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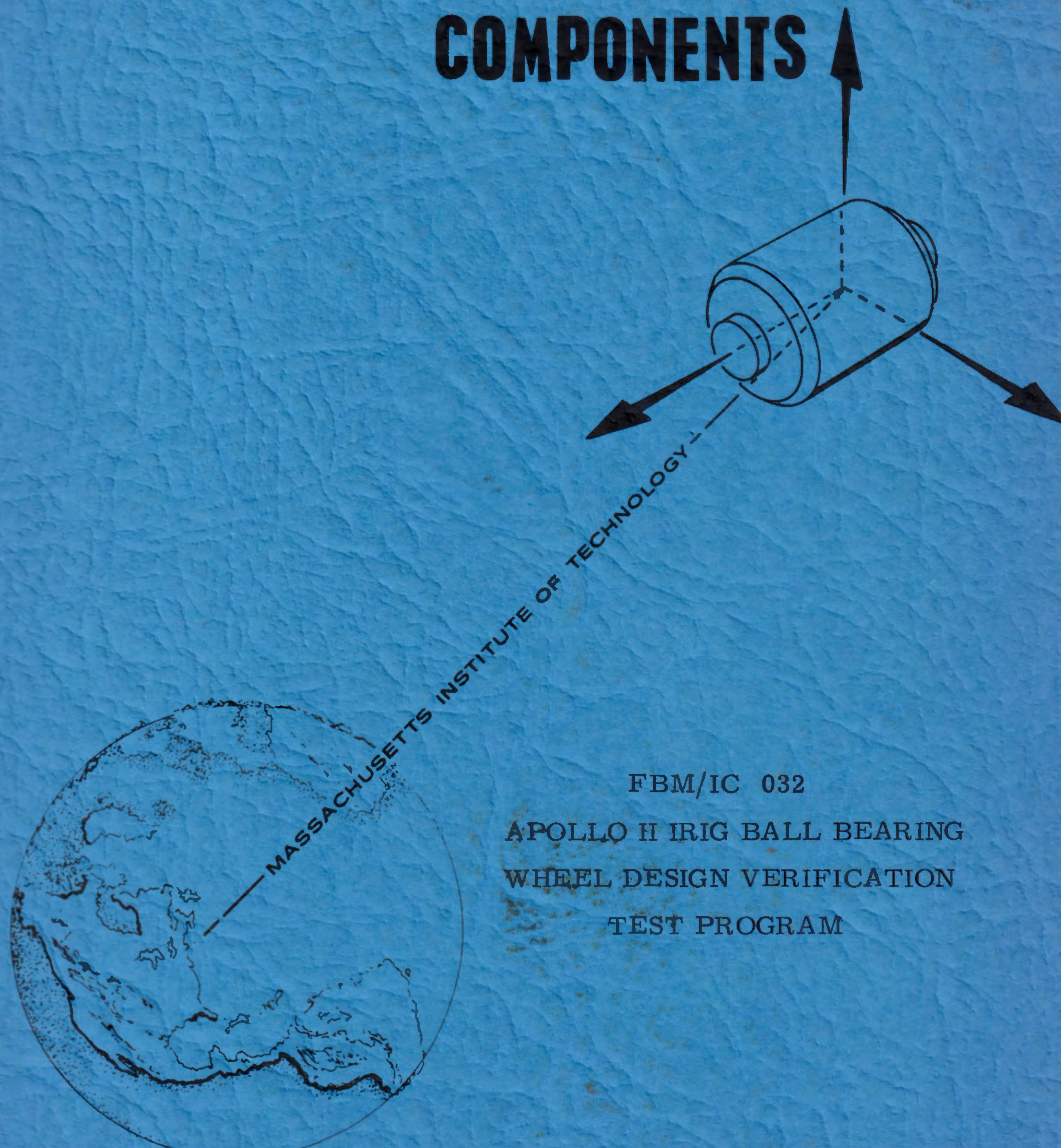

FBM/IC 032

APOLLO II IRIG BALL BEARING WHEEL DESIGN VERIFICATION TEST PROGRAM

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APOLLO II IRIG BALL BEARING

WHEEL DESIGN VERIFICATION TEST PROGRAM

by

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APOLLO II IRIG BALL BEARING WHEEL DESIGN VERIFICATION TEST PROGRAM

1. INTRODUCTION

1.1 Purpose of Tests

The wheel verification test plan was requested by NASA-MSC for the purpose of verifying the design of the 071 and 081 configurations of the Apollo II, 25 IRIG ball bearing wheel.

The 071 wheel configuration, Drawing 2021701-071, specifies the use of Teresso V-78 oil, outer race riding nylasint retainer, three pound nominal preload, and alumina TCP stick polished races. The 081 configuration, Drawing 2021832-011, specifies the use of SRG 160 oil, inner race riding retainer, one pound nominal preload, and alumina TCP felt polished races.

1.2 Scope of Tests

The wheel verification test plan is covered in detail in reference number 1. A total of seven wheels were assembled, tested, and placed on life test at the MIT Draper Laboratory. Three of the wheels were built to the 071 configuration and the remaining four to the 081 configuration. The wheels were visually inspected and performance parameters measured and recorded at periodic intervals. A description of the tests performed is presented in Paragraph 2. Test results are covered in Paragraphs 3 and 4.

An additional nine wheels were built and placed on life test by Bendix Corporation. Four were built to the 071 configuration and five to the 081 configuration. Results of these tests will be reported separately by Bendix.

1.3 Delta 25 Criterion

A study has been made relating long term drift data to the gyro ADIA term. (See Reference No. 2.) It was found that the ADIA term for ninety percent of the gyro population tested was stable to better than 25 meru/g. Using this information, it was established that a change greater than 25 meru/g can be used to predict impending wheel failure. The stability of the ADIA drift term is a measure of the mass stability of the gyro wheel and other float parts along the spin axis. Since the wheel is the largest mass on the spin axis, this term is used as an indication of the wheel ball bearing condition. The delta 25 failure criterion was set up on the basis of an observed correlation in data between a 25 meru/g shift in the ADIA term and a simultaneous change in retainer beat frequency of 0.1075 cps. The criterion thus employs the use of retainer beat frequency stability in classifying a wheel as a predicted or catastrophic failure. This is discussed in more detail in the next paragraph.

1.4 Failure Guide Lines

Reference No. 3 outlines the failure guide lines used in the bearing verification test program. In this reference a wheel is defined as a catastrophic failure if it fails to reach synchronous speed with the application of 26.6 volts or drops out of synchronous speed when running at 26.6 volts. A second parameter used to define catastrophic failures is a level change of retainer beat frequency greater than 2.15 cps (500 meru/g Δ ADIA) across wheel rundowns.

A wheel is defined as a predicted failure if any one of the following performance limits are exceeded:

(1) Decrease in wheel rundown time of greater than 20 seconds for 071 configuration wheels and 30 seconds for 081 configuration wheels. Rundown time is measured from 24000 to 6000 rpm.

(2) Wattmeter non-periodic changes of greater than 80 mw.

(3) Level changes of retainer beat frequency between successive rundowns of greater than 0.1075 cps (25 meru/g delta ADIA).

(4) Instability of retainer beat data within a test of greater than 0.1075 cps (25 meru/g delta ADIA).

(5) Peak-to-peak variation across all rundowns in retainer beat frequency of greater than 0.215 cps (50 meru/g delta ADIA).

If the retainer beat frequency is unstable, then ball beat frequency may be monitored. The cps limits in Paragraphs 3, 4, and 5 above would then be multiplied by a factor of seven. For a wheel to fail beat frequency both retainer and ball beat frequencies must be outside of limits.

As stated in Reference No. 3, "If the number of operating hours between failure prediction and catastrophic failure is greater than 500 hours, a successful prediction is obtained. This failure would then not be counted as a failure for the inflight MTBF calculation." It was permissible to run a predicted failure wheel until catastrophic failure.

1.5 Program Goal

Reference No. 1 defines the program goals achievement to be the following:

1.5.1 To establish that the useful life expectancy is 3500 hours or more

1.5.2 To establish that the MTBF during useful life is 10,000 hours or more.

2. DESCRIPTION OF TESTS PERFORMED

2.1 Description of Test Set-Up

The wheels were life tested in a milliwattmeter fixture, MIT Drawing E-159826. They were operated in an ambient of one-half atmosphere of helium at a temperature of 137°F. Five of the wheels, three with the 071 configuration and two with 081 configuration, were tested with spin axis horizontal. (See Figure No. 1.) The remaining two 081 configuration wheels (See Figure No. 2) were tested with the spin axis vertical. Figure No. 3 is a photograph of dynamometer room showing design verification life test set-up.

2.2 Summary of Tests Performed

Itemized below are the tests performed on all wheels and the frequency of testing.

WHEEL TEST	FREQUENCY OF TEST	COMMENTS
(1) Visual inspection (Wheel operating)	2 weeks	Stability of retainers was observed.
(2) Visual inspection (Wheel not operating)	6 weeks	Condition of inner races, balls and retainers observed.
(3) Record differential milliwatt power	2 weeks	Recorded for 1 hour.
(4) Record retainer/ball beat frequency	2 weeks	Recorded for 2 hours.
(5) Wheel run-up time	2 weeks	---
(6) Wheel rundown time	2 weeks	---
(7) Minimum wheel synchronous voltage	2 weeks	---
(8) Wheel breakaway voltage	2 weeks	---

2.3 Visual Inspection (Wheel Operating)

Visual inspection with wheel operating was performed to observe the stability of retainer motion. The retainer was observed using a stroboscopic light and an American Optical binocular microscope at 10X magnification. The stroboscope was externally triggered using a variable oscillator and electronic counter. The oscillator was initially set at 243 Hz which is the retainer frequency. With slight adjustment, the retainer may be made to appear to stop. This permits observation whereby any erratic or unstable radial or circumferential motions of the retainer may be noted.

2.4 Visual Inspection (Wheel Not Operating)

Once every six weeks (1008 hours), each wheel was removed from the life test fixture and the bearings examined under 30X magnification. The bearings were not disassembled from the wheels, so that it was not possible to completely examine all the raceway surfaces. In the 25 IRIG wheel design, the inner race, balls and part of the retainer may be seen without disassembly. This is usually sufficient to determine whether or not the bearing is beginning to deteriorate.

2.5 Record Differential Wheel Power

The equipment used to record differential wheel power is specified in MIT Spec MC 25-889. See Figure No. 4 for diagrammatic set-up of milliwattmeter test. The wheel power was continuously recorded for a minimum period of one hour every two weeks. If,during any one run, there were non-periodic changes of greater than 80 mw, the wheel would have been considered to be a predicted failure.

2.6 Record Ball/Retainer Beat Frequency

The retainer beat frequency is caused by the two retainers rotating at frequencies very close to each other. With a relatively small degree of damping, a forced vibration or beating results as illustrated in Figure No. 5. The period of the beat is:

$$T_{beat} = \frac{2\pi}{\omega_1 - \omega_2}, \text{ seconds} \qquad (1)$$

where ω_1 and ω_2 are rotational frequencies of the two retainers in radians/sec.

Figure 6(A) shows a technique for measuring the period of each retainer. Knowing the period of each retainer, the rotational frequencies may be found by the following relationship:

$$\omega_1 = \frac{2\pi}{t_1}, \text{ rad/sec} \qquad (2)$$

where t_1 = period of no. 1 retainer in seconds. With ω_1 and ω_2 known, the beat period is easily obtained from Equation (1).

The method used in this program is illustrated in Figure 6(B). Here a Columbia accelerometer is used as a pick-up. The signal from the accelerometer is amplified by the cathode follower which also serves to match the output impedance of the accelerometer. A wave analyzer is used to detect the beat frequency so that it may be recorded by the Sanborn recorder. If there is any doubt as to whether the frequency being recorded is the beat frequency, the method shown in Figure 6(A) may be used as verification.

The retainer beat frequency was recorded for two hours continuously once every two weeks. If the retainer beat frequency was stable, the ball beat frequency was also recorded for a short period of time (approximately ten minutes). If the retainer beat frequency trace became unstable so that an accurate determination of the retainer beat frequency was not possible, then the ball beat frequency was recorded for the two hour period. In this case the unstable retainer beat frequency was recorded for the ten minute interval. The failure criteria for excessive changes in retainer/ball beat frequency was previously covered in Paragraph 1.4.

2.7 Wheel Run Up Time

A number of factors affect wheel run up and rundown times. The main factors in an angular contact ball bearing are:

(a) Friction due to bearing preload and surface finishes at the rolling contact surfaces

(b) Separator rubbing friction

(c) Lubricant drag due to viscosity and amount of free oil

(d) Windage effects

(e) Bearing tolerances

(f) Operating temperature

Assuming constant operating temperature, the first three items are probably the most significant ones for explaining variation in run up time between different wheels. Typical run up time for the 071 configuration was 80 seconds and for the 081 configuration 70 seconds. The difference may be attributed primarily to the lower preload required for the 081 configuration. Wheel run up time was recorded once every two weeks. Rundown time is more significant than run up time in that it is not affected by variations in wheel power supply. Wheel run up time was not used to classify a wheel as a predicted or catastrophic failure.

2.8 Wheel Run Down Time

The wheel run down time is obtained by placing a short circuit between both phases of the wheel for a three second period. This is done immediately after opening the line between the wheel power supply and stator windings while the wheel is running at synchronous speed. The wheel run down time was measured once every two weeks. A change in wheel run down time, measured from 24,000 to 6,000 rpm of greater than 20 seconds on 071 configuration wheels and 30 seconds on 081 configuration wheels was considered excessive. A wheel exceeding these limits was classified as a predicted failure. Typical run down time range for the 071 configuration varied from 110 to 130 seconds and for the 081 configuration from 125 to 160 seconds.

2.9 Minimum Wheel Synchronous Voltage

Minimum synchronous voltage is the lowest voltage value required to achieve and maintain synchronous speed. The Apollo specification sets the maximum value for this parameter at 26.6 volts. Since MIT wheel fixturing affords visual accessibility, a strobotac is used to determine the minimum synchronous voltage. The strobe light is triggered by the wheel supply oscillator to ensure an in-phase condition. The voltage is attenuated until the wheel drops out of synchronous speed. At this point, the voltage is increased in 1/2 volt increments until the strobotac flashes a "stationary" image. If this image does not drift or is locked in a "hunting" mode, the wheel is said to be at synchronous speed.

Minimum wheel synchronous voltage is measured once every two weeks. As stated in Paragraph 1.4, "A wheel is defined as a catastrophic failure if it fails to reach synchronous speed with the application of 26.6 volts or drops out of synchronous speed when running at 26.6 volts." A typical value of minimum wheel synchronous voltage is 18.5 volts.

2.10 Wheel Breakaway Voltage

This measurement is accomplished by a slow and gradual application of power to the wheel. The voltage required to start the wheel rotating is the breakaway voltage. There is no specific requirement for this test other than a reasonable repeatability of the starting voltages, usually within two volts across all readings. A trend of increasing breakaway voltage provides a useful indicator of bearing problems. An occasional non-conforming value may reflect erratic retainer performance. Wheel breakaway voltage was measured once every two weeks.

2.11 Teardown Analysis

After the life tests were completed, representative wheels were disassembled for the purpose of correlating the final condition of the bearing hardware with test results. To accomplish this, one 071 configuration and one 081 configuration wheel were disassembled and processed through a teardown analysis. Results are presented in Appendix A.

3. TEST RESULTS

3.1 Visual Inspection (Wheel Not Operating)

Visual assessment of the bearing and lubrication condition constitutes a most important phase of wheel life test evaluation. It offers the invaluable opportunity of correlating visual changes with recorded data.

3.1.1 Visual Inspection of 071 Configuration Wheels

3.1.1.1 Wheel CR-107B

At the completion of 330 hours of dynamometer testing, visual inspection revealed no discoloration, debris, or residue deposits. All bearing surfaces were liberally lubricated and oil menisci were present under the balls. The -SRA balls had faint gray multiple bands. The +SRA balls were not banded. The wheel was accepted and placed on life test with SRA horizontal. At 1500 hours, a narrow band of dark lubricant residue was seen on the upper portion of both inner races. There was no change in the banding of the -SRA balls. Oil conditions were as before. After 5000 hours, the -SRA ball banding was more noticeable. The visual inspection at 7126 hours showed that oil breakdown residue deposits, particularly on the +SRA bearing had increased. The gray banding had widened on the -SRA balls. At 8632 hours, markedly heavier residue deposits were observed on the +SRA end. The -SRA ball bands were becoming frosty gray and the inner race residue accumulation at this end had also increased. Bearing roughness was apparent when the wheel was spun by hand.

3.1.1.2 Wheel CV-112A

Upon completing 213 hours of dynamometer testing, the visual inspection revealed no discoloration, debris, or residue deposits. There was good lubrication throughout the bearings and oil menisci under all balls. Shiny wear bands were noticed on the -SRA balls. The wheel was accepted and placed on life test with SRA horizontal. At 1012 hours, the -SRA inner race had developed a wide dark residue band. The shiny ball banding was unchanged. After 1540 hours, the -SRA inner race ball track area was discolored and light gray bands were seen on the balls. The +SRA bearing, for the first time, showed discoloration on the ball track and a residue deposit band above it. Good lubrication and oil menisci were still in evidence. At 8141 hours, the status of both bearings remained essentially the same. The wheel felt smooth when spun by hand.

3.1.1.3 Wheel CR-113B

Upon completing 242 hours of dynamometer testing, the visual inspection revealed no discoloration, debris, or oil breakdown. All bearing surfaces were liberally lubricated and oil menisci were seen under the balls. The balls of both bearings had light gray wear bands. The wheel was accepted and placed on life test with SRA horizontal. At 450 hours the -SRA inner race ball track had become discolored. Above this straw colored track was a ring of unevenly deposited residue. A frosty gray band edged with discoloration was now noted on the seven balls. After 1080 hours, there was a darkening of the residue deposit band on the -SRA inner race, while the other conditions appeared unchanged. The +SRA bearing was now showing deterioration. This raceway had a frosted gray wear track with a residue band above it. The ball banding had changed to a medium gray shade. Lubrication was still adequate. The condition of both bearings continued to degrade with running time. At 7582 hours, the -SRA bearing showed no trace of oil film. The raceway was dry and gritty. A heavy dark gummy residue belt circled the upper portion of the inner race. Fragments of varnish and retainer debris were scattered on both sides of the ball track. Prominent bronze colored bands girdled the balls.

The +SRA bearing was adequately lubricated, although the oil was murky in character. The balls were criss-crossed with multiple gray wear bands. Adjacent to the dark gray ball track, on the load side, was a dark caked ring of oil residuum. The wheel felt very gritty when spun by hand.

At 3975 hours, on June 19, 1969, the wheel was classified as a predicted failure because of its unstable beat frequency data. All other test data remained within limits. The wheel was run to 7713 hours, at which time on December 11, 1969, life tests on 071 configuration wheels terminated per instructions from NASA-MSC. During the data check periods, the beat frequencies remained unstable. All other test results were within specified limits.

3.1.2 Visual Inspection of 081 Configuration Wheels

3.1.2.1 <u>Wheel CV-115E</u>

Upon completing 216 hours of dynamometer testing, visual examination showed both bearings to be free of discoloration, debris, and residue deposits. Good lubrication and oil menisci were present. No ball banding was noted on either end. The wheel was accepted and placed on life test with SRA vertical. After 9124 hours, there were no visible anomalies on either bearing. Good lubrication and oil menisci were still evident on both ends. The wheel felt smooth when spun by hand.

