gold to provide a reflective surface. None of the gold plating remained and the cylindrical surface was lightly coated with a fine white powder.

(4) The compressor wheel and scroll, except for surface material discolorations, were in the as-built condition.

The journal and thrust bearings were carefully disassembled with special care given to retain any foreign particles that might be in the bearings or bearing cavity. No loose particles were found.

The thrust bearing showed evidence of high speed contacts between the outer edge of the runner and the stators. The load carrying surfaces of this bearing, except for surface discolorations, were in the as-built condition.

One fixed pad in the compressor journal bearing had minor surface scratches from leading to trailing edge, indicating that small particles had been ingested. The other fixed pad had a high speed rub mark at the pad pivot point. The turbine end bearing contained no scratches or rub marks.

The journal bearing pivot components were microscopically examined. No change could be detected in these surfaces since the previous inspection at 3000 hours as reported in reference 10. Approximately 25 percent of each surface had a frosted appearance as compared to the original polished finish. Surface roughness in these areas did not exceed 4 microinches (0.10 μ).

The compressor end journal had a light surface scratch around the complete circumference that matched the pad scratch. The entire rotor had a variety of surface discolorations. The magnetic pole pieces were blue, the nonmagnetic separator was a light copper, and portions of both journals were light rust-colored.

The alternator housing at the turbine end had traces of a white powder that appeared to be the same as that found on the copper heat shunt. The exposed potting compound and insulation materials were carefully inspected. No visible changes could be detected and there appeared to be no hardening or softening of these materials.

Several analytical techniques were used in an attempt to identify the various coatings and deposits. The predominate elements in the coatings were identified, but the chemical combined form of these elements could not be identified.

The black powder on the turbine wheel contained mostly manganese, with nickel and chromium. The rust-colored coating on the seal shroud contained mostly iron, copper, and manganese. The predominate element in the white powder on the copper heat shunt and in the turbine end of the alternator was silicon.

The rotating components were magnafluxed for cracks and defects. The results indicated no defects. These components were also dimensionally inspected and the measurements compared with the as-fabricated measurements. The turbine wheel measurements showed a diametrical increase of 0.0014 inch (0.035 mm). No other measurable differences were noted.

The unit was reassembled using the original parts. All the internal instrumentation except for three thermocouples that monitor alternator "hot-spot" temperature were excluded in this assembly.

HISTORY AND INSPECTION OF BRU-4

BRU-4 was tested in parallel with the flight type Brayton engine tests in a "Power Conversion Loop" identical in configuration to that of the flight type Brayton engine (ref. 6).

The Power Conversion Loop consisted of the Brayton rotating unit, Brayton Heat Exchanger Unit, connecting ducting, and bellows. The Brayton Heat Exchanger Unit (BHXU) incorporates a gas-to-gas recuperator and a liquid-to-gas waste heat exchanger. A schematic of the test system is shown in figure 6. Energy was supplied to the loop by an electric heat source (ref. 11). The working fluid was helium-xenon (M.W. - 83.8), and the cooling fluid used was a dimethyl polysiloxane (D.C. - 200), a silicone liquid.

This facility was operated on a 24 hours per day, seven days per week schedule. Performance tests were conducted during the normal work day. Unattended operation occurred during the nonwork hours.

An 8 percent degradation of performance was detected after approximately 5500 hours of operation. All other aspects of the operation were normal. Testing continued until it was verified that a gas flow restriction had developed. A scheduled shutdown was made at 5730 hours of operation to remove the components for inspection. Prior to and during the shutdown, all dynamic motions of the BRU rotor bearing system were normal.

Inspection of the loop showed that a leak had developed in the gas-to-liquid heat exchanger and that the coolant was being transported throughout the gas system. According to the manufacturer, this oil will, at temperatures above 1200° F (922 K), break down into silicon dioxide, silicon carbide, silicon, methane, ethane, free radicals, and carbon. These products were apparently formed in the 1900° F (1311 K) region in the electric heater and were then carried throughout the loop.

Removal and inspection of the turbine scroll revealed a 10-mil (0.254-mm) deposit on the surface of the turbine nozzle vanes. Calculations verified that the reduction in flow area resulting from a 10-mil (0.254-mm) deposit would reduce system performance about 8 percent.

As a part of the normal post-test inspection of the BRU, after removal from the system and prior to disassembly, the shaft was floated by means of the jacking gas system. Reverse shaft rotation verified complete freedom of rotation and normal flow of the jacking gas.

The rotor bearing characteristics observed prior to and during the shutdown along with the check made prior to disassembly led to the expectation that the bearings would be in the as-built condition. However, disassembly and inspection of the bearings revealed that hard particles, larger than the running clearance, had been ingested by the journal bearings. Both shaft journals were scored around the full circumference. Furrows were plowed in the surface of the fixed pads, extending from the leading to the trailing edge. Marks on the surface at the edges of the pads and marks on the shaft indicated that excessive roll motions of the pads resulted in shaft-to-pad contacts at these edges. One rigid beam supported pad in each bearing showed evidence of high speed shaft-to-pad contacts at the pad pivot point.

The origin and makeup of the particles that caused the journal bearing damage were not established. It is probable, however, that they were one of the byproducts of the oil that broke down in the heater. Silicon dioxide or silicon carbide particles would certainly have the required hardness.

A microscopic examination was made of the pad pivot ball and socket. Pivot wear in all the pivots was the same as that found in BRU's inspected after 700 and 3000 hours. Approximately 25 percent of the contact area had a frosted appearance in contrast to the original highly polished surface.

The thrust bearing was in the as-built condition, except for surface discolorations which were typical of all previous BRU's that have been inspected.

The damaged areas of the shaft journals were hand dressed with diamond paste and the pads were lightly lapped with a cast iron master. The scale was removed from the turbine nozzle and the complete unit was thoroughly cleaned. The unit was then reassembled using all the original parts and reinstalled in the loop. An additional 5487 hours of run time were accumulated for a total accumulation of 10 987 hours during which the BRU performed normally. Upon completion of the test program the test facility and power conversion loop were dismantled. BRU-4 was disassembled and the results of the post-test inspection are reported subsequently.

A helium leak check prior to disassembly after a total of 10 987 hours of operation showed BRU-4 to be leak tight. The scrolls were removed and the bearing lift-off check performed. The jacking gas accelerated the shaft in reverse rotation with no indication of any shaft-to-bearing interference. The electrical shaft-to-frame continuity check indicated a normal open circuit from shaft to ground.

BRU-4 was then completely disassembled and the following observations were noted:

(1) The turbine wheel (figs. 10 and 11) was coated with what appeared to be the same black powder found on the turbine wheel in BRU-2.

(2) The dark area of the seal shroud (figs. 10 and 11) was a dark blue color. The nickel plating in this area was gone. This condition also existed on the inside surface.

(3) The copper heat shunt retained the gold plating, although there were random areas on the inside surface that were tarnished.

(4) The compressor wheel and scroll, except for surface discolorations, were in the as-built condition.

(5) A microscopic examination was made of the pad pivot ball and socket surfaces. Approximately 25 percent of each surface had a frosted appearance. This was the same condition observed at the inspection after 5700 hours.

(6) The pad and shaft journal surfaces appeared to be in the same condition as assembled after the last inspection. No new shaft or pad scratches or high speed rub marks were detected.

(7) The thrust bearing stator and runner surfaces, except for surface discolorations, were in their original condition.

(8) The alternator housing, alternator potting compound, and insulation materials were visually inspected and appeared to be in their original condition.

The components of the rotating assembly were all magnaflux inspected. The results showed no defects. The dimensional inspection of these components showed that no measurable change had occurred.

RESULTS AND DISCUSSION

The turbine scroll is the only potential life-limiting component identified in the BRU's after 21 000 hours of operation. This weakness (weld failure) can be eliminated by changing the configuration from the conventional torus, as used in the BRU, to a simple plenum. The plenum configuration is much simpler to fabricate and eliminates most of the present welds. Wall thickness can be increased in the plenum, thus reducing the operating stresses and increasing cycle fatigue life.

The only measurable creep detected was less than 0.03 percent in 20 000 hours. This occurred in the turbine wheel of BRU-2 and is well below the design goal of less than 0.5 percent creep in 50 000 hours.

The alternator system appears to have been unaffected. The fact that no changes were detected in alternator performance and no changes could be detected in any of the exposed insulation materials reinforces this observation.

The deposits found on both turbine wheels consisted primarily of manganese with some chromium and nickel. The most likely origin of these elements was the facility heat source. The resistance heating elements in the heater were Inconel 600 tubes. The tubes were supported by ceramic headers. These headers were no doubt the source of the white powder found on the copper heat shunt and in the alternator cavity of BRU-2.

Performance of the turbine was apparently unaffected by the deposits on the wheel since there was no measurable change in performance of either BRU.

The purpose of the reflective surfaces on the turbine seal holder and copper heat shunt was to reflect heat radiating from the turbine away from the alternator. Alternator winding temperatures were unaffected by the loss of these reflective surfaces. Winding temperatures in both BRU's were normal through all of the testing.

BRU's have now been inspected after 700, 3000, 5700, 11 000, and 21 000 hours of operation. The surface condition of the bearing pivots was very much the same for each inspection. These results demonstrate that after an initial "wear in," which occurs in less than 700 hours, additional wear is not detectable after operation through 21 000 hours.

BRU-2 ingested a hard particle in the compressor journal bearing as evidenced by the scratch marks on one pad and around the journal. This caused a shaft-to-pad contact in the other fixed pad as evidenced by the rub mark. The resulting conical shaft gyrations explain the edge contact between the runner and stator in the journal bearing. This is at least the third time the bearing system has demonstrated the ability to ingest particles and sustain high speed rubs without impairment to performance or life.

The thrust bearing appears to be immune to particles in the bearing cavity. This is most likely the result of the way the thrust bearing is packaged. The thrust runner is totally encased, except at the hub, by the stators and the stator spacer.

BRU-2 has been reassembled with the original parts. Removal of the surface deposits was the only rework performed. In this build-up all the internal instrumentation (proximity probes and thermocouples), except three alternator hot-spot thermocouples, has been eliminated. The unit has again been placed on endurance test and is presently operating unattended.

CONCLUDING REMARKS

This report presents prior history and the results of post-test inspections conducted on two Brayton rotating units (BRU's) after 11 000 and 21 000 hours of operation.

These tests have demonstrated that the BRU satisfies the design performance objectives and post-test inspections have verified the mechanical integrity of the design with the possible exception of the turbine scroll. This potential problem can be eliminated by redesigning the scroll to change the configuration from a torus to a plenum.

Coatings deposited on the turbine wheel did not affect performance. The loss of reflective coatings on the heat shield and seal housing at the turbine end did not result in an increase in alternator winding temperatures, thereby demonstrating that the reflective coatings are not needed.

The alternator insulation system was unaffected by 21 000 hours of operation. No change was detected in the exposed surfaces of the insulating materials.

Extremely rugged and reliable operation of the gas bearing system was demonstrated. It has repeatedly demonstrated the ability to ingest hard particles larger than the film thickness and sustain shaft-to-pad high speed contacts without affecting performance or life.

Pivot wear after 11 000 and 21 000 hours was the same as that observed in BRU's inspected after 700 and 3000 hours. These results lead to the conclusion that, after an initial "wear in" which occurs within 700 hours, the wear rate decreases to a point where the additional wear is not detectable after an additional 21 000 hours.

Sufficient confidence has been developed in the bearing system that BRU-2 has been reassembled and is now on endurance test without the bearing instrumentation.

The BRU tests that have been conducted and the results of the post-test inspections verify that a major portion of the NASA program objective has been achieved. The technology required to produce a thermo-mechanical power conversion unit for use in a high-efficiency Brayton power system has been demonstrated.