3.1.2.2 Wheel CV-92J

Upon completing 279 hours of dynamometer testing, visual inspection showed both bearings to be free of discoloration, debris, and residue accumulation. Liberal lubrication and oil menisci were present at both ends. Partial light gray bands were visible on the -SRA balls. The wheel was accepted and placed on life test with SRA vertical. At 3879 hours, a narrow faint spotty residue line was noticed on the high end of the -SRA inner race. There were no other changes in either bearing. Visual examination at 7230 hours showed continued good lubrication, menisci, and no change in bearing surface conditions. However, one nylasint ball pocket and the adjacent ID surface of the -SRA retainer were markedly stained. At 8380 hours, no further changes were seen in bearing, retainer, or lubrication conditions. The wheel felt smooth when spun by hand.

3.1.2.3 Wheel CV-123B

Upon completing 238 hours of dynamometer testing, visual inspection showed both bearings to be free of discoloration, debris, and residue deposits. The bearings were liberally lubricated and oil menisci were observed under the balls. The wheel was accepted and placed on life test with SRA horizontal. At 1754 hours, shiny ball banding appeared on the +SRA end. At 6615 hours, the +SRA bearing began to show spotty residue on the upper portion of the inner race slope. No change in lubrication was observed at 7933 hours. There was no discoloration or debris on either raceway. Shiny bands were still present on the +SRA balls. The uneven residue ring on the +SRA shaft slope was darker. There were no other changes in the bearings. The wheel felt smooth when spun by hand.

3.1.2.4 Wheel CV-121D

Upon completing 235 hours of dynamometer testing, the visual examination showed both bearings to be free of discoloration, debris, and residue deposits. All bearing surfaces were liberally lubricated and oil menisci were observed under all balls. The wheel was accepted and placed on life test with SRA horizontal. The first change was noted at 5984 hours. Narrow shiny bands were seen on the -SRA balls and light gray banding on the +SRA balls. An occasional spot of residue dotted the upper portion of the +SRA inner race slope. Visual inspection at 7302 hours showed no change from the previous examination. The wheel felt smooth when spun by hand.

3.1.3 Comparison of Visual Inspection Results of 071 and 081 Configurations

There were several significant differences observed during visual inspection between the 071 and 081 configurations. The foremost difference was metal discoloration on the inner race ball track. Bearings of two of the three 071 wheels, CV-112A and CR-113B, were discolored. No discoloration was noted on 081 bearings.

Ball banding was also more prominent on the 071 bearings than the 081 bearings. Two 071 wheels, CV-112A and CR-113B, had wide frosty gray to bronze-colored wear bands. 081 ball banding ranged from a shiny to a light gray color. Both configurations had balls which were not affected.

Another notable difference was the early formation of residue on the inner race of the 071 bearings. This condition began within 450 to 2000 hours and usually worsened. The 081 bearings were less seriously affected. CV-92J (081 configuration) developed a light spotty deposit at 3879 hours. At 8380 hours, no further change was observed. Both CV-123B and CV-121D (081 configuration) ran approximately 6000 hours before light spotty deposits appeared. CV-115E (081 configuration) at 9124 hours was completely free of inner race residue.

Both of the 071 wheels (CV-112A and CR-113B) which showed bearing degradation reflected this condition in the roughness felt while hand spinning the rotor. The 081 wheels, which were visually superior, felt very smooth when they were spun by hand.

3.2 Differential Wheel Power

In evaluating the differential power recordings, trace quality and stability were carefully considered. Increasing hash width, trace wander, non-periodic power variations, jogs, and spikes are among the trace characteristics reflecting a wheel's performance. However, in evaluating milliwattmeter traces, it must be kept in mind that electromagnetics and instrumentation may also influence the trace behavior. See Figure No. 7 for recording chart speed and sensitivity.

3.2.1 Differential Wheel Power of 071 Configuration Wheels

3.2.1.1 Wheel CR-107B

All of the differential milliwattmeter recordings were within design verification test program (DVTP) specification limits. The trace quality was reflective of the liberal oil content of the bearings and displayed the characteristic power irregularities, large jogs, and variable hash widths typical of oil build-up. See Figure No. 8.

3.2.1.2 Wheel CV-112A

All of the differential milliwattmeter recordings were within DVTP specification limits. The trace quality reflected the liberal oil content of the bearings. The trace quality was generally good. Oil build-up, however, contributed to minor power irregularities. See Figure No. 9.

3.2.1.3 Wheel CR-113B

All of the differential milliwattmeter recordings were within DVTP limits. The trace hash varied, but the overall trace quality was good. Oil jogs disappeared after 5,568 hours. There were no prominent power irregularities. The good trace quality belied the wheel's poor visual appearance. See Figure No. 10.

3.2.2 Differential Wheel Power of 081 Configuration Wheels

3.2.2.1 Wheel CV-115E

The quality of both dynamometer and differential milliwattmeter recordings reflect high oil content. The trace history is a continuous delineation of hashy irregularities, spikes, and oil jogs. However, in over 9000 hours of running in the SRA vertical position, despite poor trace quality and the later appearance of power spikes, the bearings retained their visual excellence. See Figure No. 11.

3.2.2.2 Wheel CV-92J

After 1000 hours, the differential milliwattmeter trace began to reflect increased oil bleedout rate from the retainers. Large oil jogs and trace irregularities became characteristic of this wheel. Variations were within DVTP limits. Visual inspections, during approximately 9000 hours of running in the SRA vertical position, showed a good bearing condition and confirmed that the trace irregularities were a function of the liberal oil supply. See Figure No. 12.

3.2.2.3 Wheel CV-123B

In approximately 8000 hours of running, the differential milliwattmeter recordings remained within DVTP limits. There were some power irregularities typical of oil build-up. However, the trace quality was generally good and the mean power levels were stable. See Figure No. 13.

3.2.2.4 Wheel CV-121D

The 7000 hour history of differential milliwattmeter traces for this wheel were generally smooth. There were mild power irregularities and a few jogs reflecting an occasional oil film build-up. For the most part, the trace recordings were uneventful. See Figure No. 14.

3.2.3 Comparison of Differential Power Results of 071 and 081 Configurations

There were no obvious power trace characteristics peculiar to a particular configuration. Both configurations were similarly responsive to varying oil film conditions and equally reflected individual wheel behavior patterns through power variation. No one characteristic, i.e. trace width, oil jogs, or non-periodic power variations, predominated any one configuration.

3.3 Retainer/Ball Beat Frequency and Visual Inspection (Wheel Operating)

The retainer and ball beat frequencies (243 Hz and 1201 Hz respectively) were recorded and studied for frequency stability. Beat frequency limits were previously covered in Paragraph 1.4.

As described in Paragraph 2.3, bearings were observed with the wheel operating. The purpose of this was to note any correlation between changes in retainer motion and beat frequency. See Figure No. 7 for sample traces and chart speeds.

3.3.1 Retainer/Ball Beat Frequency of 071 Configuration Wheels

3.3.1.1 Wheel CR-107B

The retainer beat frequency was outside the DVTP limit by 0.04 Hz across all measurements, while between tests the requirement was met. See Figure No. 15. The ball beat frequency deltas were inside limits. See Figure No. 16. Both beat frequency patterns were reasonably stable and the waveshapes were relatively undistorted. See Figures 17 and 18. Visual observations showed that the retainer behavior in both bearings varied from stable periods to periods of mild radial instability.

3.3.1.2 Wheel CV-112A

The retainer beat frequency was outside the limit by 0.13 Hz across all measurements. Between tests the retainer beat frequency was out by 0.06 Hz. See Figure No. 19. The ball beat frequency deltas were inside limits. See Figure No. 20. There was moderate amplitude variation in both beat frequency patterns. Also there were irregularities in the waveshapes. See Figures 21 and 22.

Early in the life of the wheel, visual studies of the retainer behavior revealed radial instability of light to medium intensity. After 3500 hours, the retainers settled down to more quiescent modes.

3.3.1.3 Wheel CR-113B

The retainer beat frequency was outside the DVTP limit by 0.13 Hz across all measurements. Between test points the discrepancy was 0.09 Hz. See Figure No. 23. The ball beat frequency was also outside limits. See Figure No. 24. The retainer beat wave shape began to degrade at about 5500 hours. See Figure No. 25. The ball beat trace deterioration began at 4000 hours. See Figure No. 26. The traces became erratic and unreadable. The wheel was classified as a predicted failure at 3975 hours on June 19, 1969. Continued unstable retainer and ball beat frequencies after this date prohibited requalification.

Visual retainer motion studies showed that up to 4000 hours the performance was mostly stable with occasional light radial displacements. At 4700 hours, periodic radial pulsing began and has continued varying only in intensity. There was correlation between retainer stability and stable retainer beat traces and vice versa.

3.3.2 Retainer/Ball Beat Frequency of 081 Configuration Wheels

3.3.2.1 Wheel CV-115E

The retainer beat frequency deltas were inside DVTP limits. See Figure No. 27. The ball beat frequency was outside the limit by 0.08 Hz between test points but was acceptable across all measurements. See Figure No. 28. Both beat frequency patterns and waveshapes showed irregularities typical of unstable retainer behavior. See Figures 29 and 30. At 9512 hours, a visual study confirmed that the -SRA retainer's spasmodic rotational instability was coincident with power spikes that appeared in the differential millwatt-meter traces. Regular visual inspections in the running mode were not feasible due to the fixturing required to operate this wheel in the SRA vertical position.

3.3.2.2 Wheel CV-92J

The retainer beat frequency readings were within specification limits. See Figure No. 31. The ball beat frequency was acceptable across all measurements, but between tests, the tolerance was exceeded by 0.20 Hz. See Figure No. 32. The beat frequency patterns and waveshapes displayed a number of anomalies such as undulating envelopes, occasional irregular waveshapes, and varying peak amplitudes. See Figures 33 and 34. Regular visuals in the operating mode were not scheduled because this wheel was fixtured to run in the SRA vertical attitude making visual inspection not possible. However, one visual study was made at 9194 hours by transferring the wheel to a standard fixture. Both retainers displayed instability from light to moderate intensity. The -SRA retainer had a high frequency rotational oscillation, and the +SRA retainer experienced light radial displacements.

3.3.2.3 Wheel CV-123B

The retainer beat frequency was marginally outside limits across all measurements. The tolerance was exceeded by 0.01 Hz. Between measurements the limit was exceeded by 0.05 Hz. See Figure No. 35. The ball beat frequency was well within the specified limit. See Figure No. 36. After 512 hours the retainer beat frequency pattern developed trace irregularities. See Figure No. 37. The ball beat frequency, although subject to varying beat periods, presented a regular waveshape. See Figure 38. The visual retainer behavior history ranged from stable periods to light or mild perturbations which did not appear to be always coincident with changes in the retainer beat frequencies.

3.3.2.4 Wheel CV-121D

Both retainer and ball beat frequencies met the DVTP requirements. See Figures 39 and 40. At approximately 3000 hours the retainer beat frequency waveshape began to display some moderate irregularities which continued without significant change until 7300 hours. At 7300 hours a change in the beat period occurred. See Figure No. 41. The ball beat pattern also experienced a frequency change at this time. See Figure No. 42. The visual study of the retainer motion shows a history of light radial instability with a few occasions of somewhat medium intensity activity.

3.3.3 Comparison of Retainer/Ball Beat Frequencies of 071 and 081 Configurations

In general, both configurations showed beat frequency irregularities. However, only CR-113B, an 071 wheel, was disqualified by failing both retainer and ball beat frequency limits. CV-121D, an 081 wheel, was the only wheel which was qualified in both beat frquency areas. The other wheels were qualified by meeting one or the other of the beat frequency limits.

Retainer motion instability was also present in both configurations and was found to vary from one inspection period to the next. CV-115E, an 081 wheel, developed an instability mode at 9148 hours which coincided with the power spikes in the differential power trace.

Since beat frequency stability is one of the parameters used to predict wheel failure, the instrumentation was sometimes a cause for concern. In some cases there were unexplained phenomena. In general, however, when a beat frequency became unstable, it was either the retainer or ball beat, but not both at the same time.

3.4 Wheel Run Up Time

There is no required specification value for the time interval required for a wheel to reach synchronous speed. However, along with other data, its trend is used to detect changes in bearing condition. The preponderance of measurements ranged between 67 to 85 seconds for both configurations. The average spread across run up times was between 12 and 15 seconds. Random non-conforming values were not uncommon and may be attributed to free oil distribution and the length of time the wheel was not running before the measurement was taken.

3.4.1 Wheel Run Up Time of 071 Configuration Wheels

3.4.1.1 Wheel CR-107B

The total spread of run up times for this wheel was 28.5 seconds. However, most of the measurements were within 16 seconds of each other and indicated no trend. See Figure No. 43A.

3.4.1.2 Wheel CV-112A

The total run up time spread for this wheel was 13 seconds. The repeatability was good and indicated no trend. See Figure No. 44A.

3.4.1.3 Wheel CR-113B

The total run up time spread for this wheel was 18 seconds. The preponderance of measurements had a spread of 12 seconds. At 6050 hours, a change in run up time level change was noted. This change reflects wear in this "predicted failure." See Appendix A for teardown report on Wheel CR-113B. See Figure 45A.

3.4.2 Wheel Run Up Time of 081 Configuration Wheels

3.4.2.1 Wheel CV-115E

The total run up time spread for this wheel was 21.5 seconds. However, 20 of the 24 measurements were within a 7.5 second spread of each other. There was a small decreasing trend in the run up times.

3.4.2.2 Wheel CV-92J

The spread across all run up time measurements for this wheel was 14.0 seconds. There were no large random changes although a moderate level shift in increased time intervals occurred during the latter half of the data checks. See Figure 47A.

3.4.2.3 Wheel CV-123B

The spread across all run up time readings for this wheel was 22.0 seconds. The latter half of the data measurements had a spread of 7.0 seconds. See Figure 48A.

3.4.2.4 Wheel CV-121D

The spread across all run up time measurements for this wheel was 13.0 seconds. There were no large random changes or level shifts. See Figure 49A.

3.4.3 Comparison of Wheel Run Up Times of 071 and 081 Configurations

There was nothing distinctive about the run up time characteristics for either configuration other than the measurement level values. The 071 configuration wheel readings were, in general, approximately 10 seconds higher due to its greater preload, all other parameters being equal. The normal response of this parameter, in cases of bearing deterioration, is to vary inversely with the run down time change.

3.5 Wheel Run Down Time

The bearing run down time has been, traditionally, an effective part of bearing condition evaluation. Poor repeatability and decreasing trends in the wheel run down time measurements are symptomatic of bearing deterioration when supported by other test data.

It has been observed that when a wheel is removed from the life test fixture for the mandatory periodic visual examination, and then replaced, that it was possible to obtain a different run down time level. It is believed that this change was caused by a difference in the positioning of the wheel and fixturing parts on reassembly. Consequently, the run down time deltas are based on measurements between wheel removal inspections rather than across all test points.

3.5.1 Wheel Run Down Time of 071 Configuration Wheels

3.5.1.1 Wheel CR-107B

The first six run down time measurements, early in the life, of this wheel exceed the 071 delta limit of 20 seconds by 2.1 seconds. This relegated the wheel to the predicted failure category. The run down time pattern then stabilized and the wheel was re-qualified. For 7500 hours, the succeeding measurements between visual inspections held within the DVTP limit. See Figure No. 50.

3.5.1.2 Wheel CV-112A

All run down time measurements between visual inspections were within the DVTP limit of 20 seconds. See Figure No. 51.

3.5.1.3 Wheel CR-113B

All run down time measurements between visual inspections were within the DVTP limit of 20 seconds. See Figure No. 52.

3.5.2 Wheel Run Down Time of 081 Configuration Wheels

3.5.2.1 Wheel CV-115E

All run down time measurements between visual inspections were within the DVTP limit of 30 seconds. See Figure No. 53.

3.5.2.2 Wheel CV-92J

All run down time measurements between visual inspections were within the DVTP limit of 30 seconds. See Figure No. 54.

3.5.2.3 Wheel CV-123B

All run down time measurements between visual inspections were within the DVTP limit of 30 seconds. See Figure No. 55.

3.5.2.4 Wheel CV-121D

All run down time measurements between visual inspections were within the DVTP limit of 30 seconds. See Figure No. 56.

3.5.3 Comparison of Run Down Time of 071 and 081 Configurations

The run down time level difference anticipated between the two configurations as a function of preload did not materialize. Two of the three 071 wheels (CV-112A and CR-113B) had measurements typical of the more lightly loaded 081 wheels. CV-92J, an 081 wheel, had the shorter run down interval representative of the three pound 071 configuration.

The run down time repeatability was essentially the same for both designs. The 30 seconds delta limit set for the 081 configuration proved to be unnecessary. All of the 081 wheels met the 071 delta limit of 20 seconds. The 071 wheels also fulfilled this requirement.

3.6 Minimum Wheel Synchronous Voltage

The maximum limit of 26.6 volts to reach and maintain synchronous speed was easily met by all of the life test wheels. The average minimum voltage values to attain synchronous speed varied from 17.2 to 19.5 volts.

3.6.1 Minimum Wheel Synchronous Voltage of 071 Configuration Wheels

3.6.1.1 Wheel CR-107B

The minimum synchronous voltage range was from 17.5 to 21.0 volts with a delta of 3.5 volts.

See Figure 43B. Since the other wheel parameters were within specification, the high delta was not considered serious.

3.6.1.2 Wheel CV-112A

The minimum synchronous voltage range was from 18.5 to 20 volts for a delta of 1.5 volts. See Figure 44B.

3.6.1.3 Wheel CR-113B

The minimum synchronous voltage range was from 16.5 to 18.5 volts for an acceptable delta of 2.0 volts. See Figure 45B.

3.6.2 Minimum Wheel Synchronous Voltage of 081 Configuration Wheels

3.6.2.1 Wheel CV-115E

The minimum synchronous voltage range was from 18 to 19.5 volts for an acceptable delta of 1.5 volts. See Figure 46B.

3.6.2.2 Wheel CV-92J

The minimum synchronous voltage range was from 17.5 to 19.0 volts for an acceptable delta of 1.5 volts. See Figure 47B.

3.6.2.3 Wheel CV-123B

The minimum synchronous voltage range was from 18.0 to 19.5 volts for an acceptable delta of 1.5 volts. See Figure 48B.

3.6.2.4 Wheel CV-121D

The minimum synchronous voltage range was from 17.5 to 18.0 volts for an excellent delta of 0.5

volts. See Figure 49B.

3.6.3 Comparison of Minimum Wheel Synchronous Voltage of 071 and 081 Configurations

The 071 configuration minimum synchronous voltage span was from 16.5 to 21.0 volts with an individual delta range of 1.5 to 3.5 volts. The 081 minimum synchronous voltage spread was from 17.5 to 19.5 volts with a smaller individual wheel delta ranging from 0.5 to 1.5 volts.

3.7 Wheel Breakaway Voltage

3.7.1 Wheel Breakaway Voltage of 071 Configuration Wheels

3.7.1.1 Wheel CR-107B

The voltage range required to start this wheel was from 12.5 to 15.0 volts for a delta of 2.5 volts. See Figure 43C.