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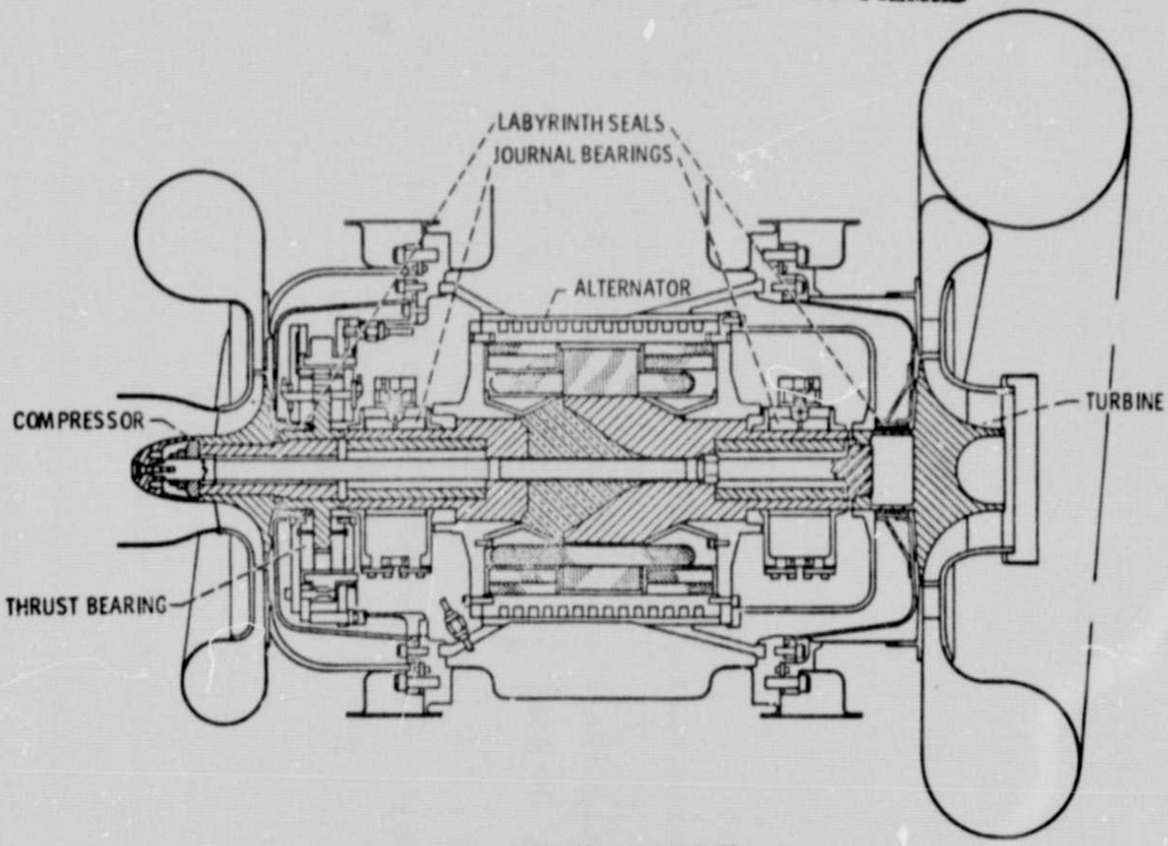
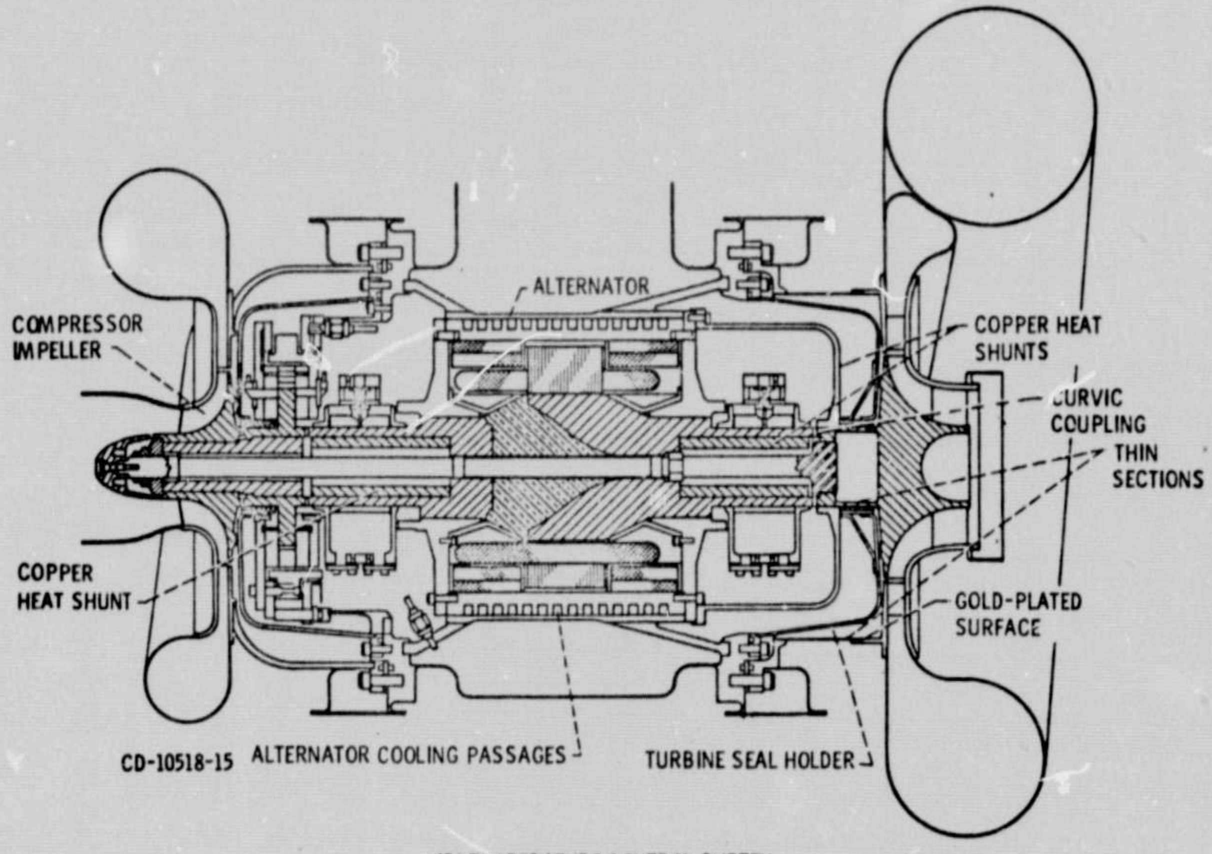


(A) MAIN COMPONENTS.



(B) TEMPERATURE CONTROL SYSTEM.

Figure 1. - Brayton rotating unit cross section.

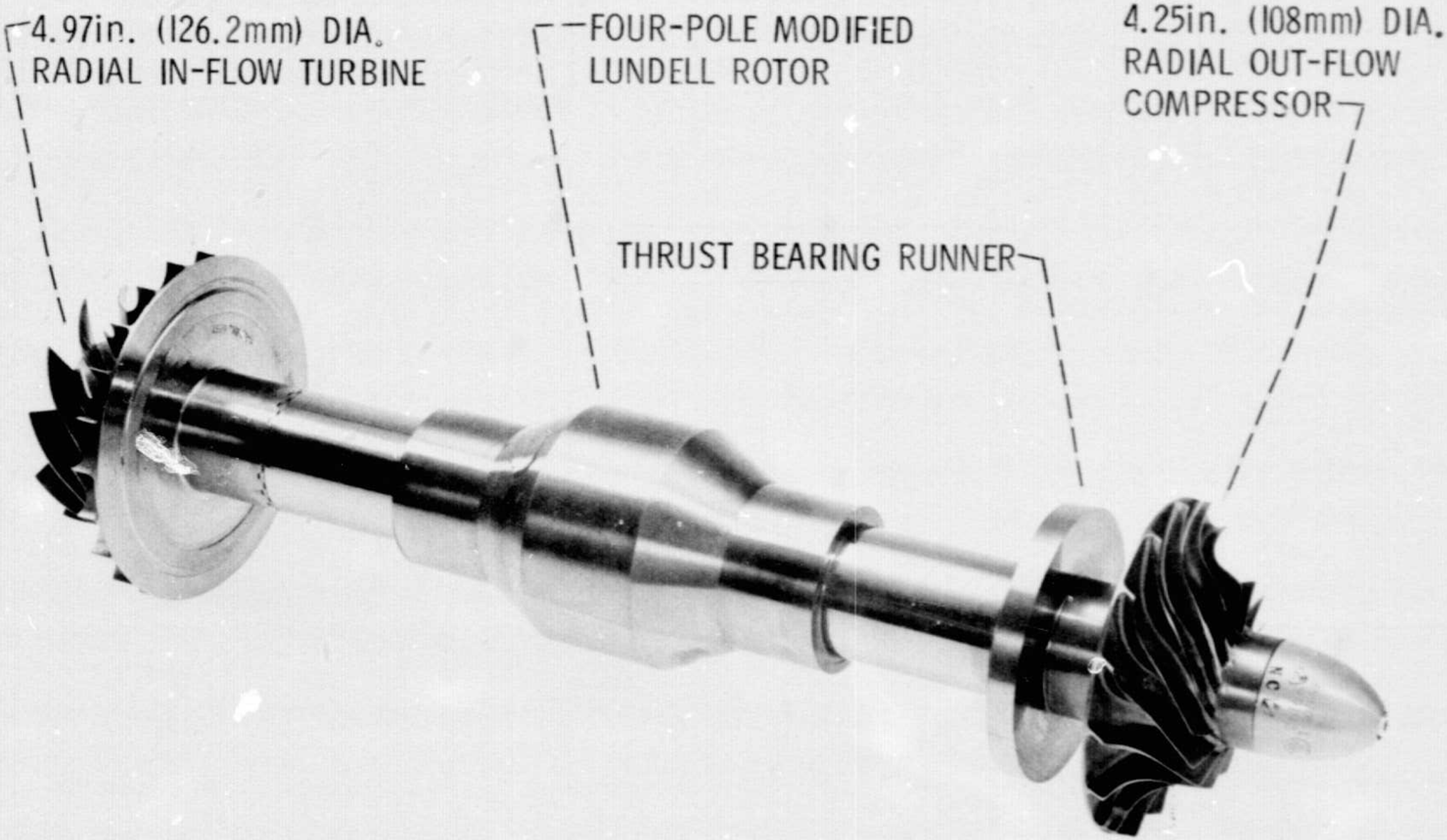


Figure 2. - Rotating assembly of the brayton rotating unit.

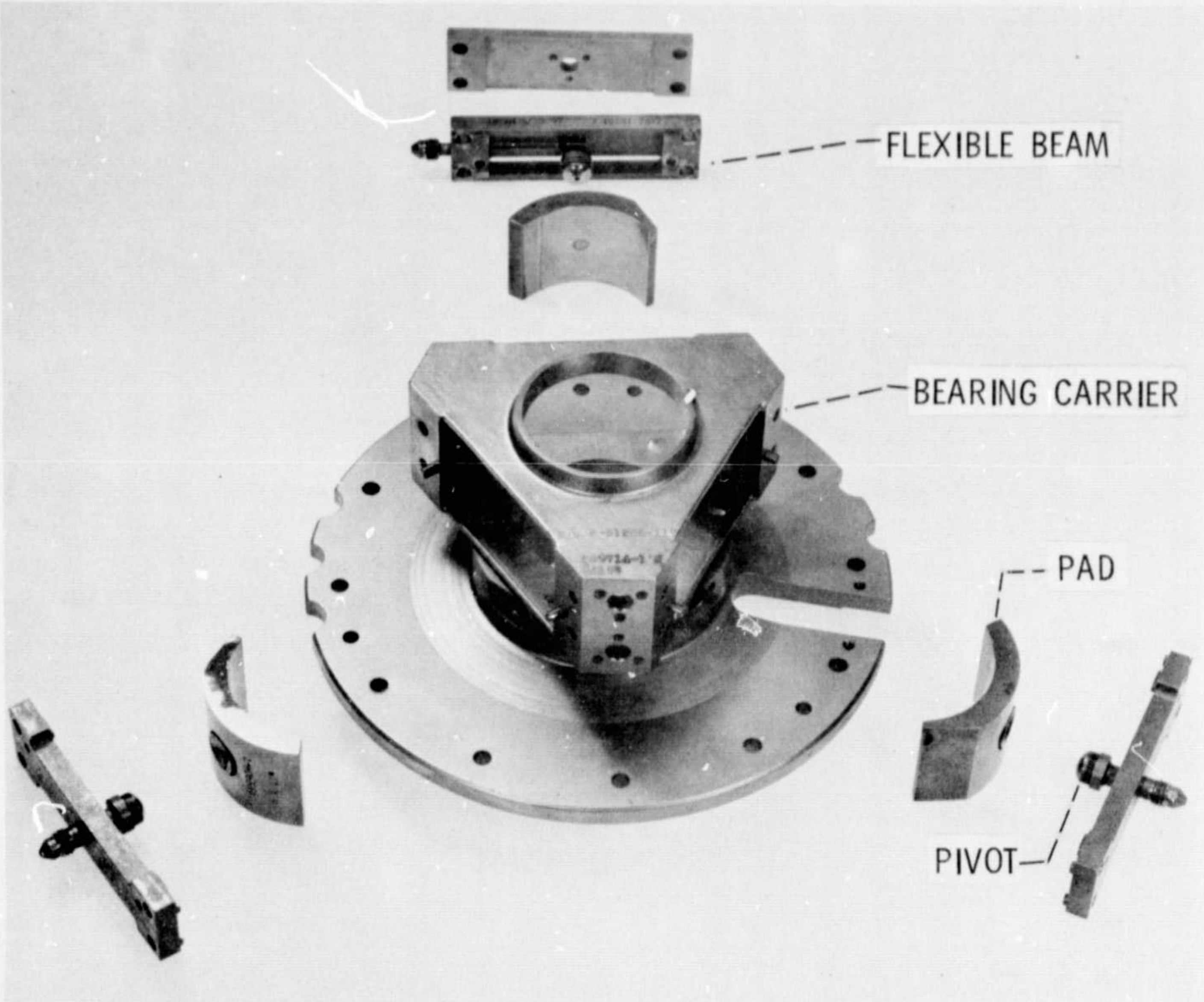


Figure 3. - Journal bearing assembly.