3.7.1.2 Wheel CV-112A

The voltage range required to start this wheel was from 12.5 to 14.0 volts for a delta of 1.5 volts. See Figure 44C.

3.7.1.3 Wheel CR-113B

The voltage range required to start this wheel was from 9.5 to 14.5 volts for a delta of 5.0 volts. See Figure 45C.

3.7.2 Wheel Breakaway Voltage of 081 Configuration Wheels

3.7.2.1 Wheel CV-115E

The voltage range required to start this wheel was from 10.5 to 12.0 volts for a delta of 1.5 volts. See Figure 46C.

3.7.2.2 Wheel CV-92J

The voltage range required to start this wheel was from 10.5 to 12.5 volts for a delta of 2.0 volts. See Figure 47C.

3.7.2.3 Wheel CV-123B

The voltage range required to start this wheel was from 10.5 to 12.0 volts for a delta of 1.5 volts. See Figure 48C.

3.7.2.4 Wheel CV-121D

The voltage range required to start this wheel was from 11.0 to 12.0 volts for a delta of 1.0 volts. See Figure 49C.

3.7.3 Comparison of Wheel Breakaway Voltage of 071 and 081 Configurations

The wheel breakaway voltage for the 071 wheel deltas ranged from 9.5 to 15.0 volts with individual wheel deltas from 1.5 to 5.0 volts. The 081 wheels starting voltage range was from 10.5 to 12.5 volts with individual wheel deltas from 1.0 to 2.0 volts.

4. SUMMARY OF TEST RESULTS

4.1 Summary of 071 Configuration Test Results

Residue from lubricant breakdown appeared early on the upper portion of the 071 inner races. It occurred to all of the wheels and usually worsened with the passage of time.

Ball banding was present in each wheel. The wear bands ranged from narrow light gray to wide medium gray, frosty gray, and bronze. Raceway discoloration was found on CV-112A and CR-113B which also had the more severe ball banding.

Beat frequency waveshape irregularities and envelope modulations were common to the trace pattern. CR-113B was classified a predicted failure because of unstable beat frequency data. The other two wheels in this group met the DVTP requirements. Retainer motion in the wheels of this configuration intermittently varied from stable to mostly mild eccentricities, with an occasional medium intense unstable mode.

The differential power traces of CV-112A and CR-113B were of acceptable quality even though both wheels had ball track discoloration, advanced residue accumulation, and bad ball banding. However, these wheels had less lubrication than CR-107B, which could have contributed to the bearing degradation. CR-107B displayed irregular, poor quality power recordings accompanied by large area oil jogs which indicated excessively high oil content.

The run down times of CV-112A and CR-113B were mostly longer than what is representative of the 071 configuration. This, too, may possibly be considered a function of the reduced oil quantity. The values of run up times, breakaway and minimum synchronous voltages in general were within expected limits.

4.2 Summary of 081 Configuration Test Results

Residue from lubricant breakdown appeared much later in the life of the 081 bearings and never reached the degree of severity found in the 071 configuration. CV-115E ran over 9000 hours without developing residue. Wheels CV-115E and CV-92J were life tested with SRA vertical to determine if wheel position had any effect on oil migration. Periodic visual inspections and the final teardown of wheel CV-115E (See Appendix A) did not show any evidence of gravity dependent oil migration.

There was no raceway discoloration on any of the 081 wheel bearings. Ball banding was moderate and appeared in shiny or light gray bands with a few instances of medium gray.

The ball beat frequency waveshape was generally better in quality than the retainer beat pattern which displayed considerable irregularity. With the exception of CV-121D, which met the requirements of both beat frequencies, the other 081 wheels qualified by meeting one or the other of the beat frequencies. Retainer motion studies of the 081 configuration showed that behavior patterns varied from stable to moderately intense instability. CV-115E, however, developed spasmodic rotational instability at 9148 hours which was reflected in both beat frequency and differential power traces.

Differential power traces of acceptable quality were recorded from CV-123B and CV-121D. Irregular and hashy power traces were produced by CV-115E and CV-92J. Both of these wheels possessed a liberal quantity of oil and were subject to frequent large area oil jogs. After 9000 hours, the differential power trace of CV-115E changed from jogs to spikes.

Run down time values for each 081 wheel repeated within an acceptable bandwidth of 20 seconds. The run down time measurements for CV-92J were lower than the other 081 wheels and more typical of the 071 configuration. The abundance of oil, as evidenced by the frequent huge oil jogs, was the probable cause for these shorter run down times.

The run up times, breakaway voltages, and minimum synchronous voltages registered within conventional ranges.

4.3 Comparison of 071 and 081 Configuration Test Results

The visual examinations of the two configurations revealed impressive differences. Without exception, the 071 bearings developed early formation of oil breakdown deposits on the inner race. Ball track discoloration and marked ball banding appeared on two of the three 071 wheels. The 081 wheels were visually superior. All of these wheels were free of ball track discoloration. Ball banding was minimal. Residue formation was light and spotty and appeared much later in life.

As a point of information, it should be noted that the 081 configuration bearings possessed a greater quantity of oil than the 071 bearings. This difference was due to a revised specification requirement calling for the presence of a static oil meniscus under the balls at various inspection periods, i.e. during dynamic balance, after retainer motion evaluation, after the design margin test, and after dynamometer qualification. Oil may be added if this requirement is not met. Oil was usually needed at one or more of these inspections. In the last instance, further dynamometer qualification was required.

Although both configurations experienced irregularities in the beat frequency area, only the 071 configuration had a wheel (CR-113B) which was a predicted failure based on instability in both retainer and ball beat frequencies. All other life test wheels met the DVTP requirements. Retainer instability was an intermittent variable that was present in all wheels.

Differential power trace quality and stability is regarded as a probable function of a particular wheel or condition rather than of a particular configuration.

The 081 run down time data equaled the 071 data repeatability by not exceeding the 20 seconds bandwidth. Run up time and wheel breakaway voltage values indicated that the viscosity of SRG 160 oil was less of a factor in these parameters than the preload. These values were lower than the corresponding parameters measurements of the 071 configuration.

It is believed that the thousands of hours of test data and periodic visual inspection results have provided sufficient evidence to indicate the superiority of the 081 configuration over the 071 design. There were a few areas that were independent of configuration. However, in no instance, was there a significant advantage favoring the 071 wheel assembly.

5. PROGRAM GOALS ACHIEVEMENT

The wheel life test hours accumulated at MIT Draper Laboratory and Bendix Corporation are tabulated in Figures 57 and 58, respectively. Testing on 071 configuration wheels was officially terminated at Bendix and MIT on December 11, 1969 per instructions from NASA-MSC. Testing on 081 wheels ended on June 30, 1970. MTBF confidence levels were calculated based on wheel running hours accumulated at these dates.

The desired program goals were stated in Paragraph 1.5 of this report. The first goal was "To establish that the useful life expectancy is 3500 hours or more." Referring to Figures 57 and 58, the wheel with the lowest number of running hours was Wheel CR-113B. This wheel had 3975 hours running time when it was classified as a predicted failure because of out of specification retainer beat frequency values. The wheel was never requalified.

The second goal was "To establish that the MTBF during useful life is 10,000 hours or more." The one-sided confidence levels at 10,000 hours mean time before failure were calculated for MIT, Bendix, and MIT and Bendix wheels combined. The confidence levels were determined using the Chi Square Distribution. Results are shown in Figure 59.

It is of interest to note that confidence level is primarily dependent upon total number of running hours and also number of failures. It is only affected by the number of wheels in the program by virtue of the fact that a greater number of wheels will result in more running hours and possibly in more failures.

There was one wheel failure in both the MIT and Bendix programs. However, the MIT life test program consisted of 7 wheels and the Bendix program 10 wheels. A somewhat higher confidence level was achieved in the Bendix program because of the greater number of running hours accumulated. The combined confidence level of both Bendix and MIT was 99.9 percent for 10,000 hours MTBF.

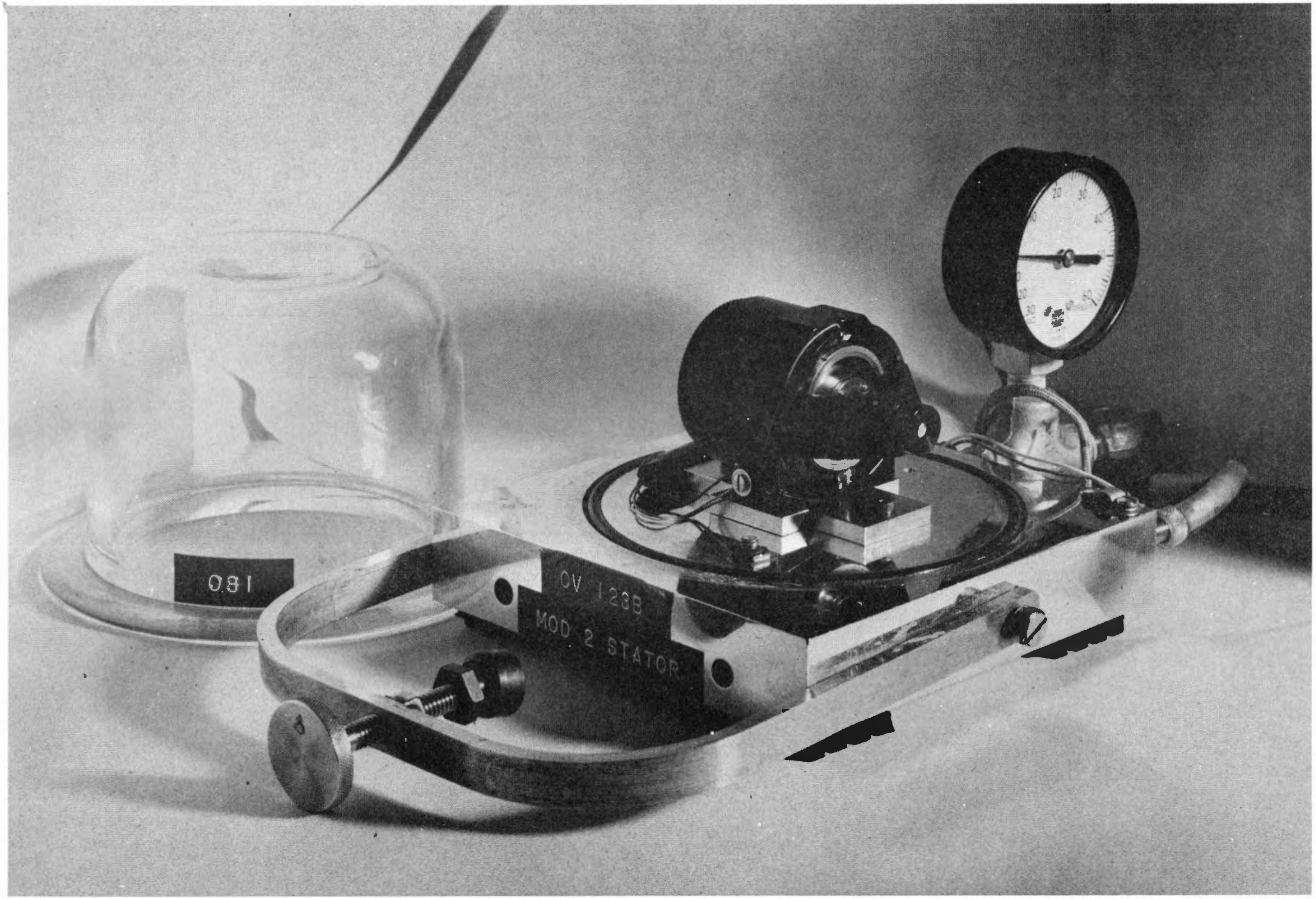


Figure 1. Wheel assembled with spin axis horizontal in milliwattmeter test fixture.

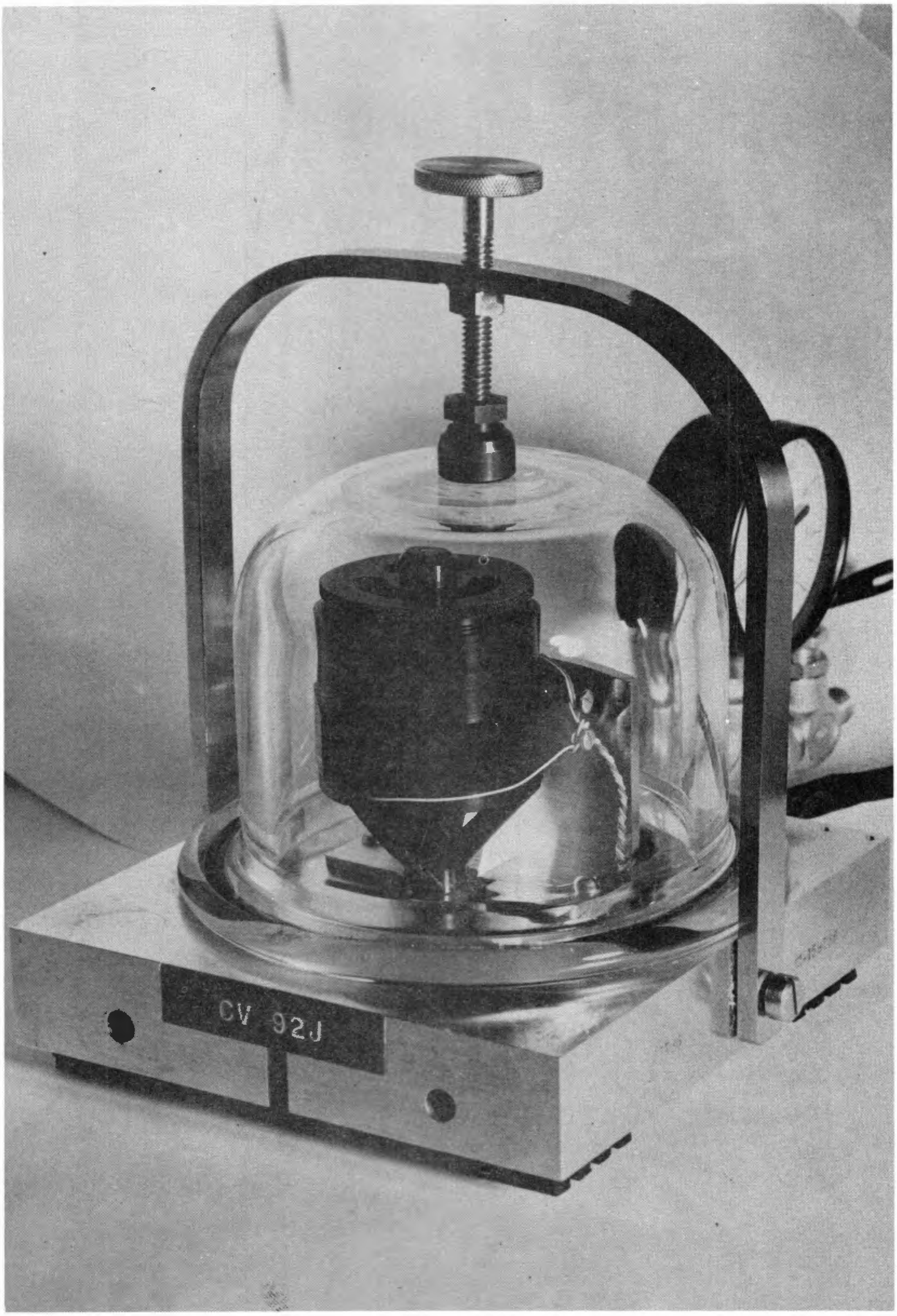


Figure 2. Wheel assembled with spin axis vertical in milliwattmeter test fixture.

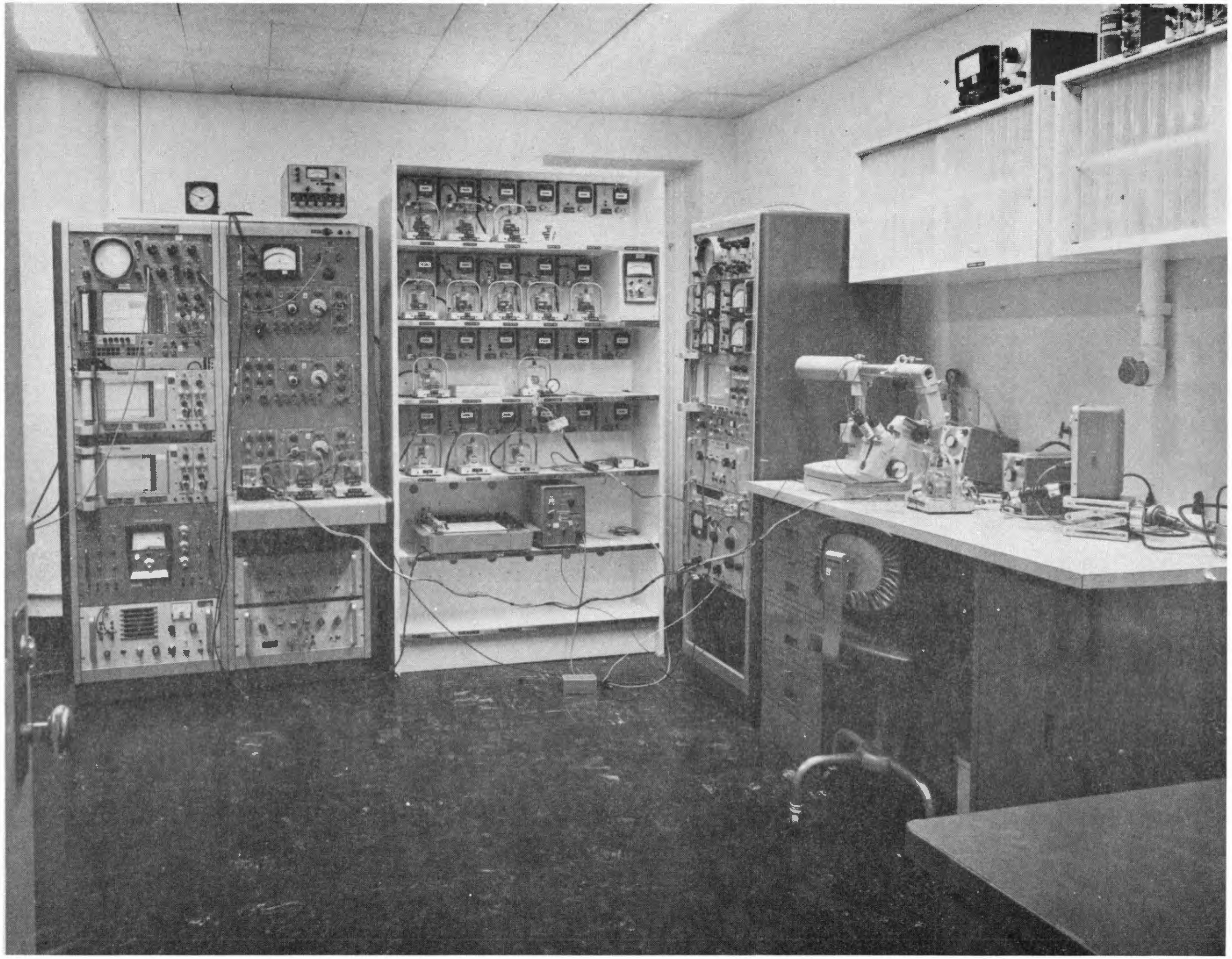


Figure 3. Ball bearing dynamometer test area showing design verification test set-up.