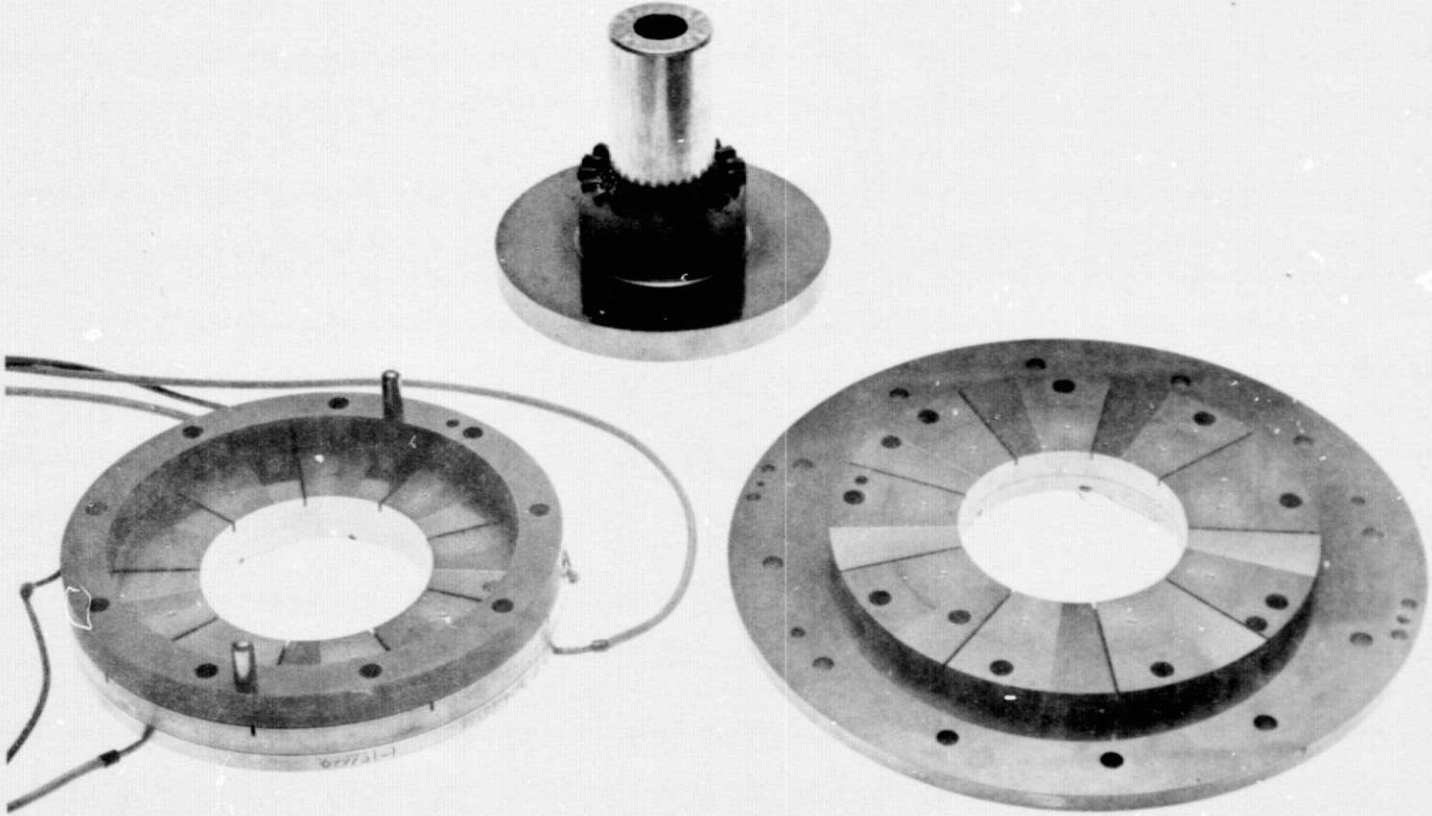


Figure 4. - Thrust bearing stators and runner.

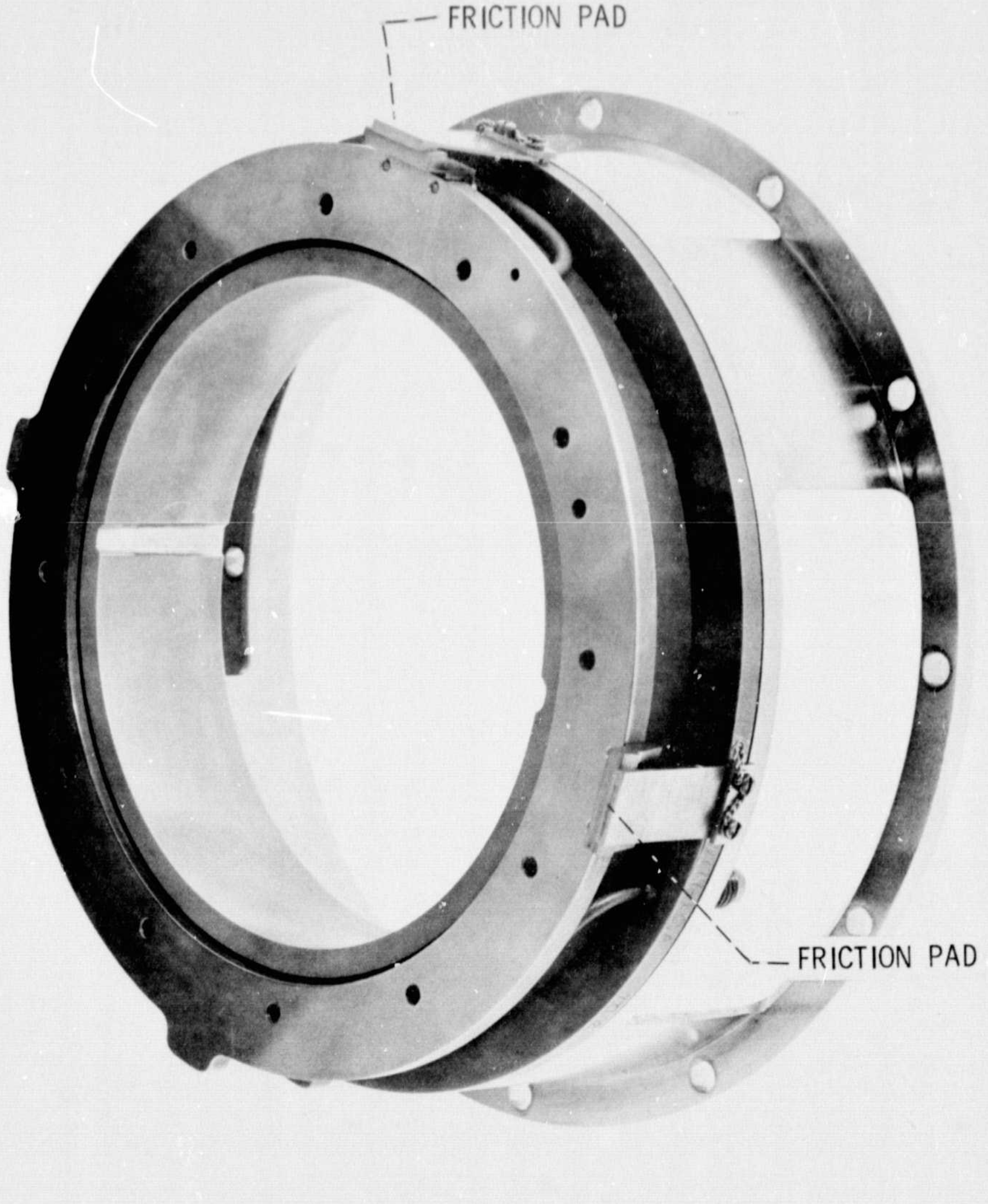


Figure 5. - Flexure pivoted gimbal assembly.