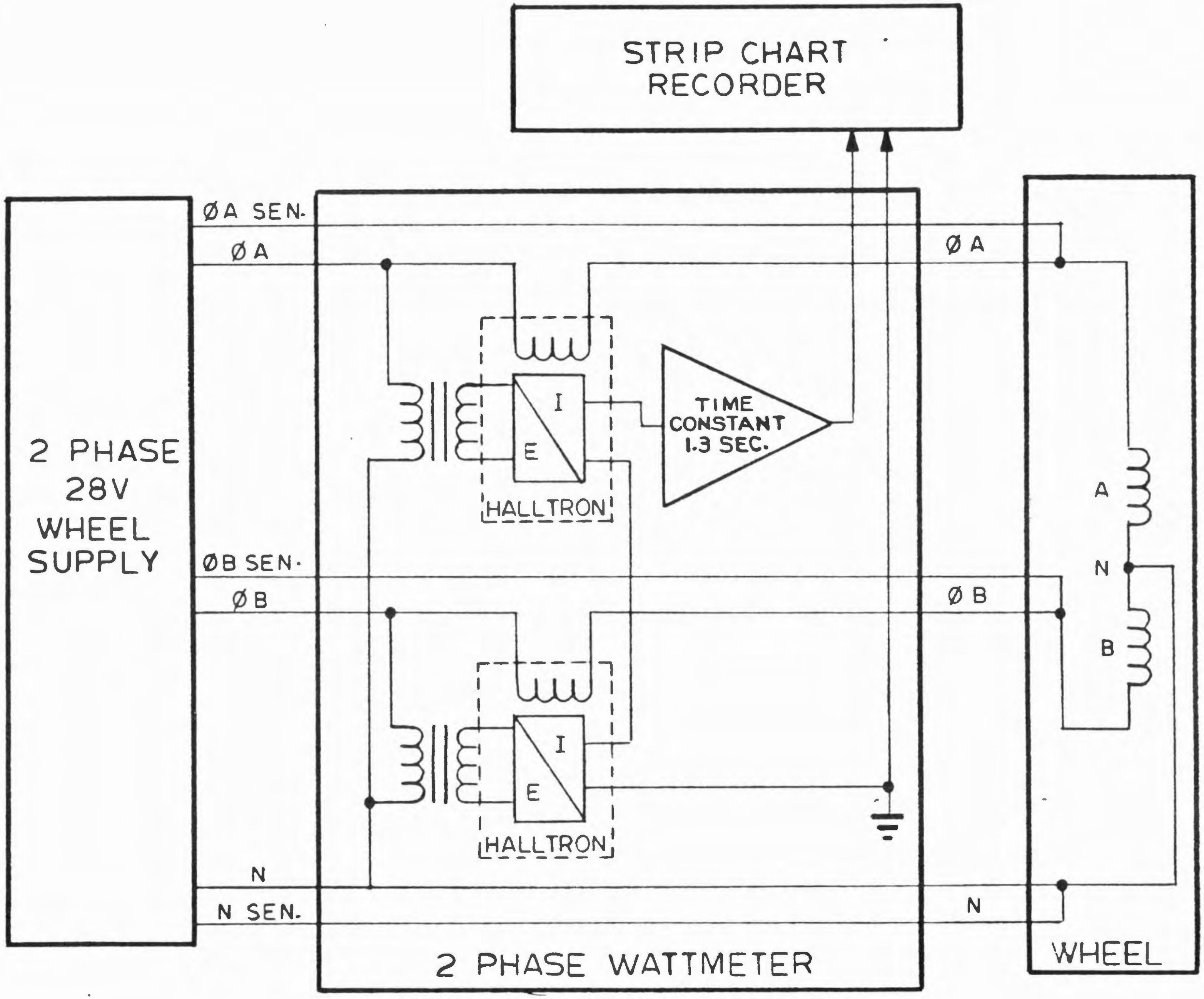
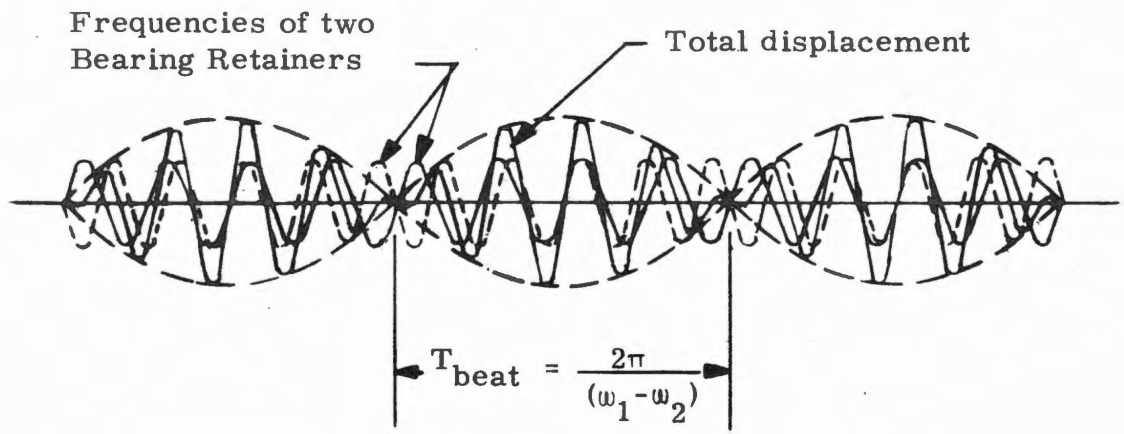


Figure 4. Diagrammatic Test Set Up to Record Differential Wheel Power.



Displacement of #1 Retainer = D_1 = A sin $2\pi f t$

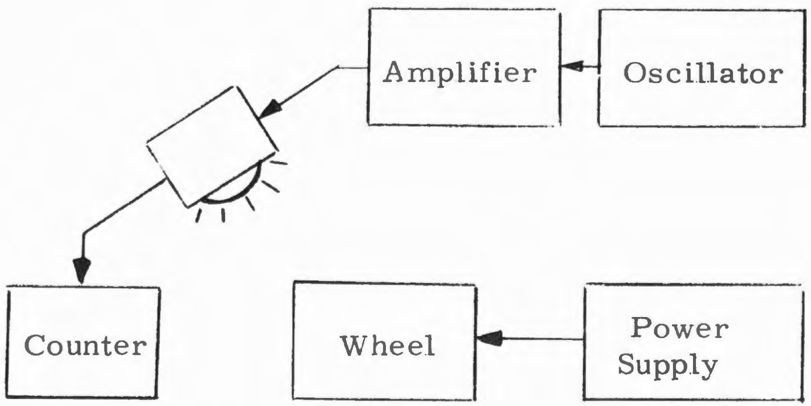
Displacement of #2 Retainer = D_2 = A sin $2\pi f^1 t$

$$\omega_{retainer} = \frac{\omega_{wheel}}{2}\left[1 + \frac{(\text{ball dia})}{(\text{pitch dia})} \cos\theta\right]$$

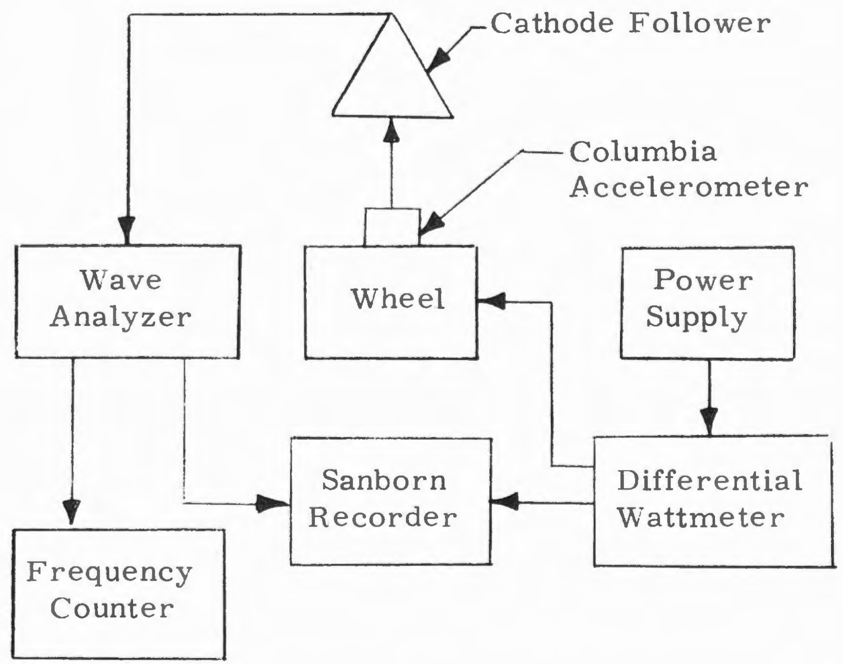
where θ = ball bearing loaded contact angle

Figure 5. Ball Bearing Beat Frequency.

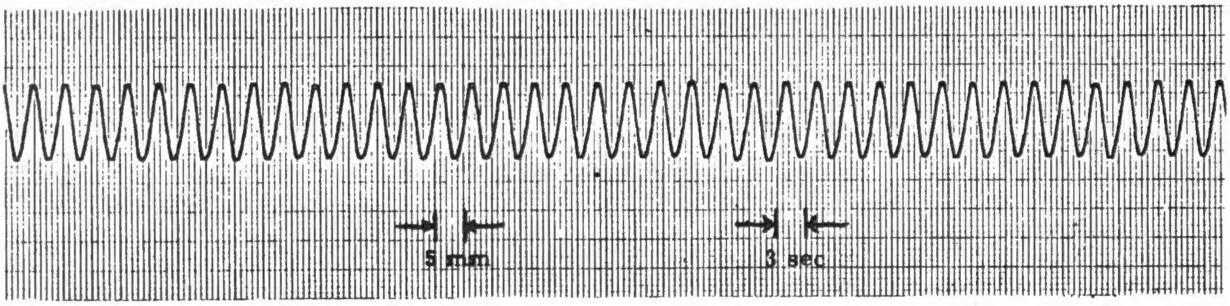
Figure 6. Set-Up for Measuring Ball Bearing Beat Frequency.



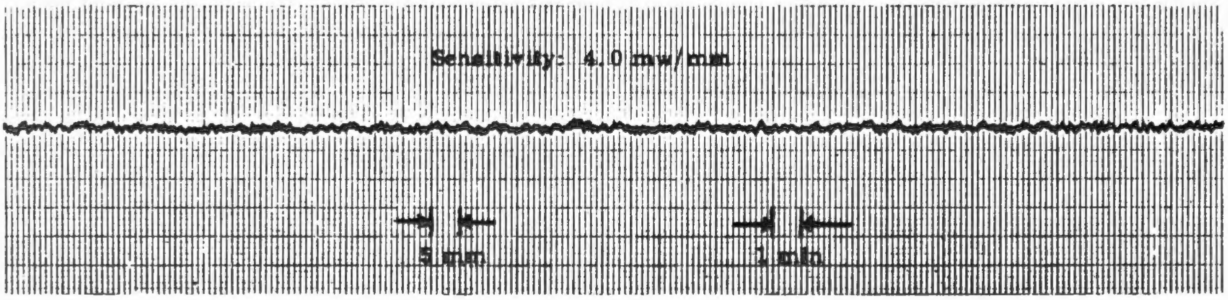
(A) Stroboscope and counter used to measure period of each bearing retainer.



(B) Comparison of Differential Wattmeter output and beat frequency from wave analyzer.



RETAINER BEAT FREQUENCY TRACE



DIFFERENTIAL MILLIWATTMETER TRACE

Figure 7. Key to Strip Chart Recording Values

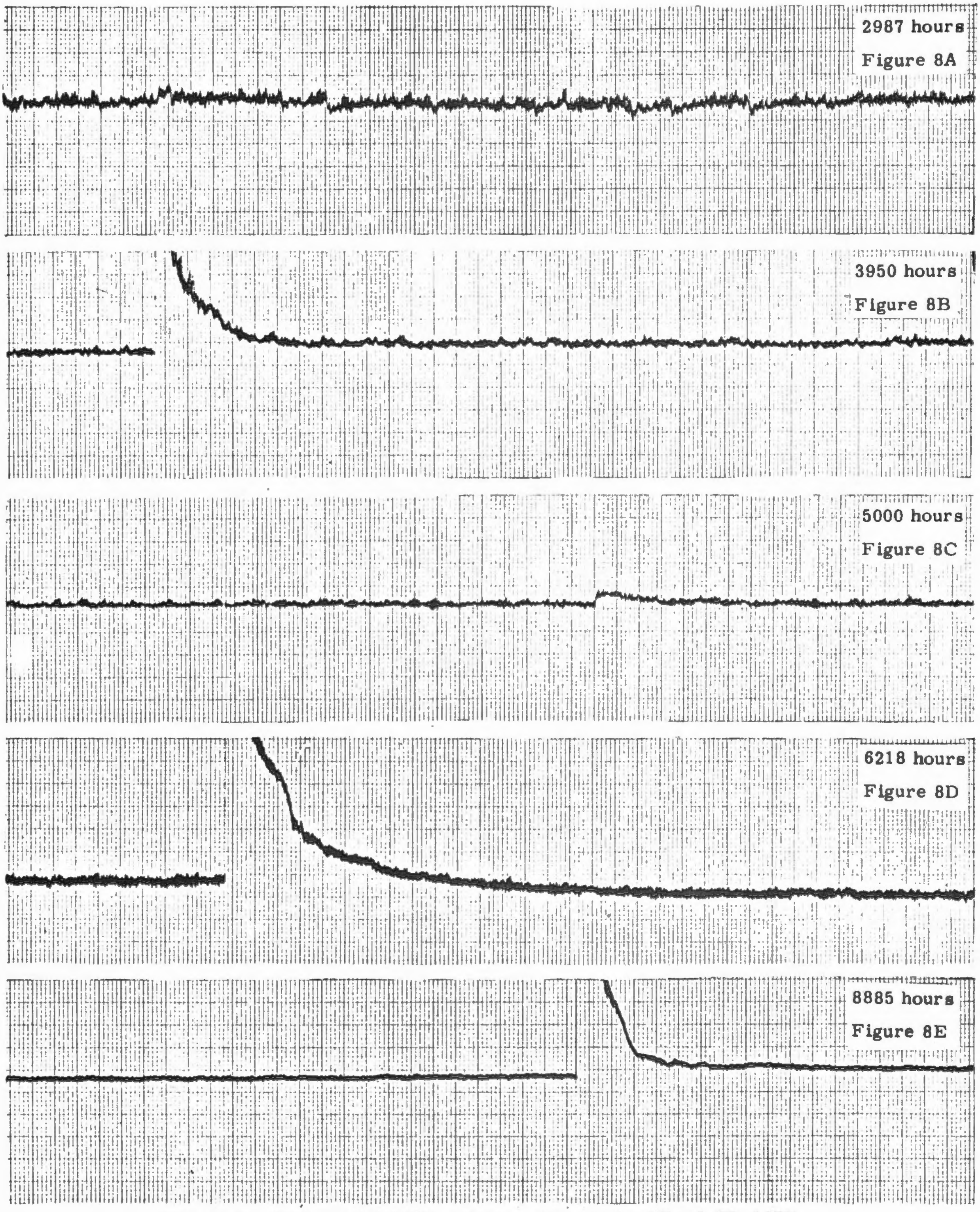


Figure 8. Differential Milliwattmeter Traces for Wheel CR-107B

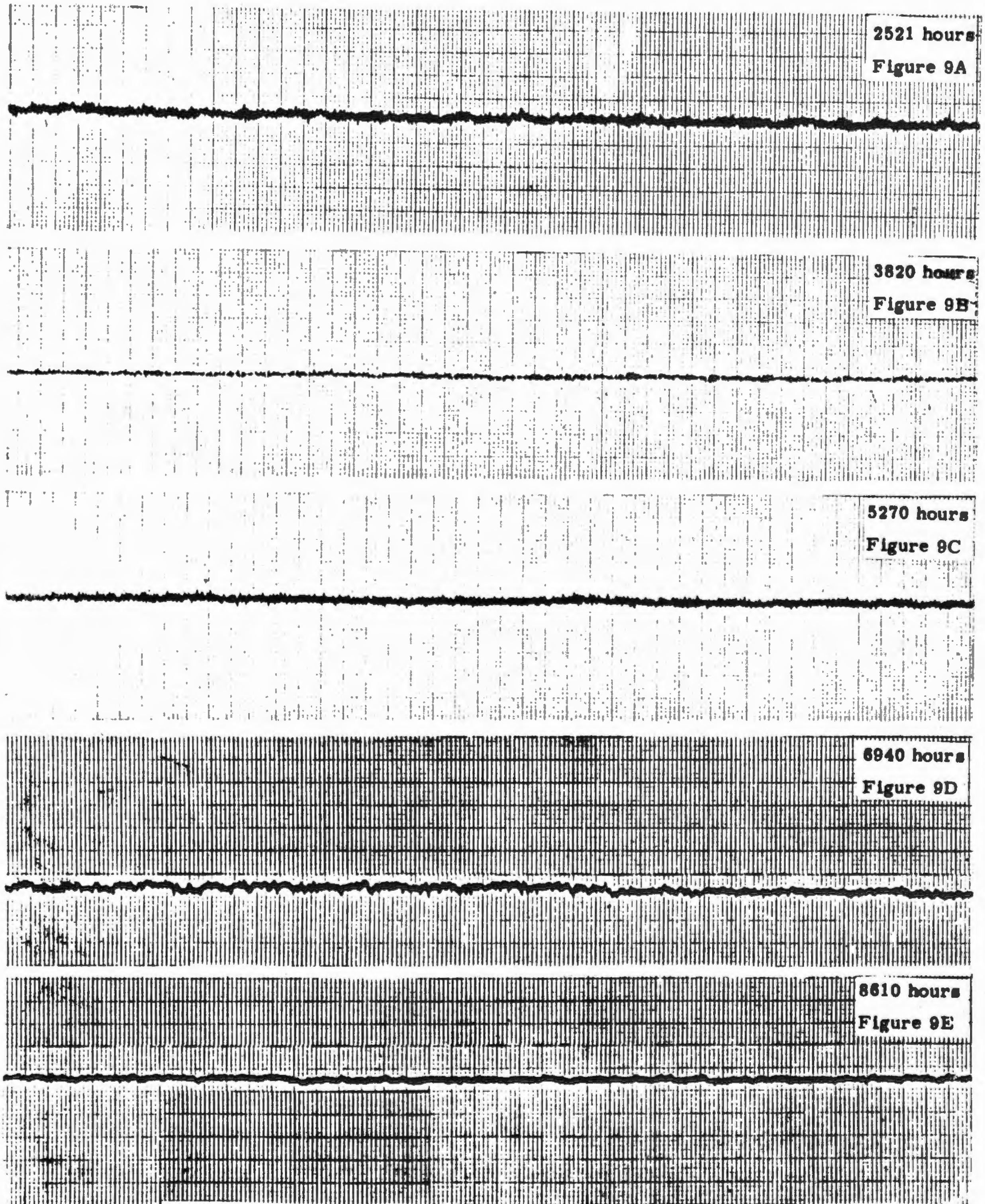


Figure 9. Differential Milliwattmeter Traces for Wheel CV-112A

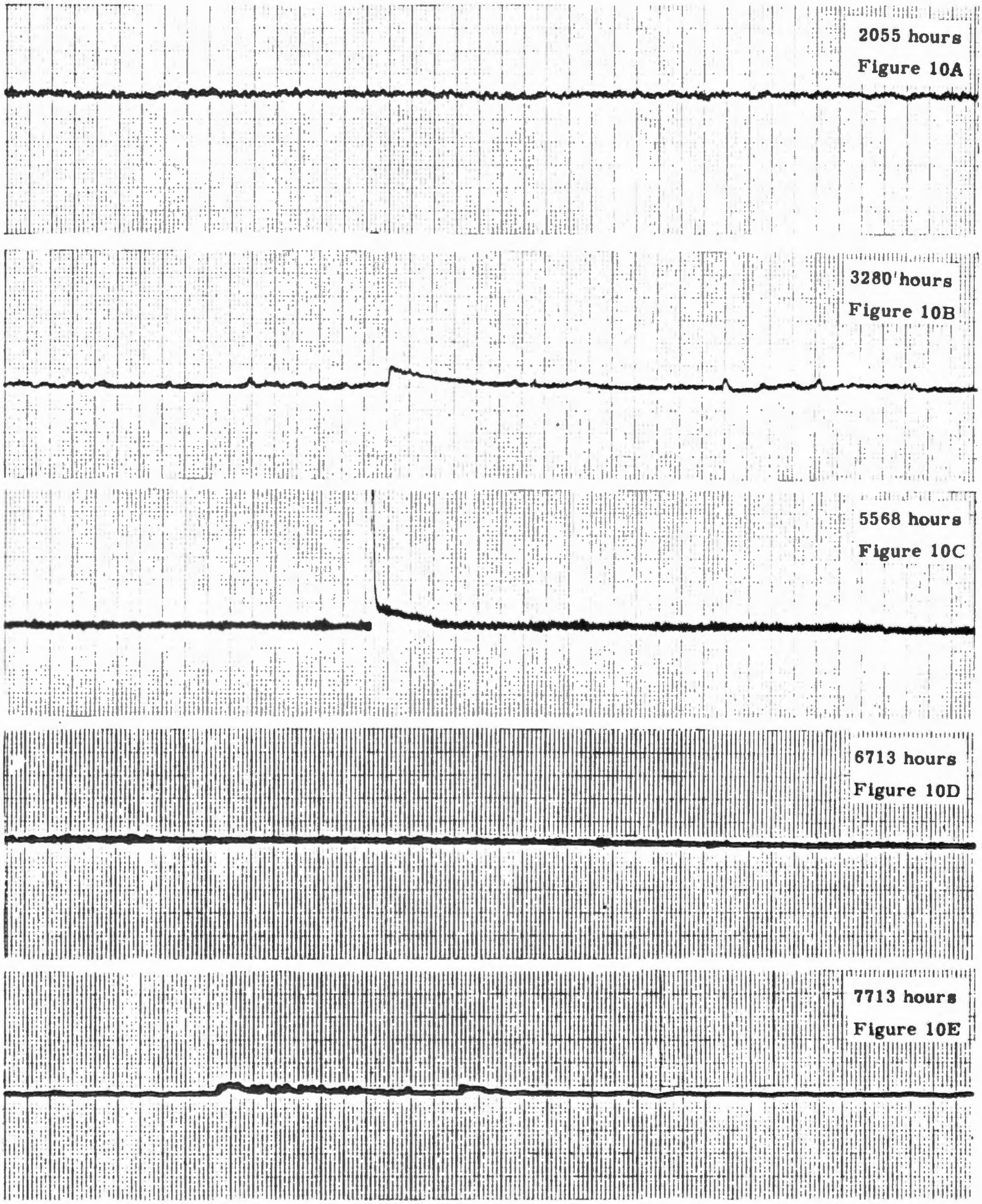


Figure 10. Differential Milliwattmeter Traces for Wheel CR-113B

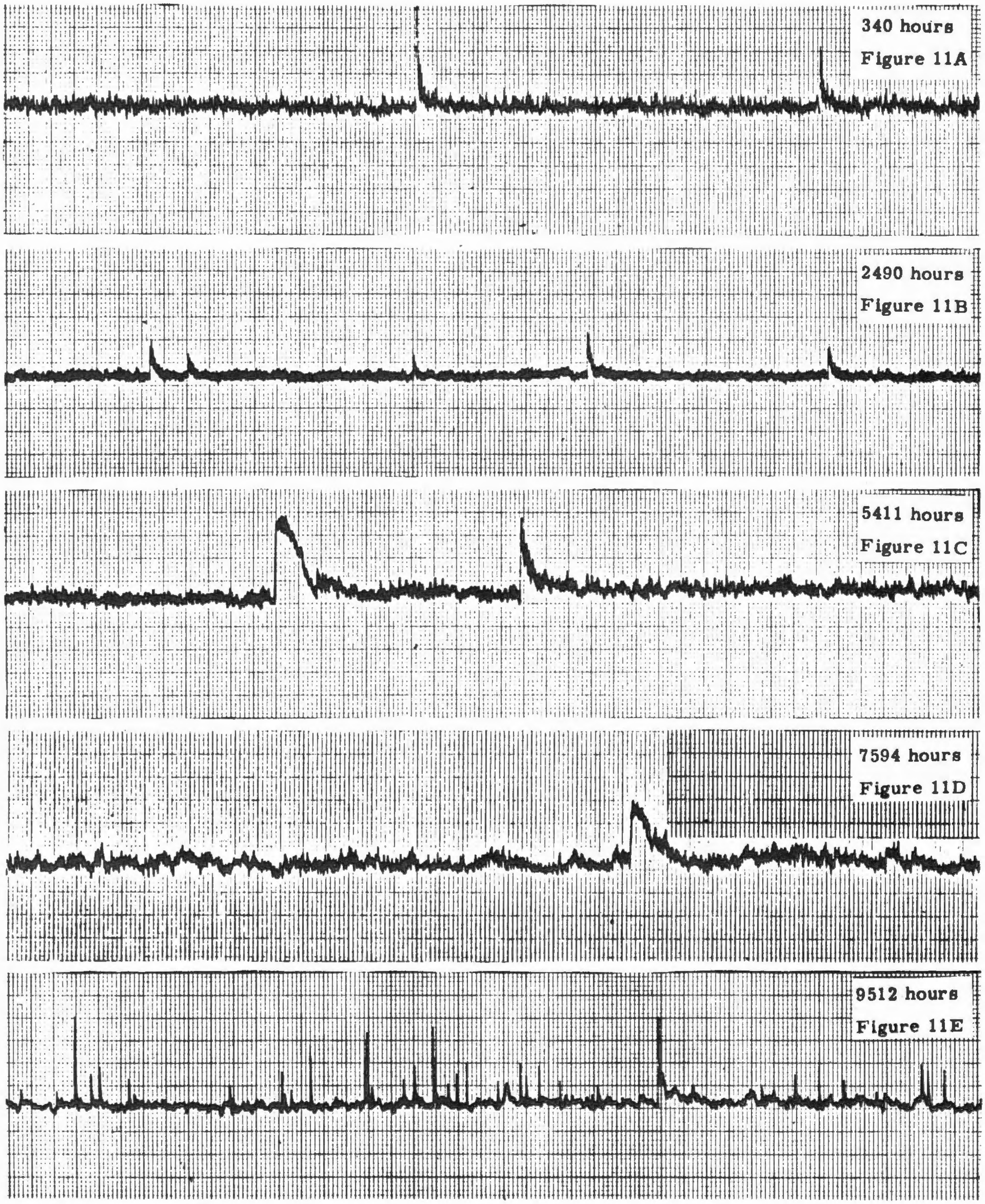


Figure 11. Differential Milliwattmeter Traces for Wheel CV-115E

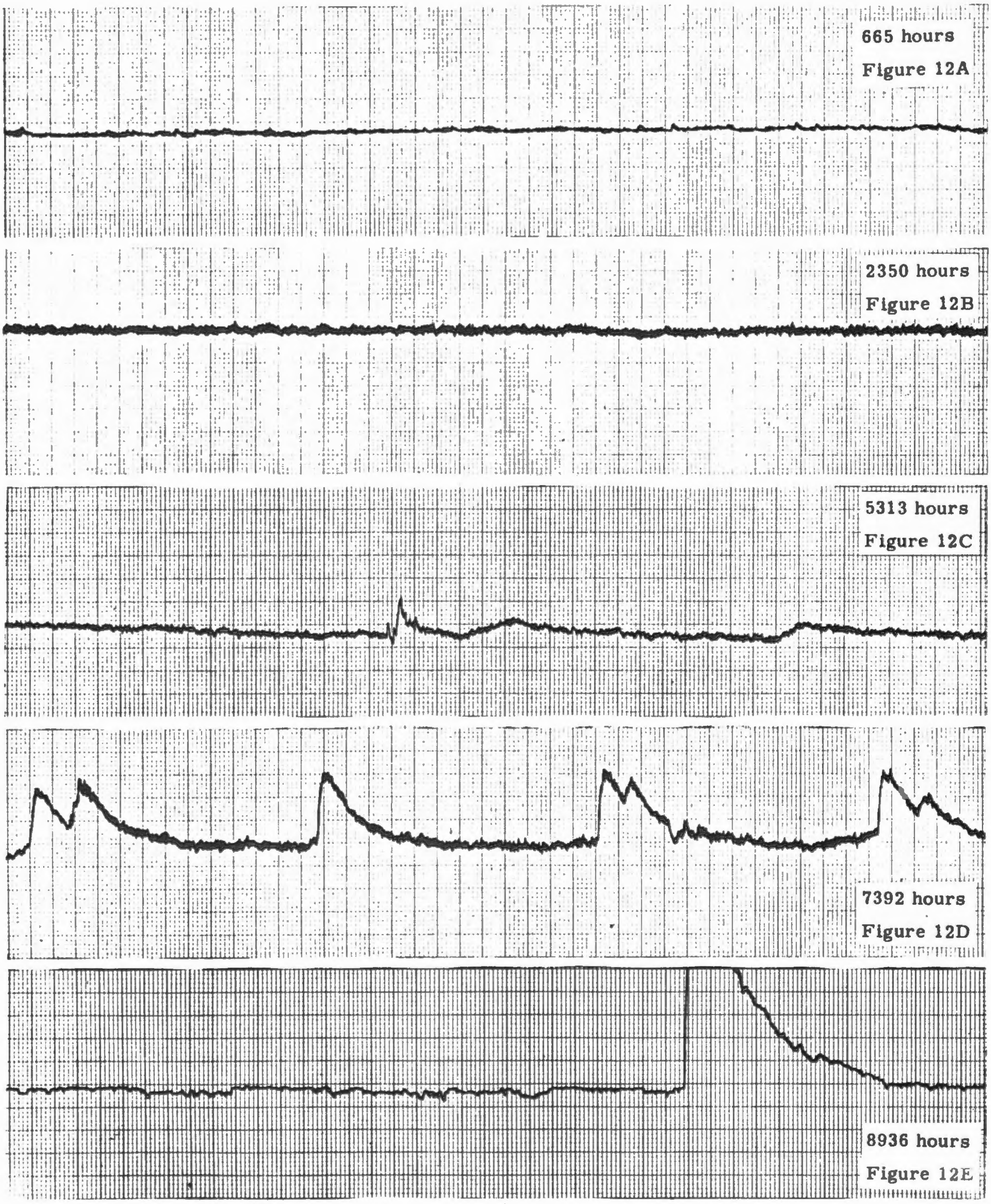


Figure 12. Differential Milliwattmeter Traces for Wheel CV-92J

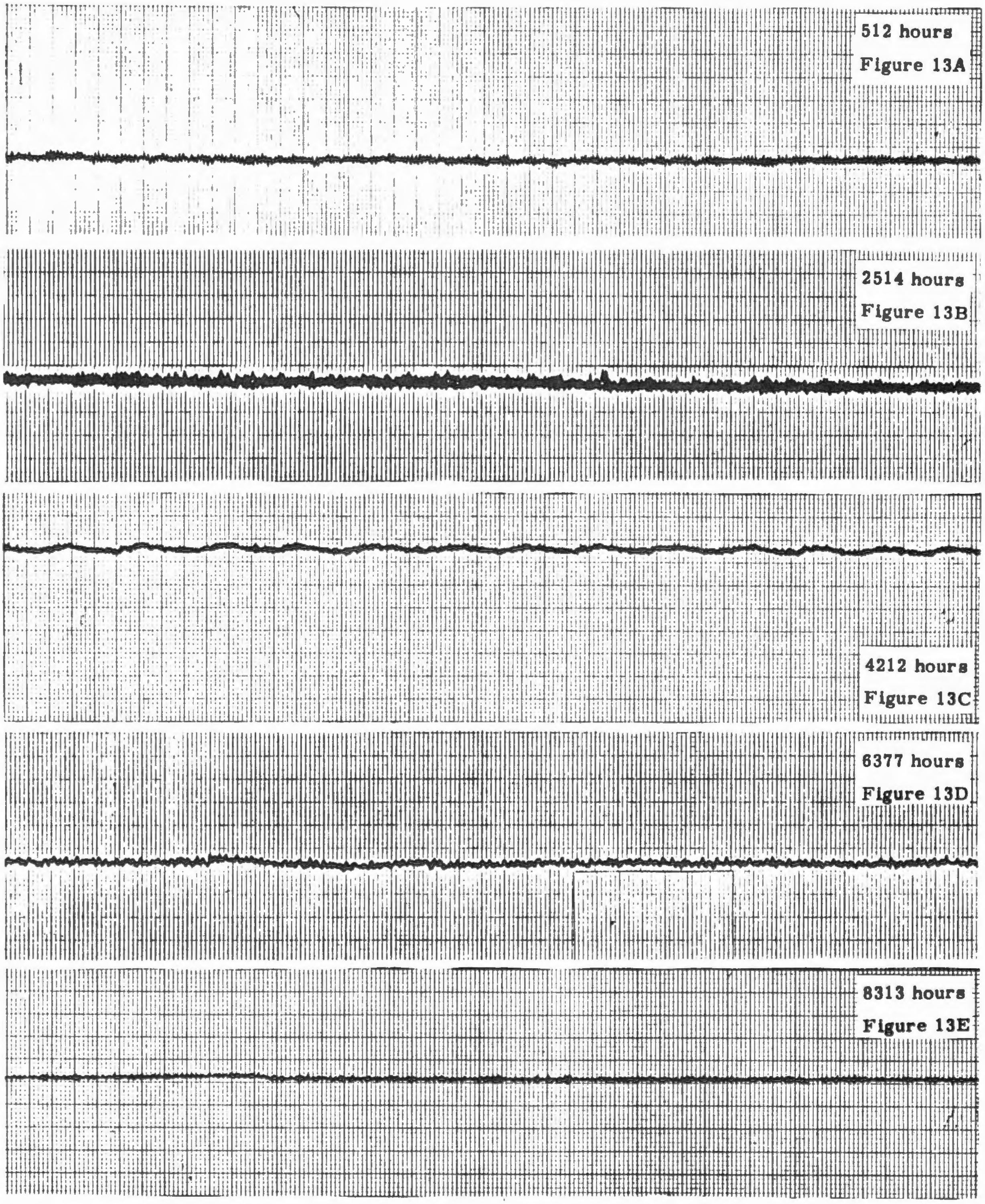


Figure 13. Differential Milliwattmeter Traces for Wheel CV-123B