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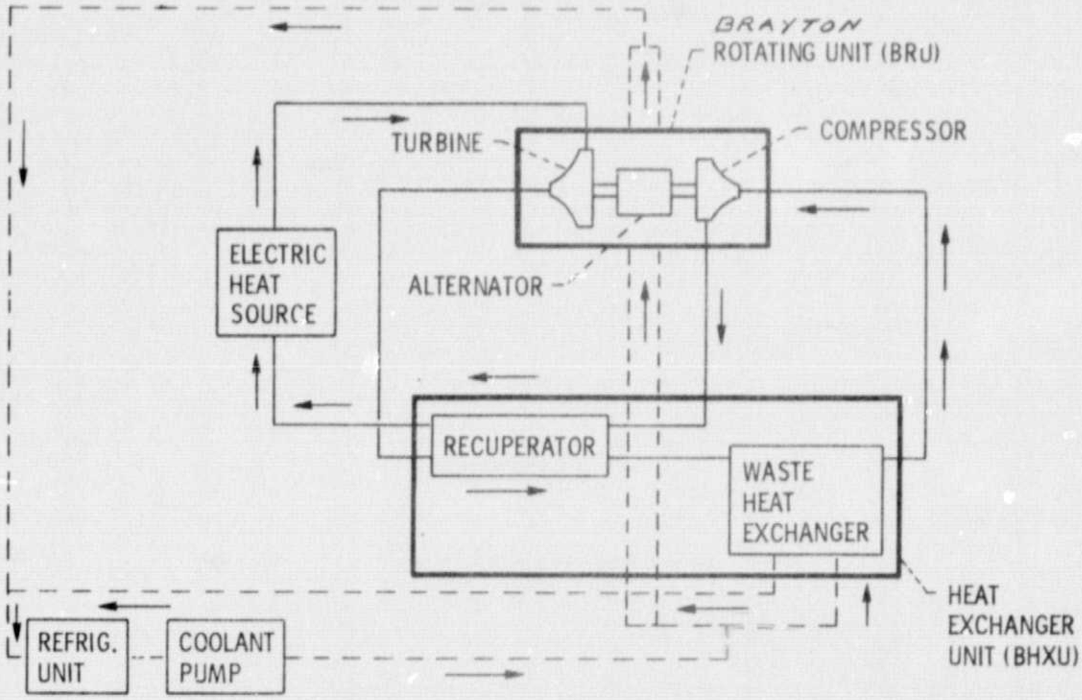

Figure 6. - Schematic of power conversion system.

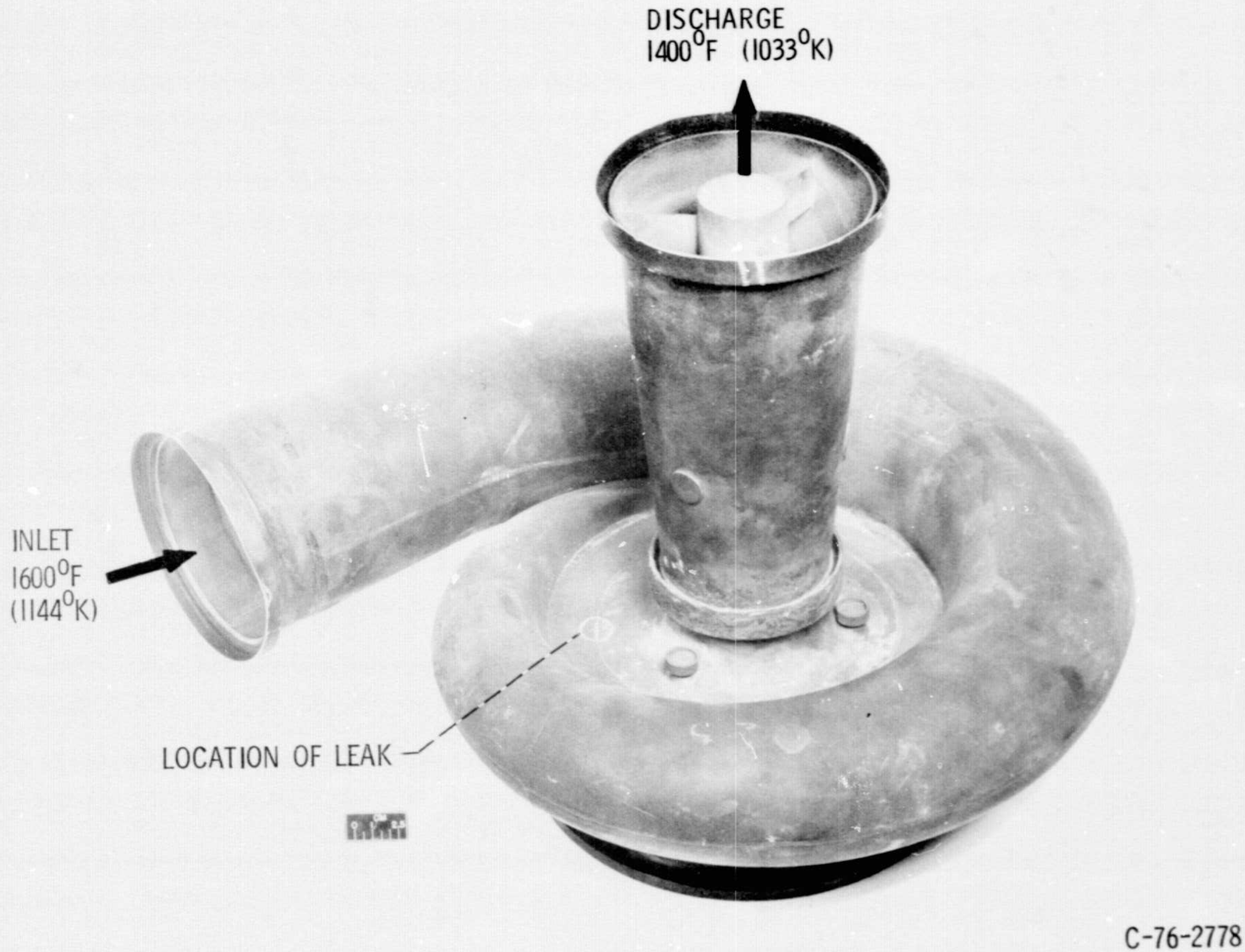

Figure 7. - Turbine scroll brayton rotating unit no. 2.