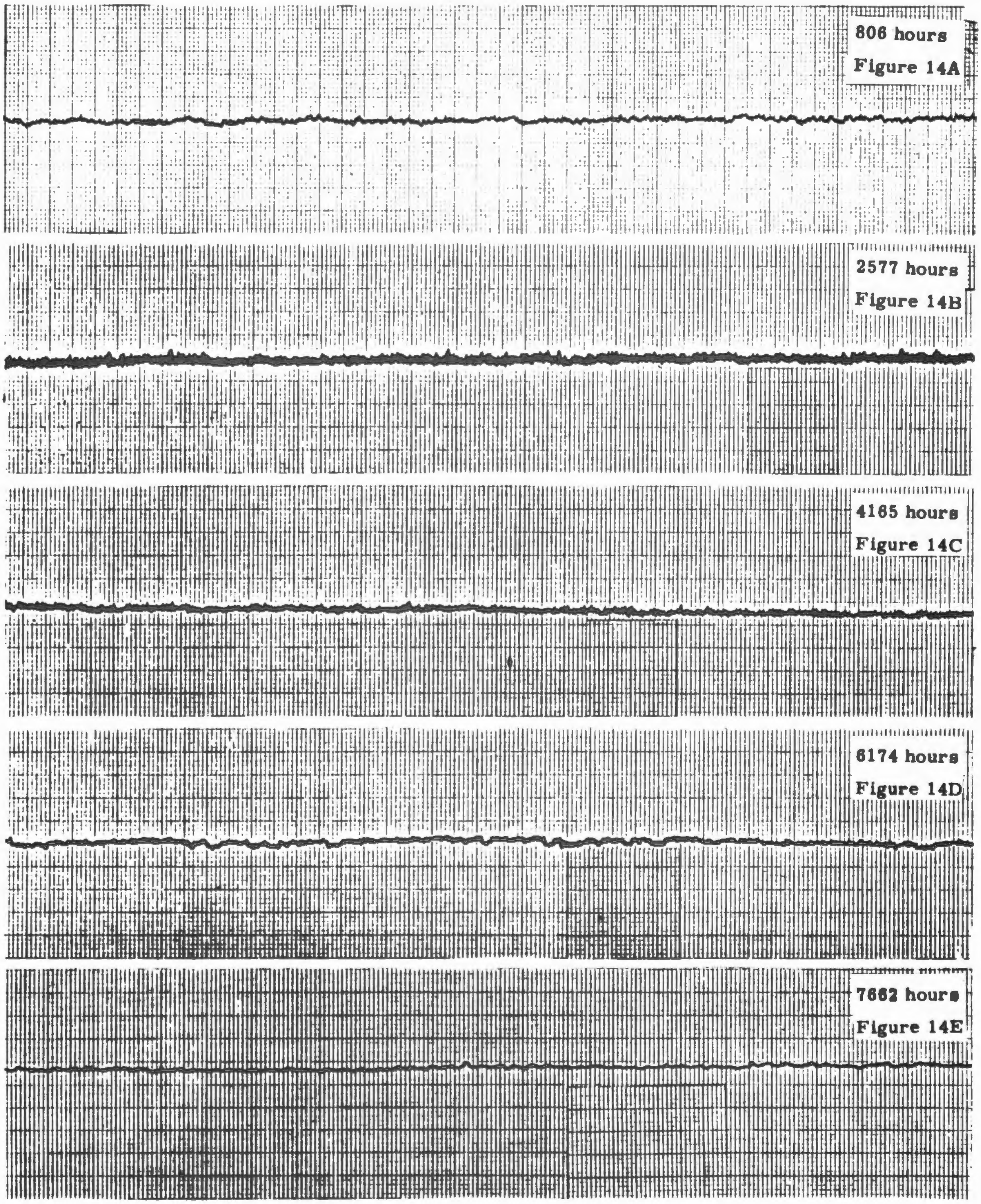


Figure 14. Differential Milliwattmeter Traces for Wheel CV-121D

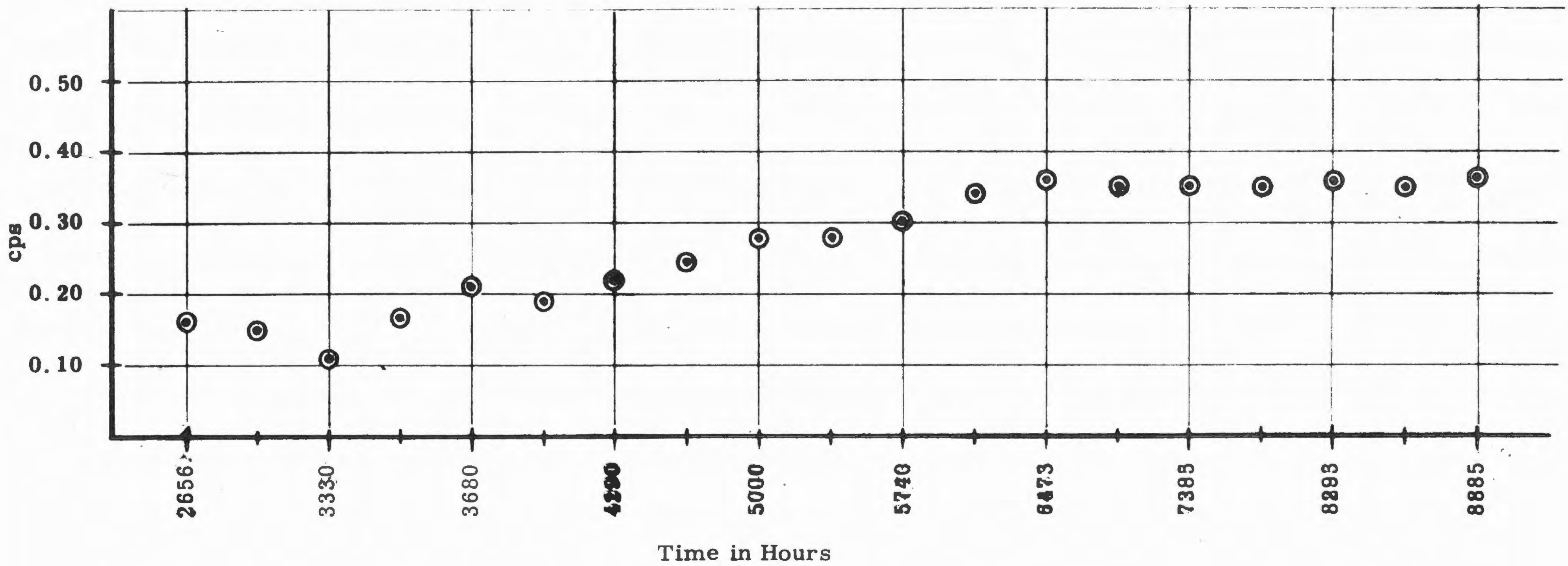


Figure 15. Retainer Beat (243 Hz) Frequency for Wheel CR-107B.

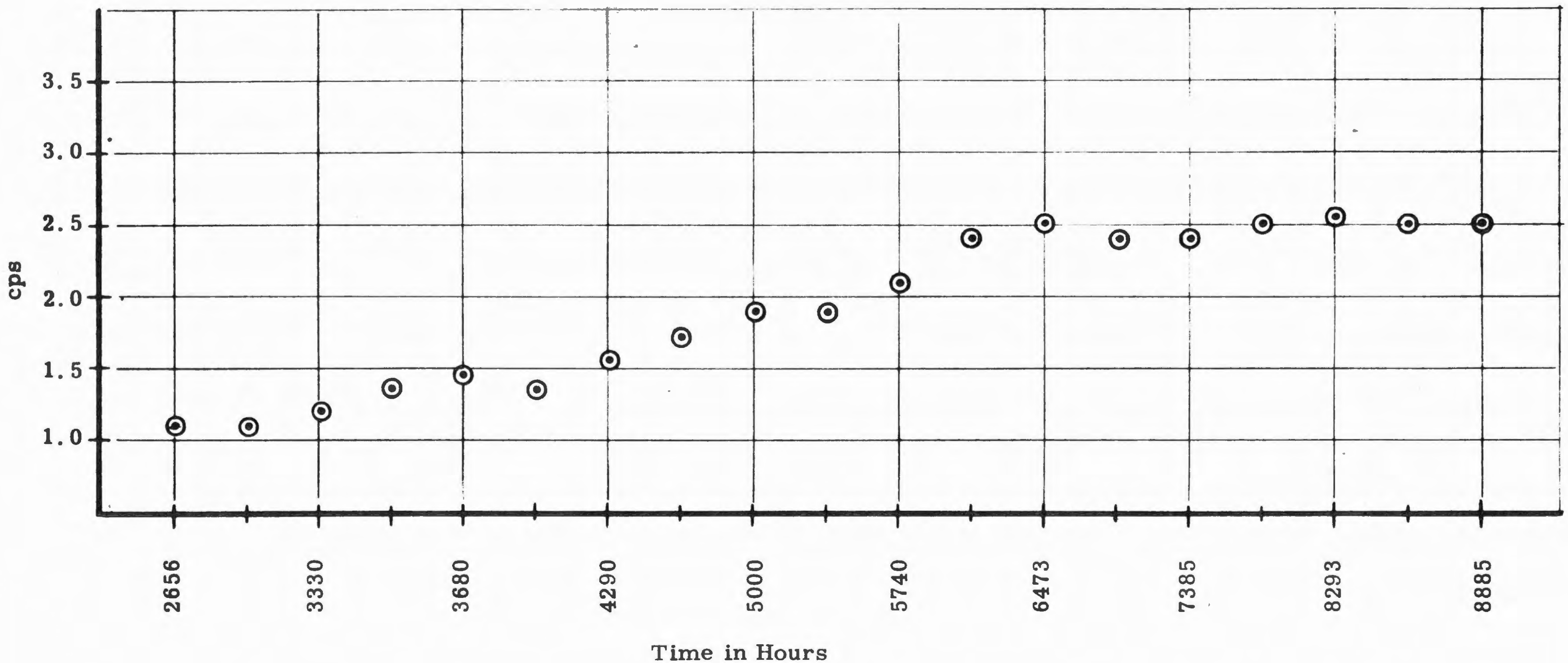


Figure 16. Ball Beat (1701 Hz) Frequency for Wheel CR-107B.

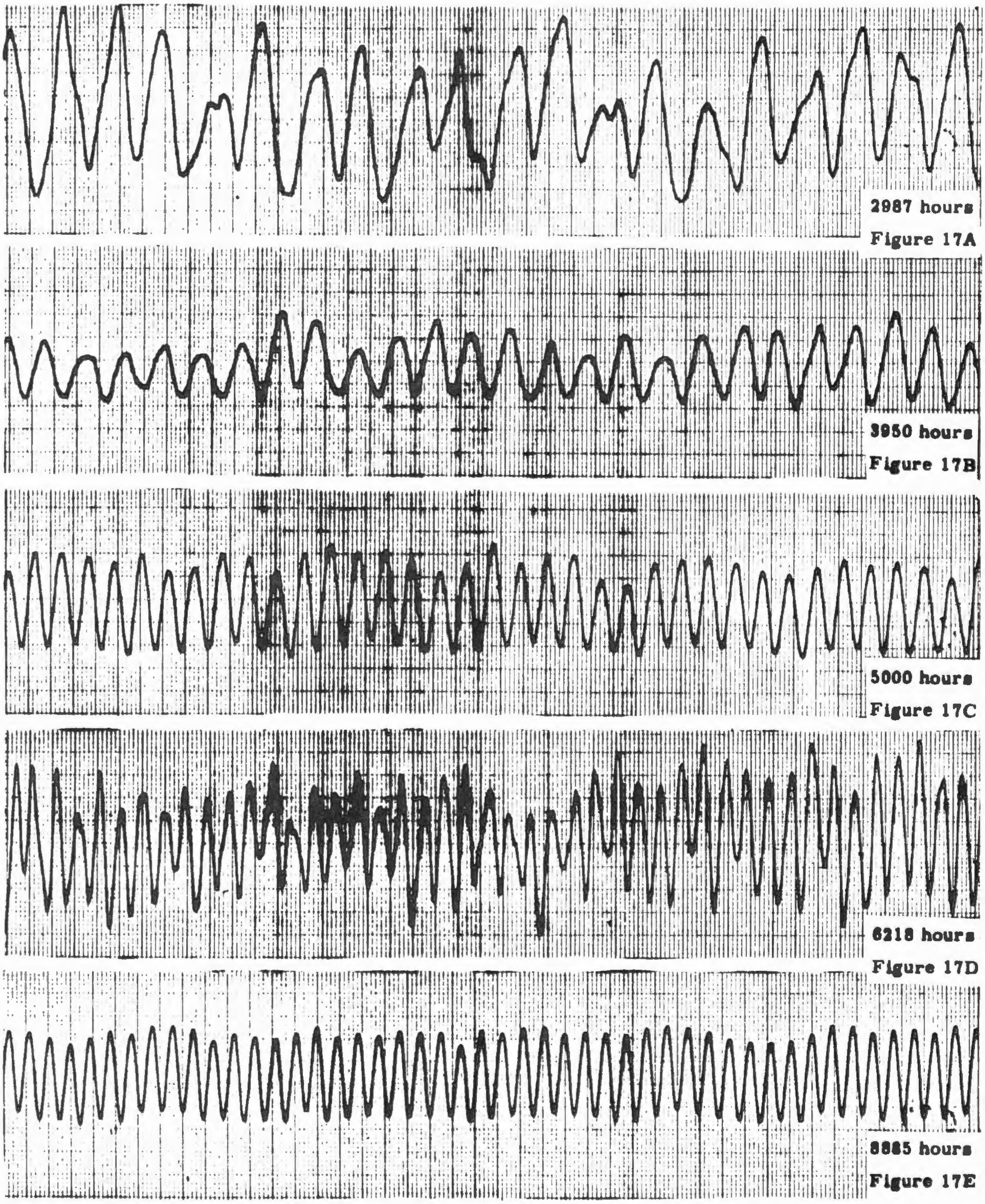


Figure 17. Retainer Beat Frequency Traces for Wheel CR-107B

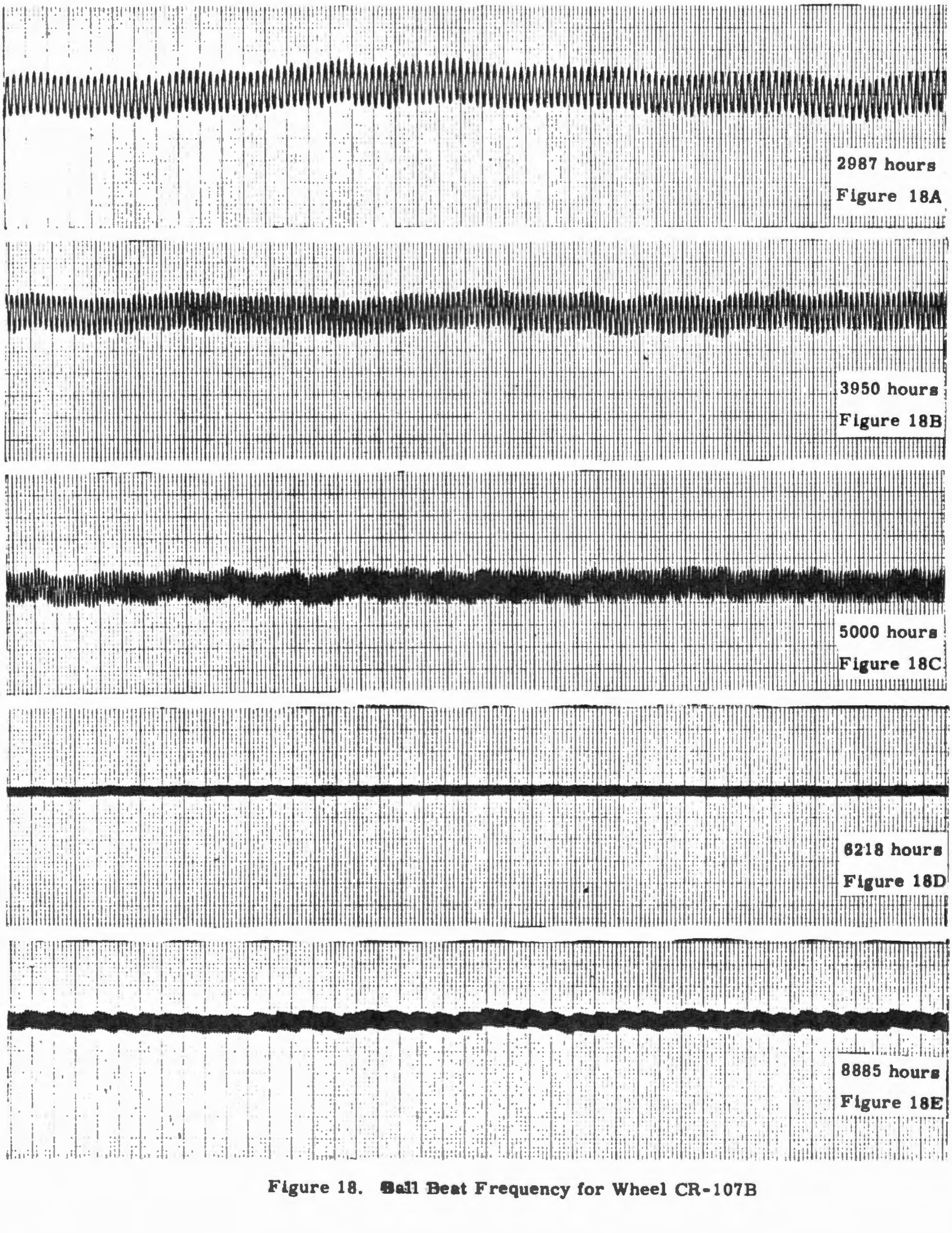


Figure 18. Ball Beat Frequency for Wheel CR-107B

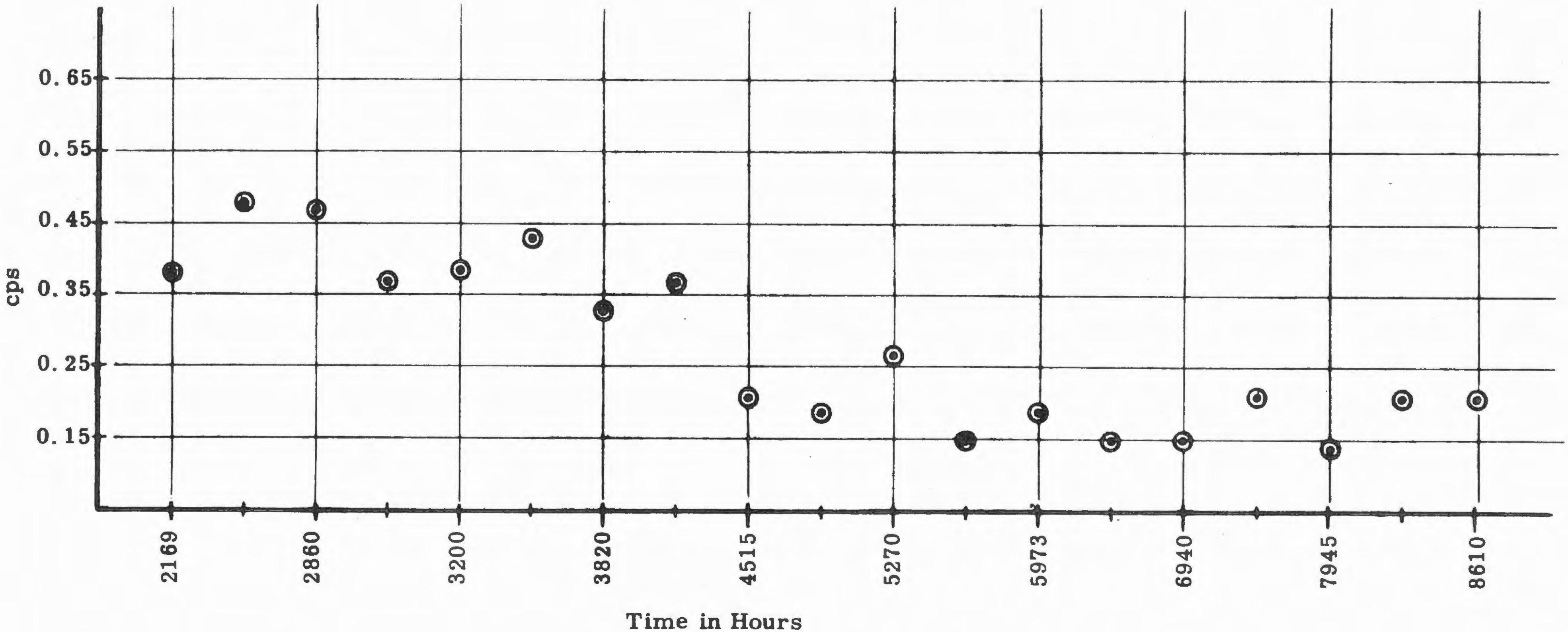


Figure 19. Retainer Beat (243 Hz) Frequency for Wheel CV-112A.

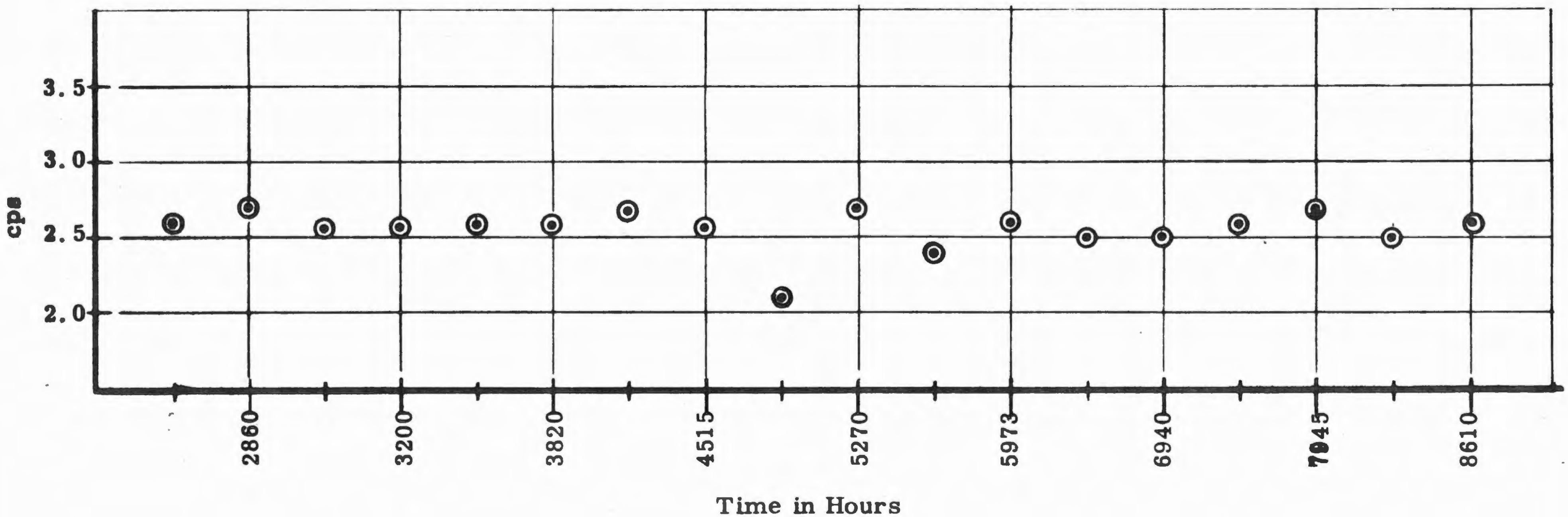


Figure 20. Ball Beat (1701 Hz) Frequency for Wheel CV-112A.

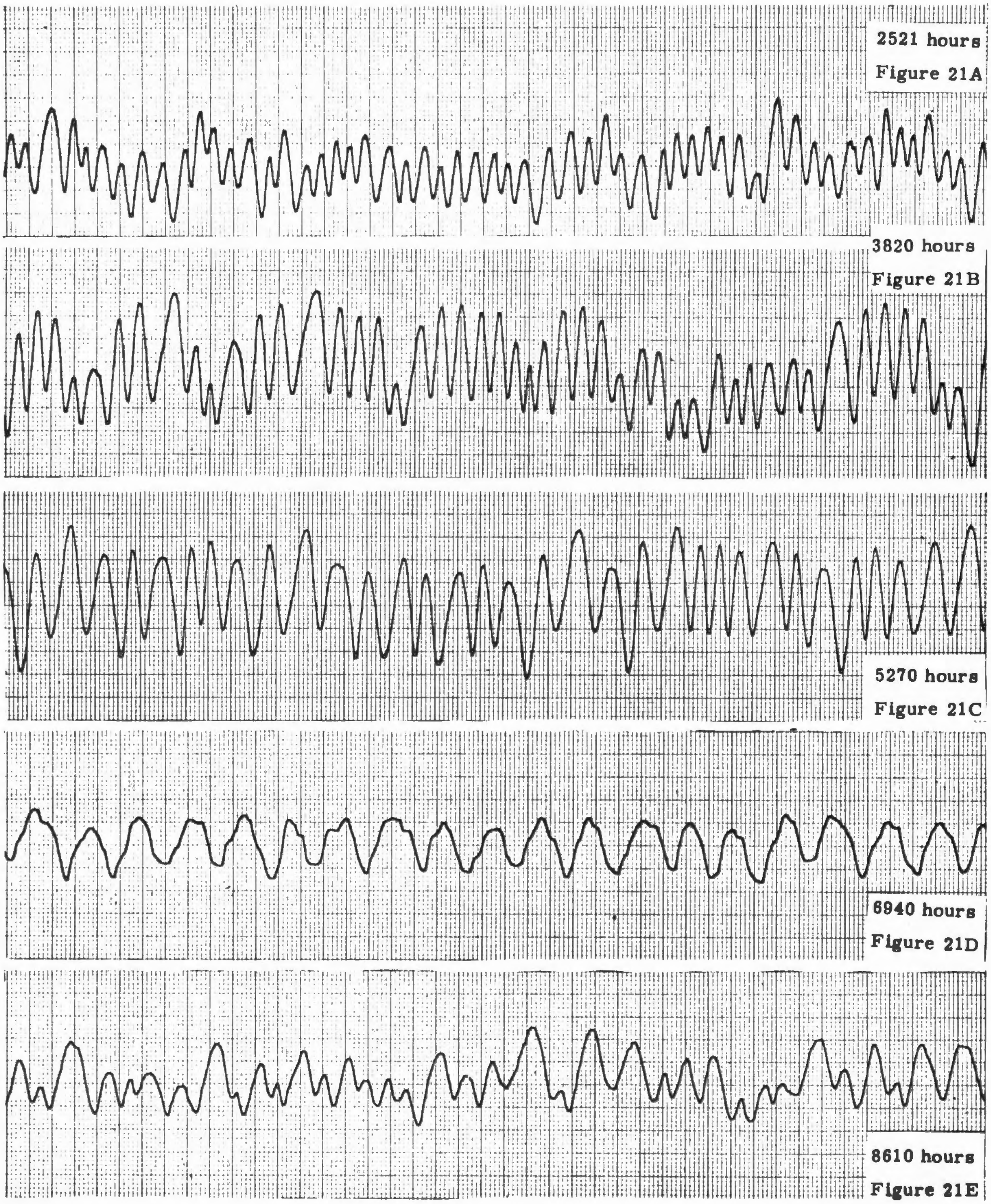


Figure 21. Retainer Beat Frequency Traces for Wheel CV-112A

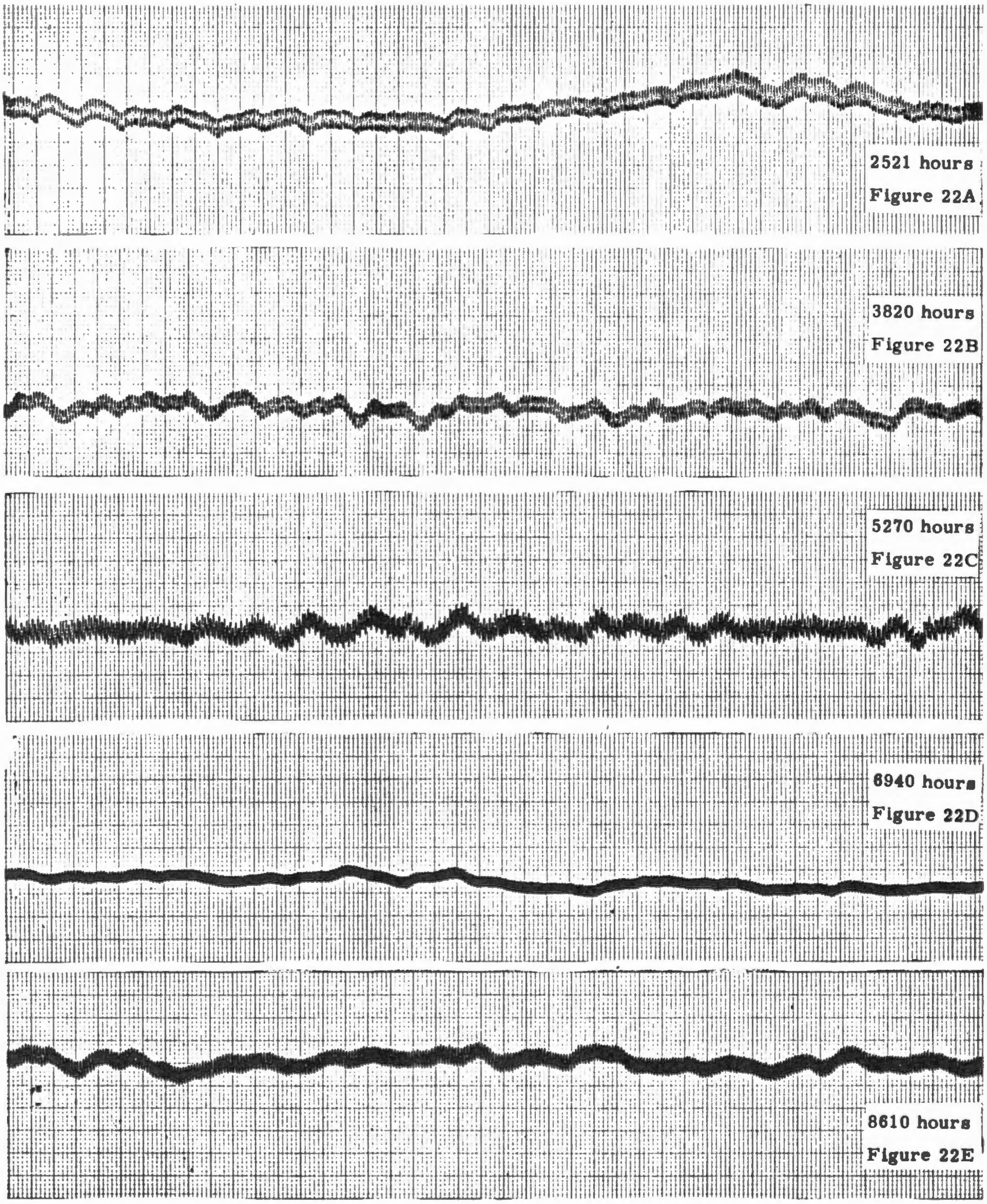


Figure 22. Ball Beat Frequency for Wheel CV-112A

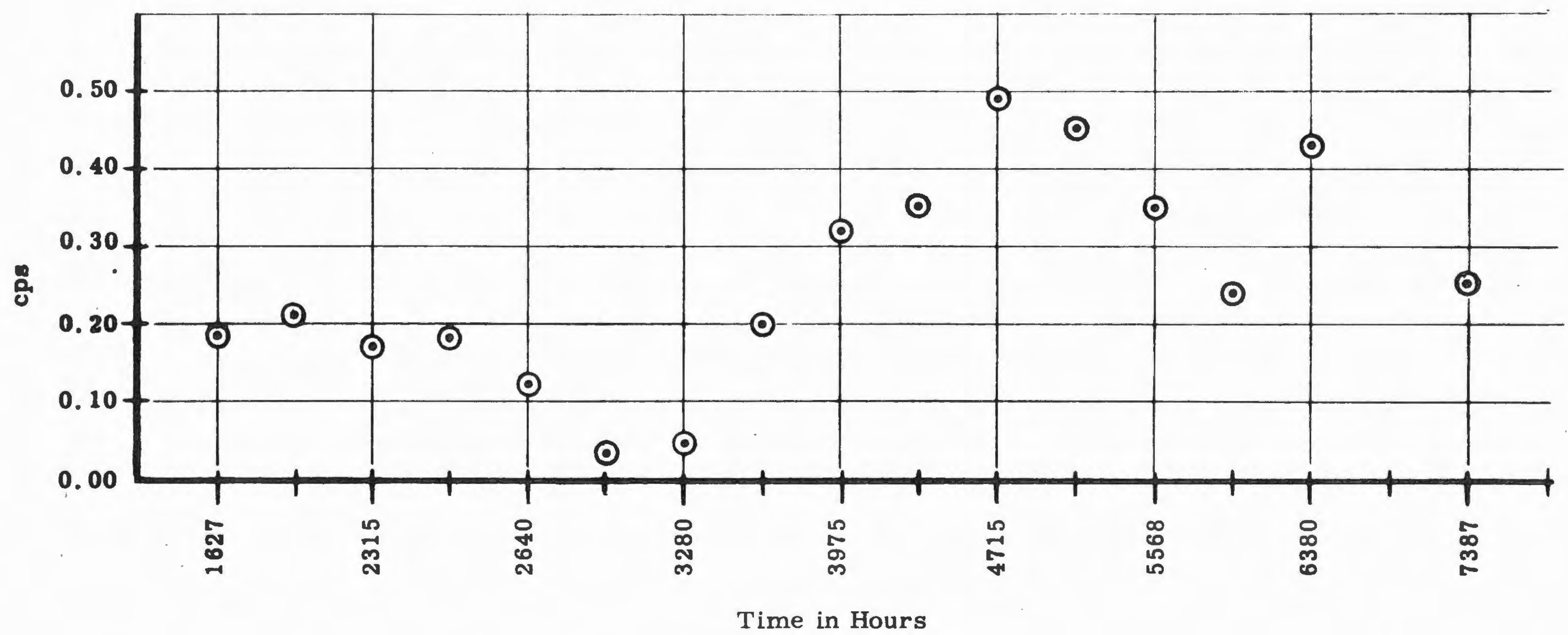


Figure 23. Retainer Beat (243 Hz) Frequency for Wheel CR-113B.

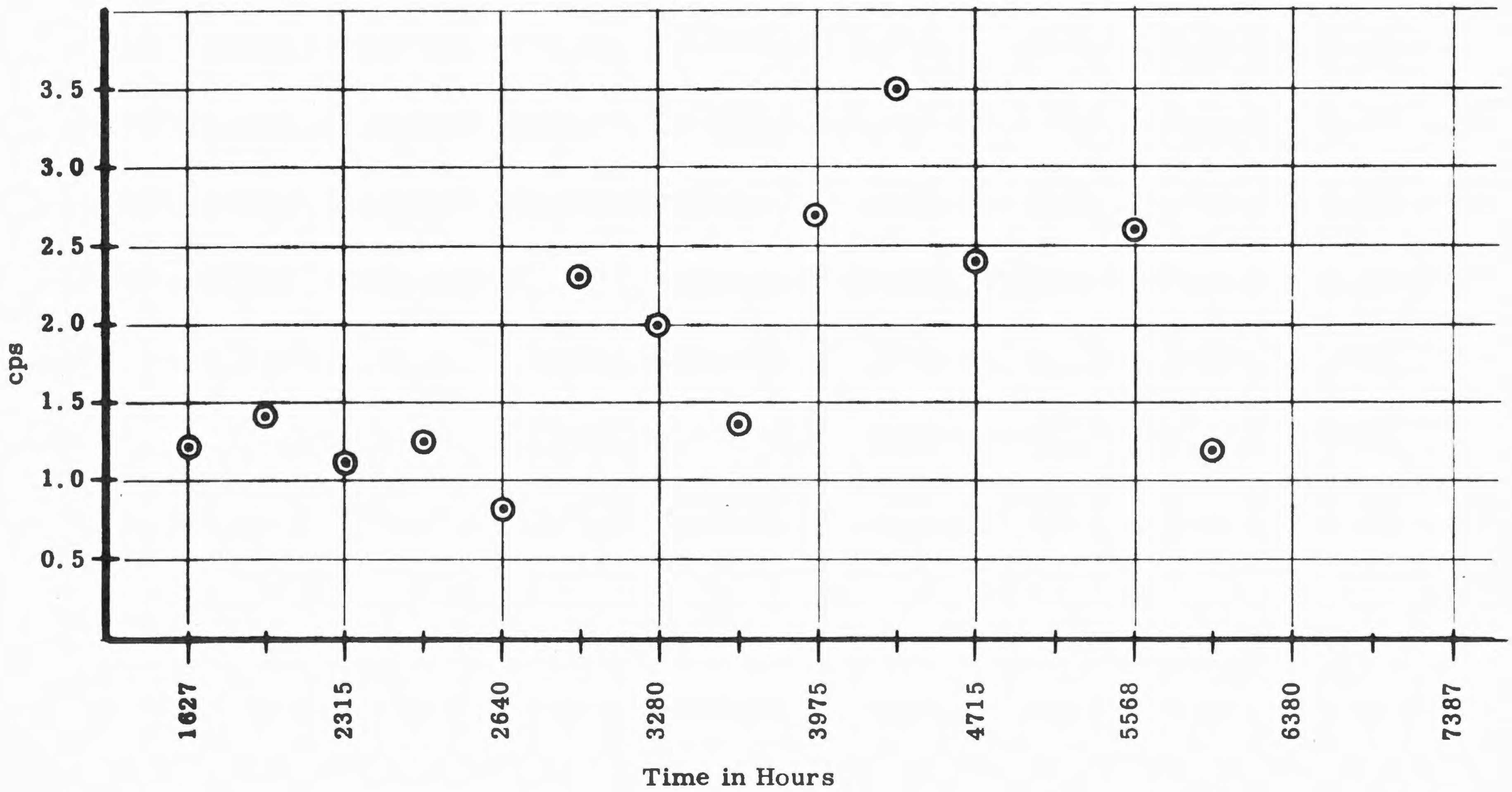


Figure 24. Ball Beat (1701 Hz) Frequency for Wheel CR-113B.