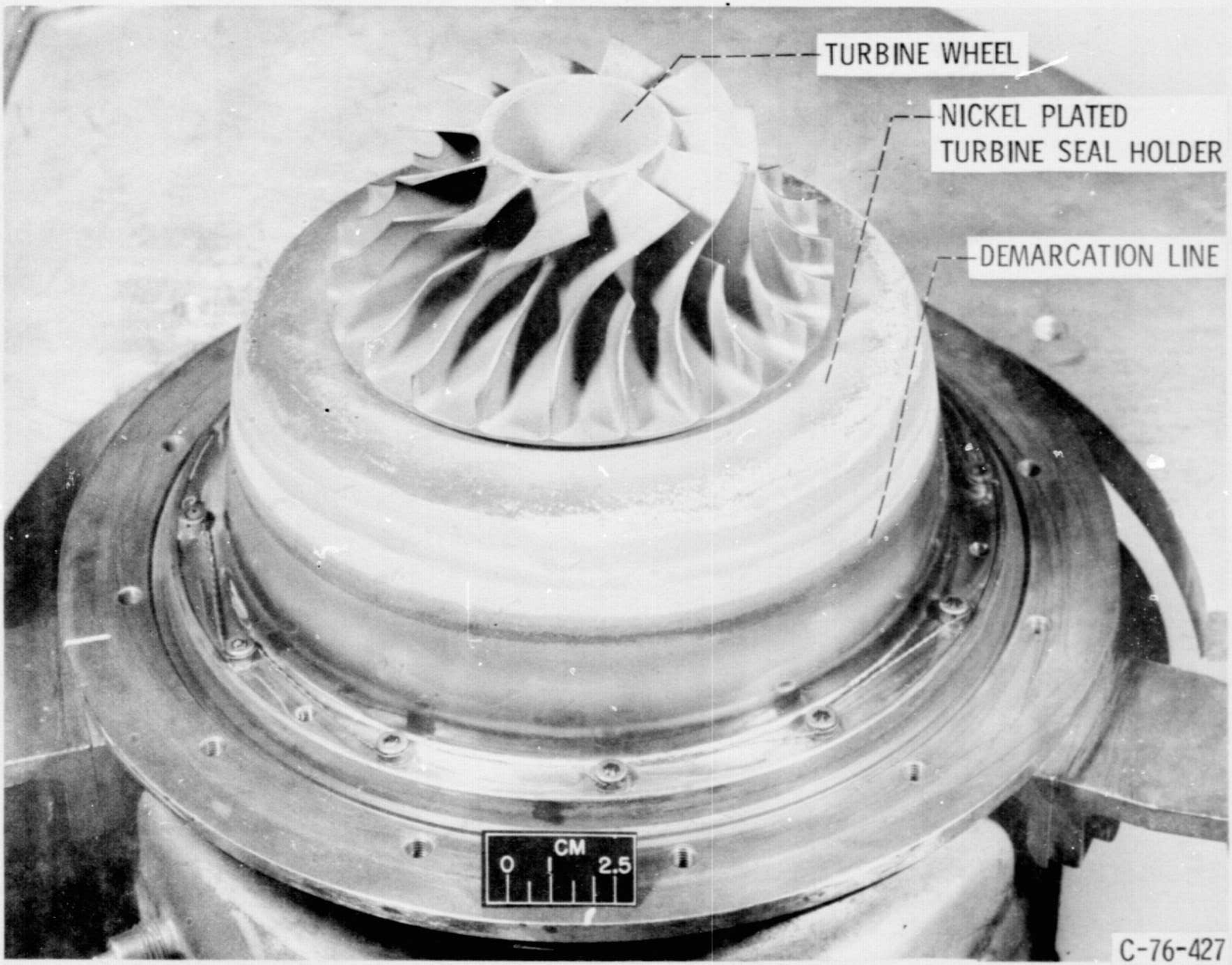

Figure 8. - Turbine wheel and seal holder bru no. 2.

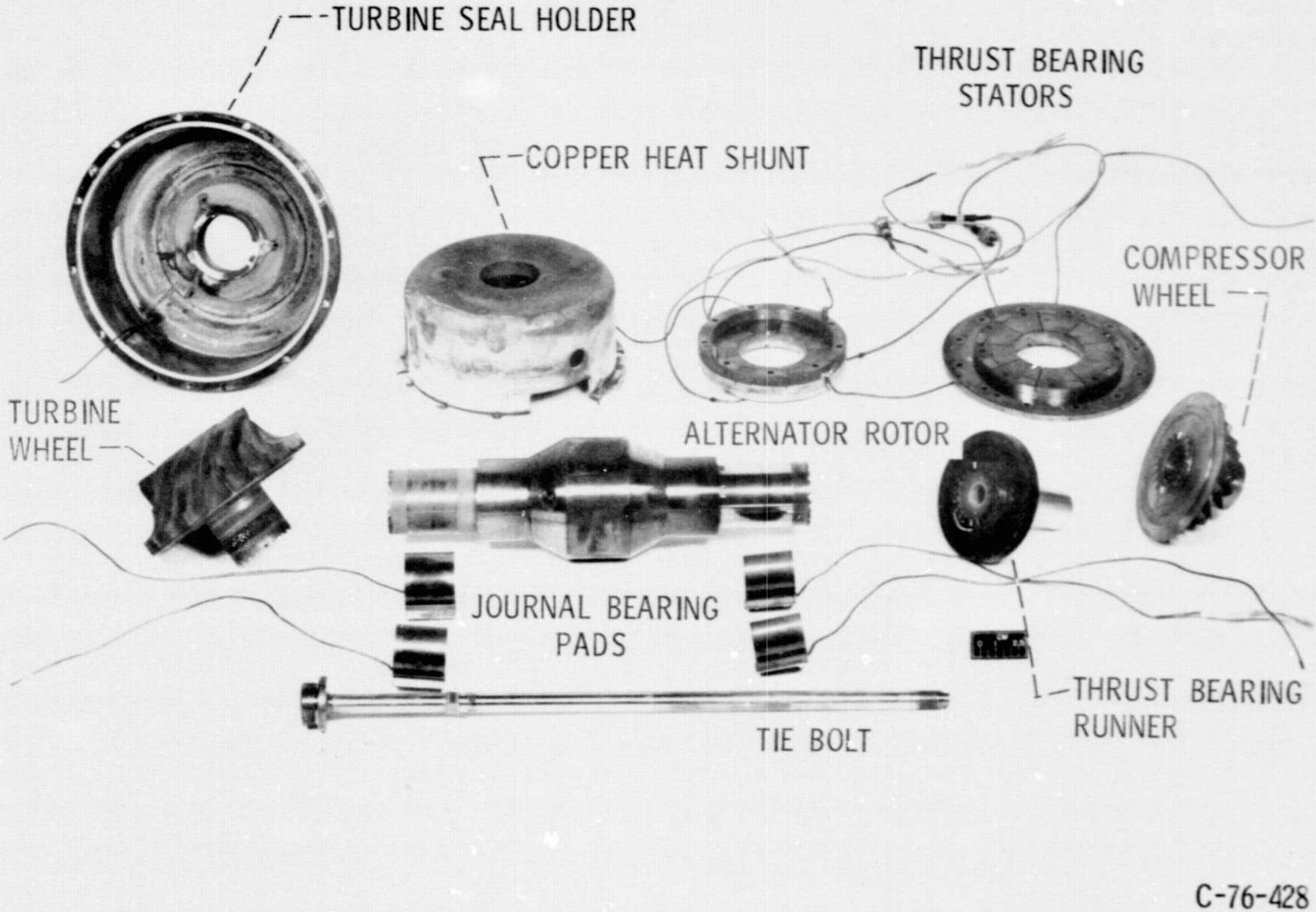

Figure 9. - Brayton rotating unit components - bru no. 2

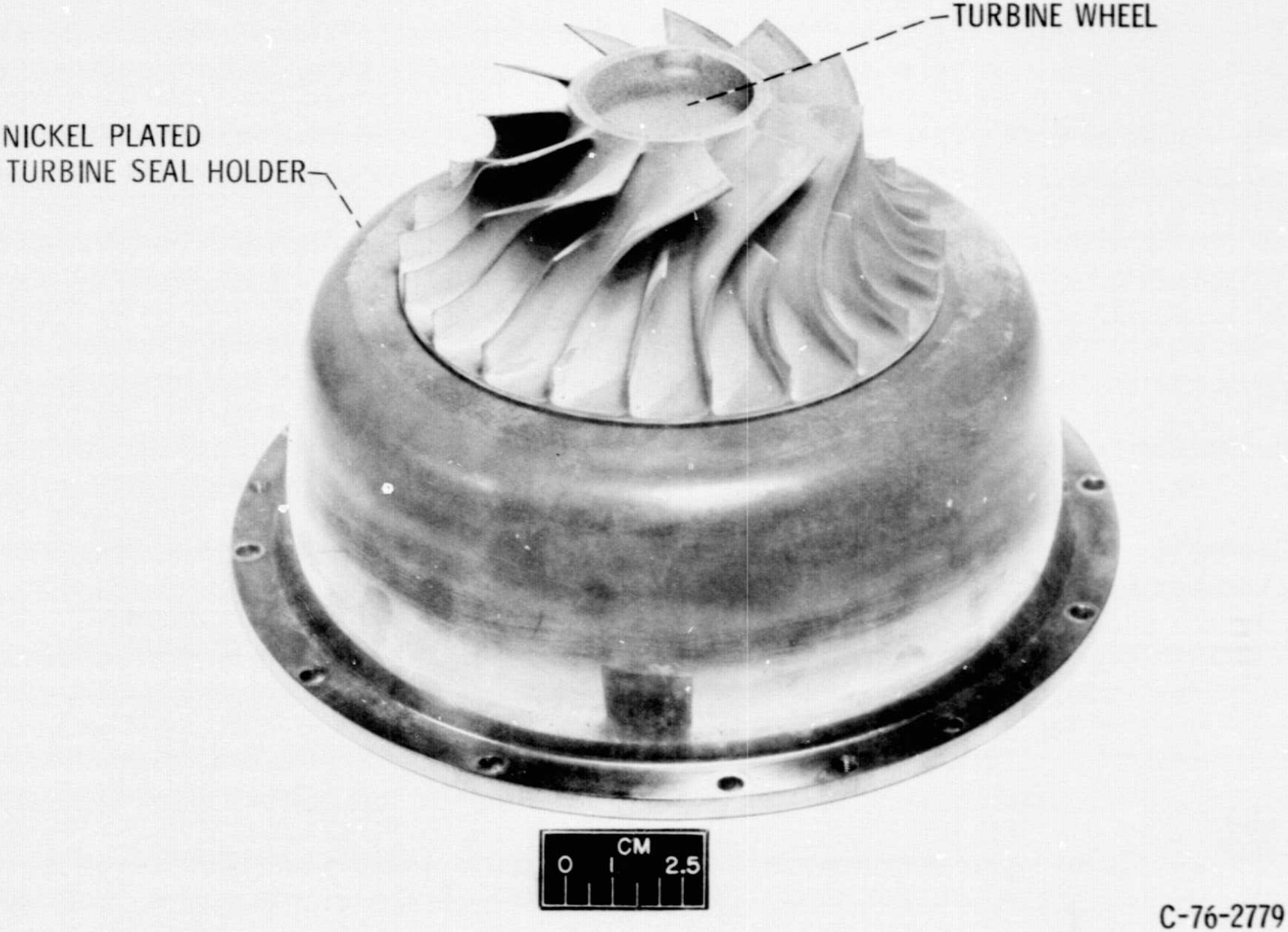

Figure 10. - Turbine wheel and seal holder - bru no. 4

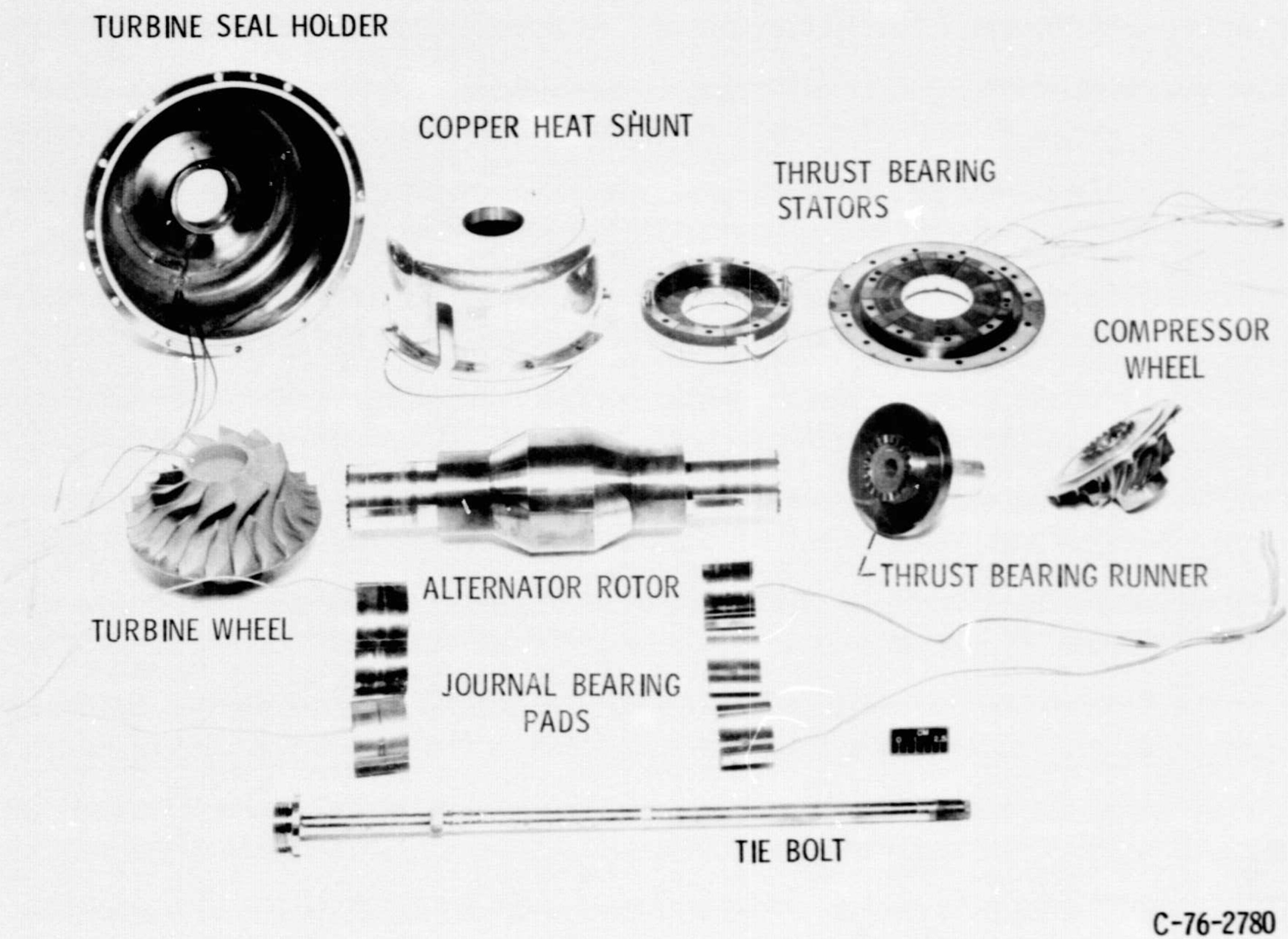

Figure 11. - Brayton rotating unit components - bru no. 4.