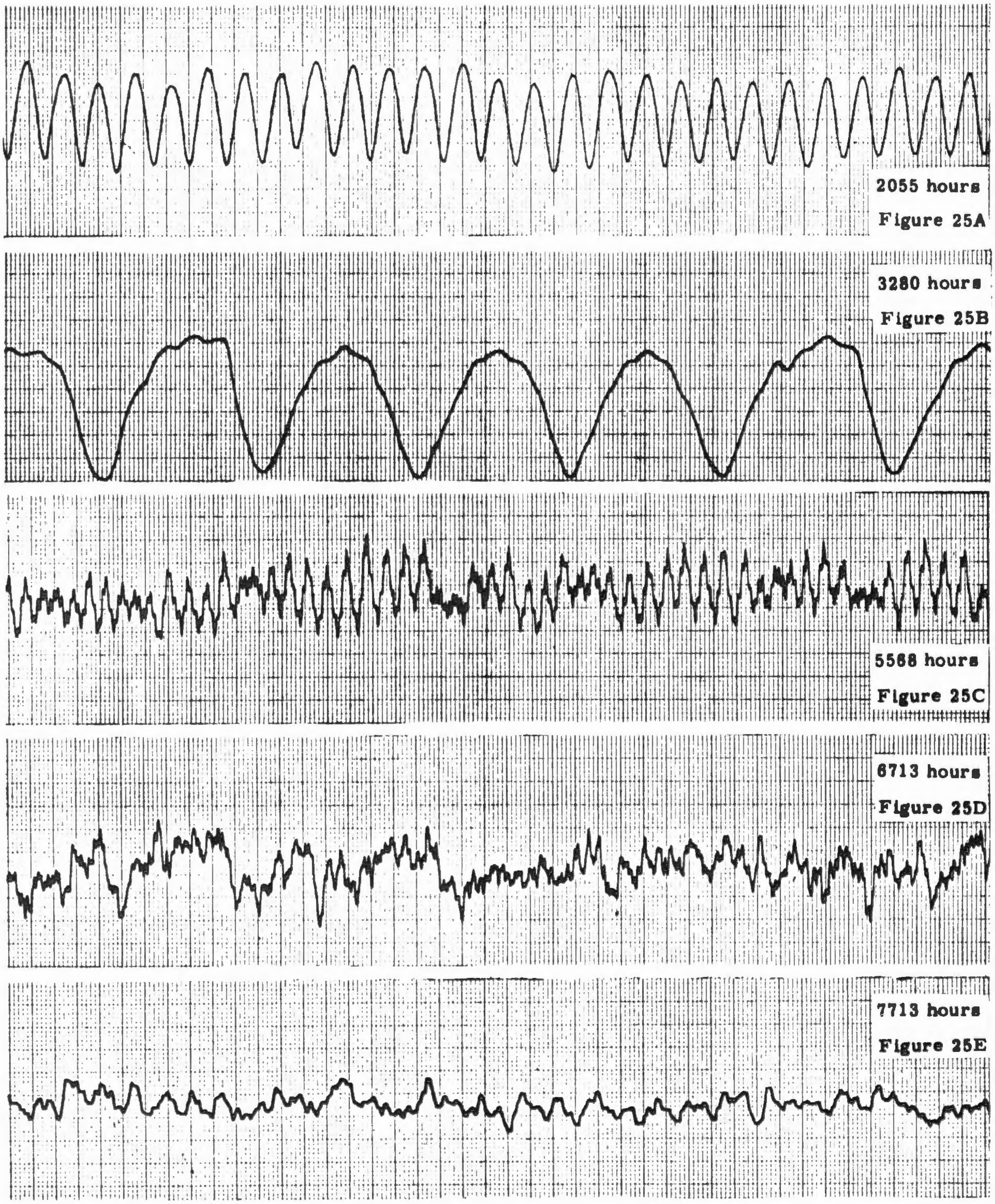


Figure 25. Retainer Beat Frequency Traces for Wheel CR-113B

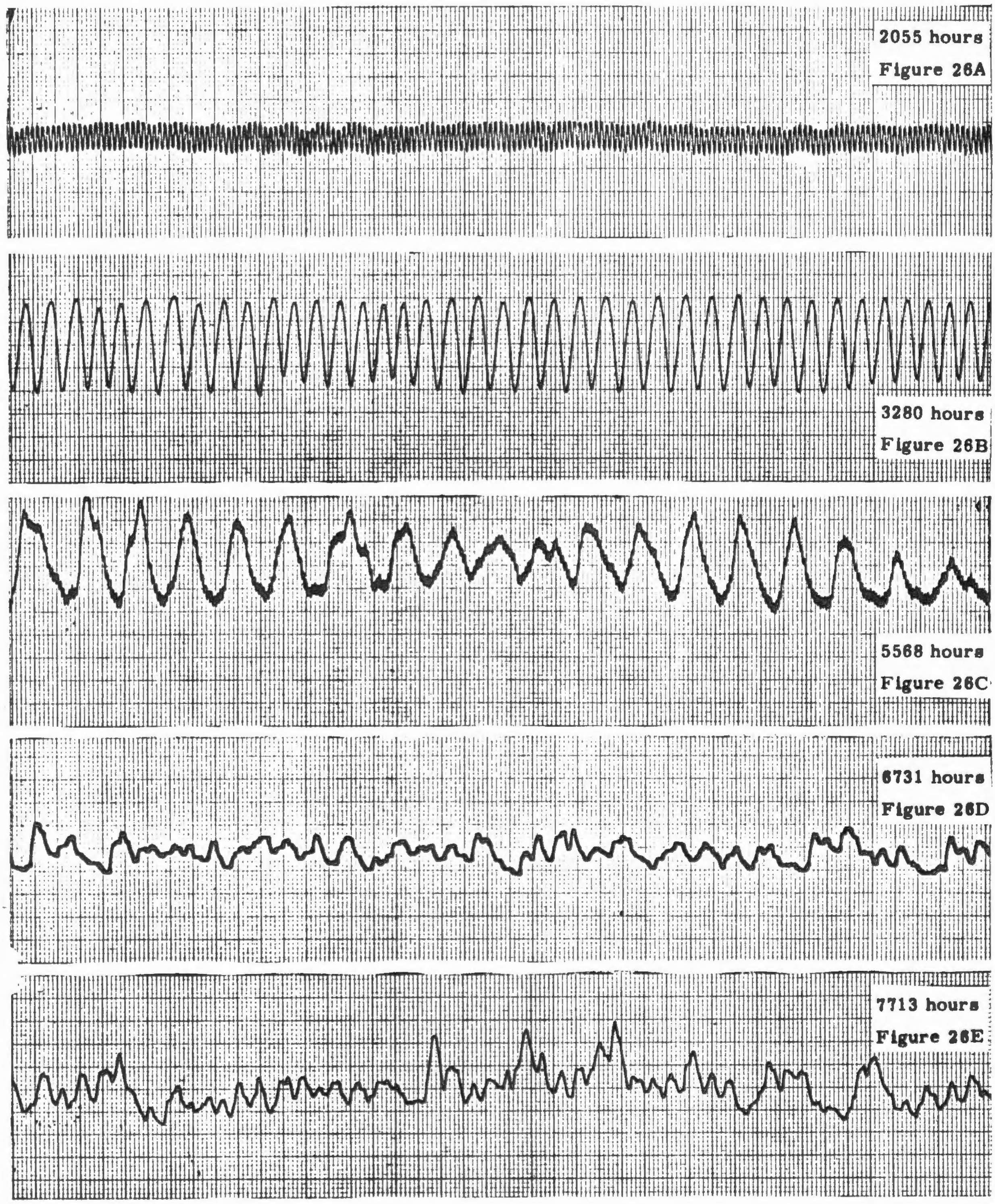


Figure 26. Ball Beat Frequency Traces for Wheel CR-113B

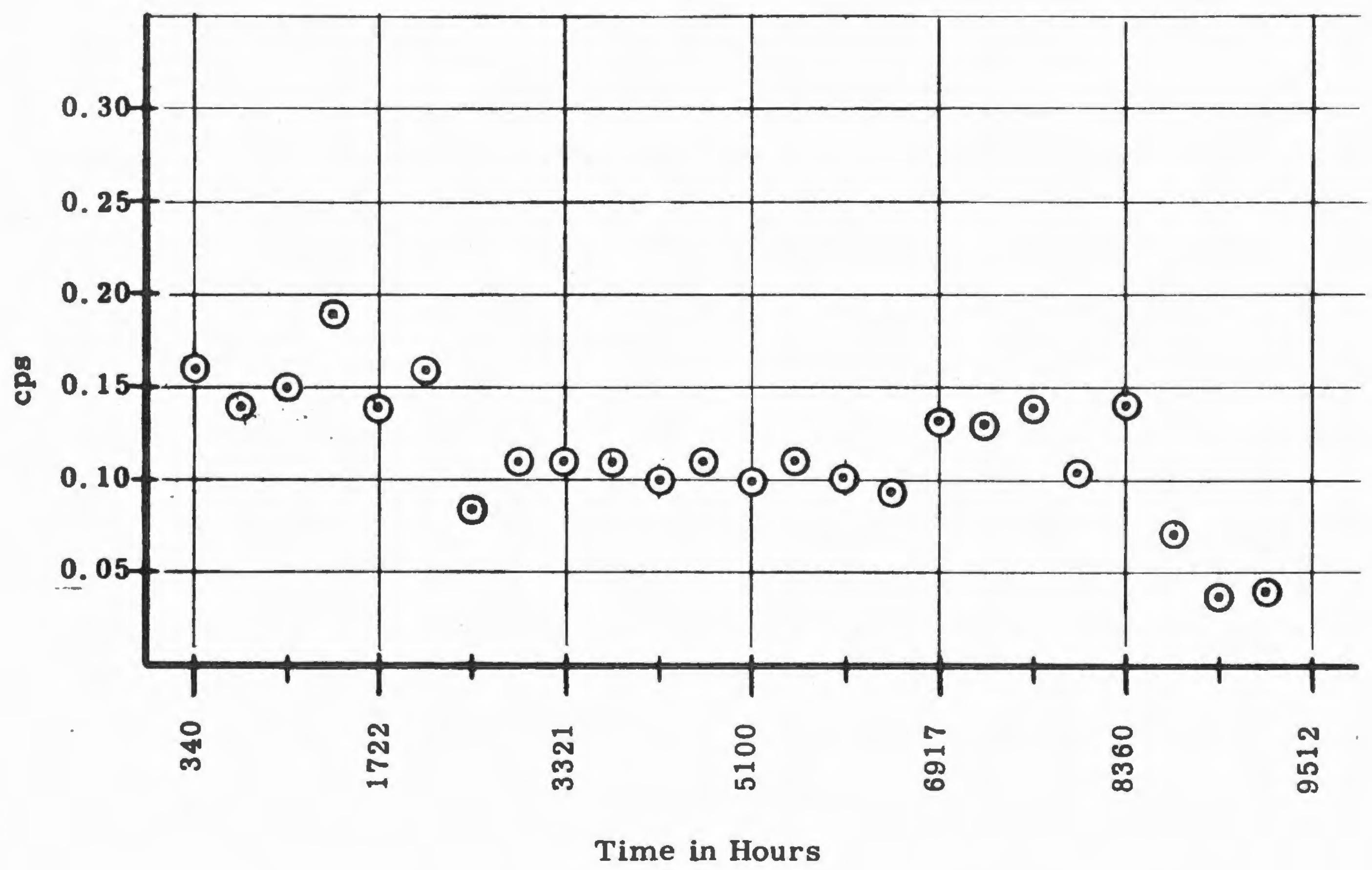


Figure 27. Retainer Beat (243 Hz) Frequency for Wheel CV-115E.

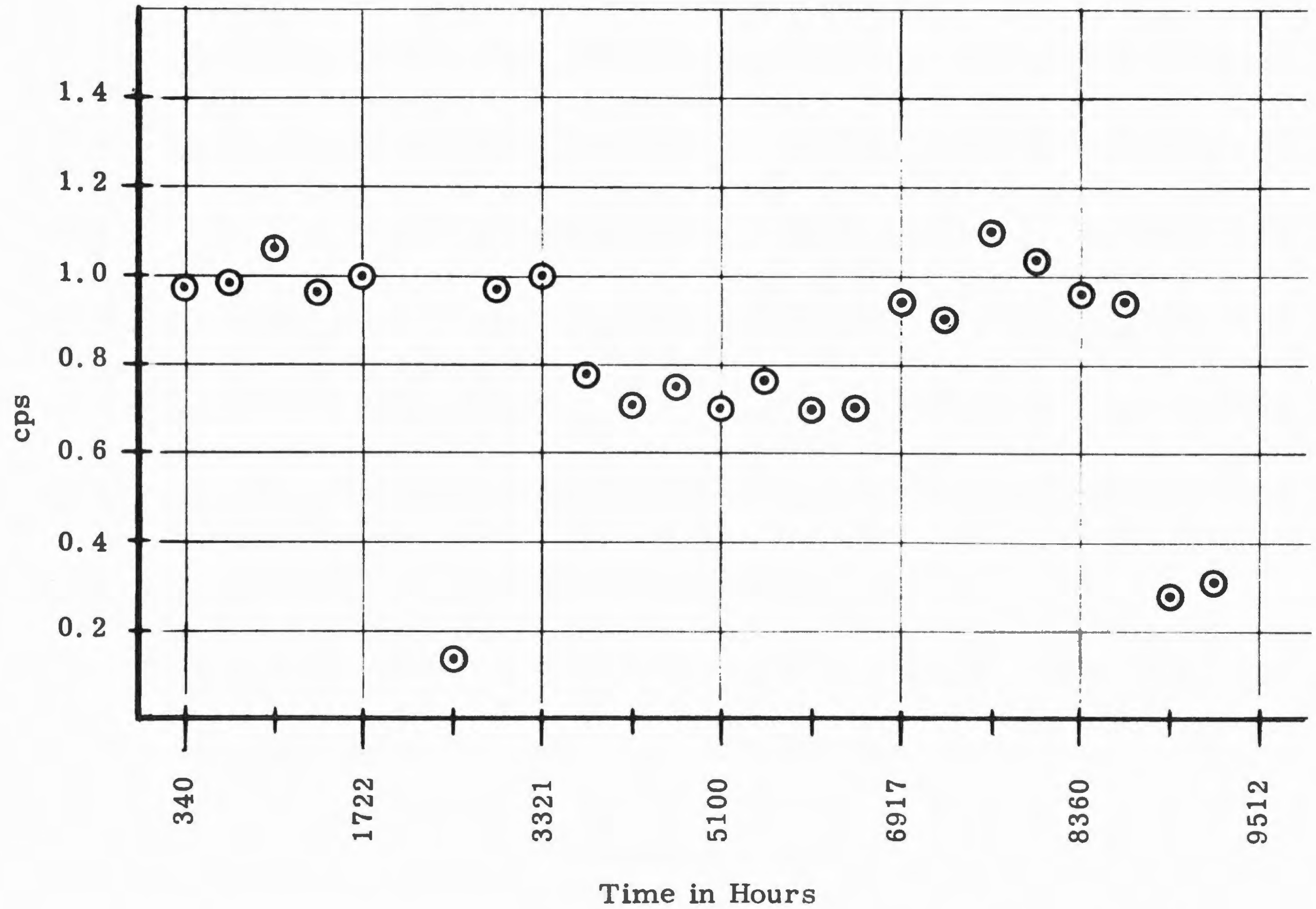


Figure 28. Ball Beat (1701 Hz) Frequency for Wheel CV-115E.

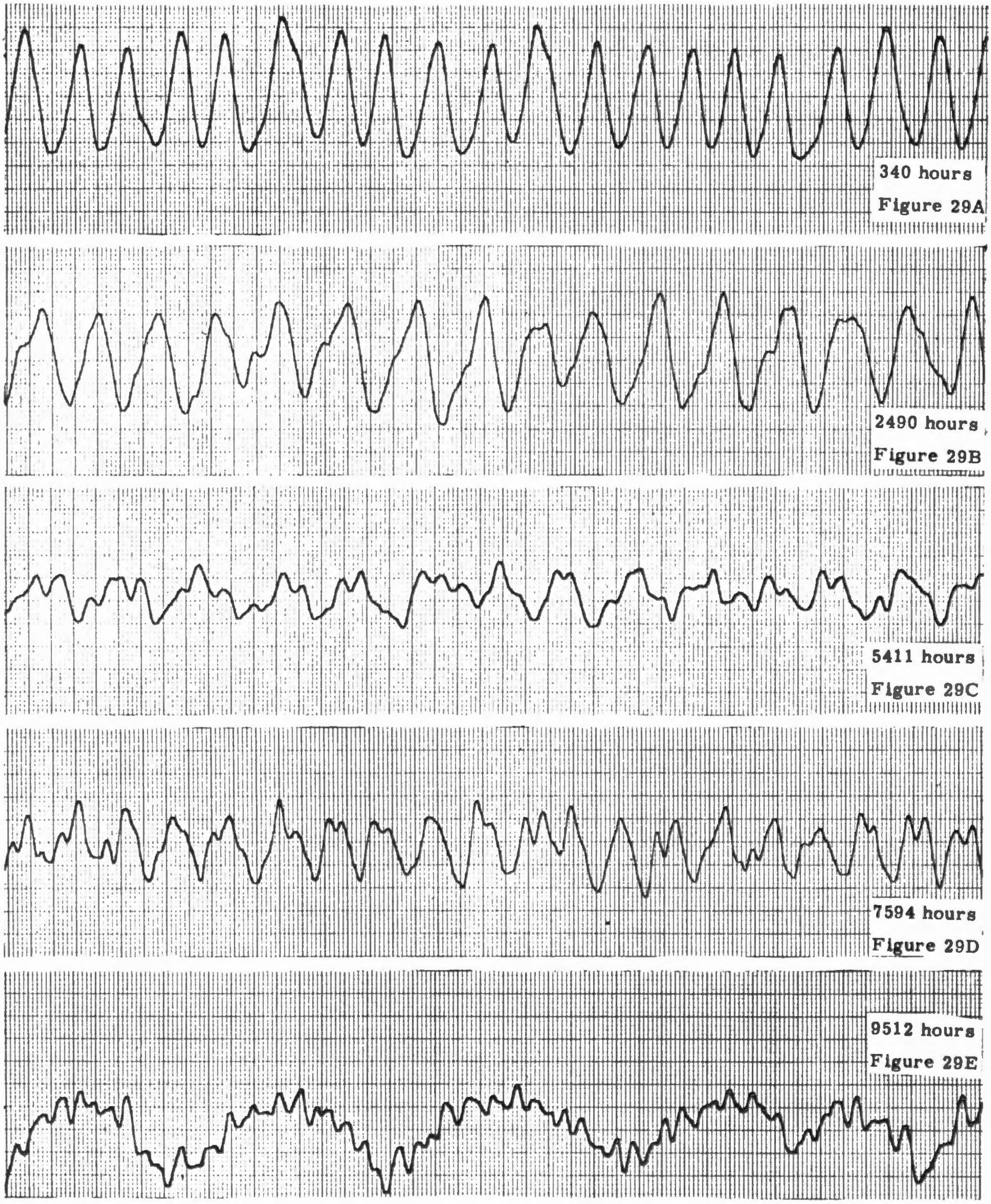


Figure 29. Retainer Beat Frequency Traces for Wheel CV-115E

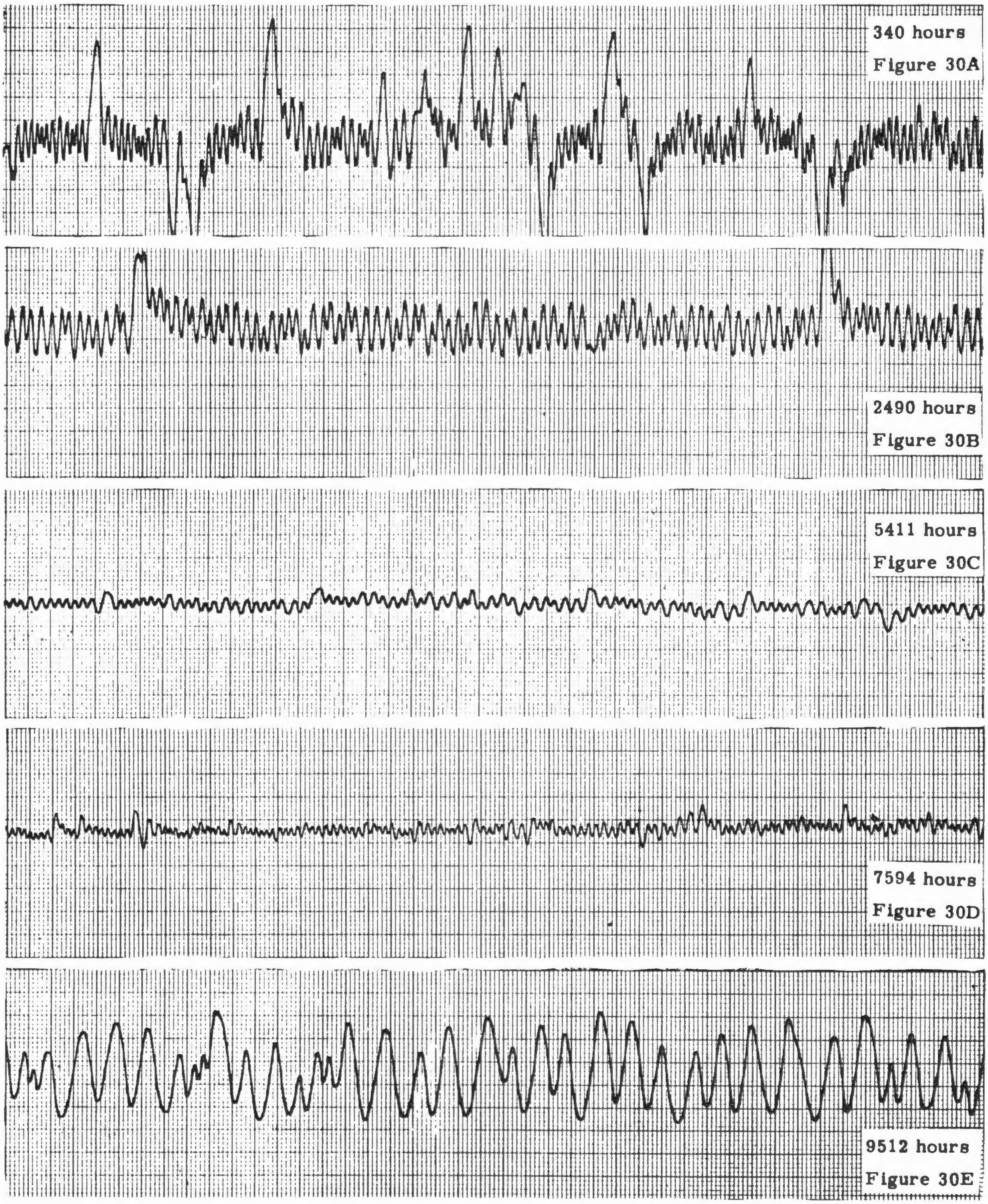


Figure 30. Ball Beat Frequency Traces for Wheel CV-115E

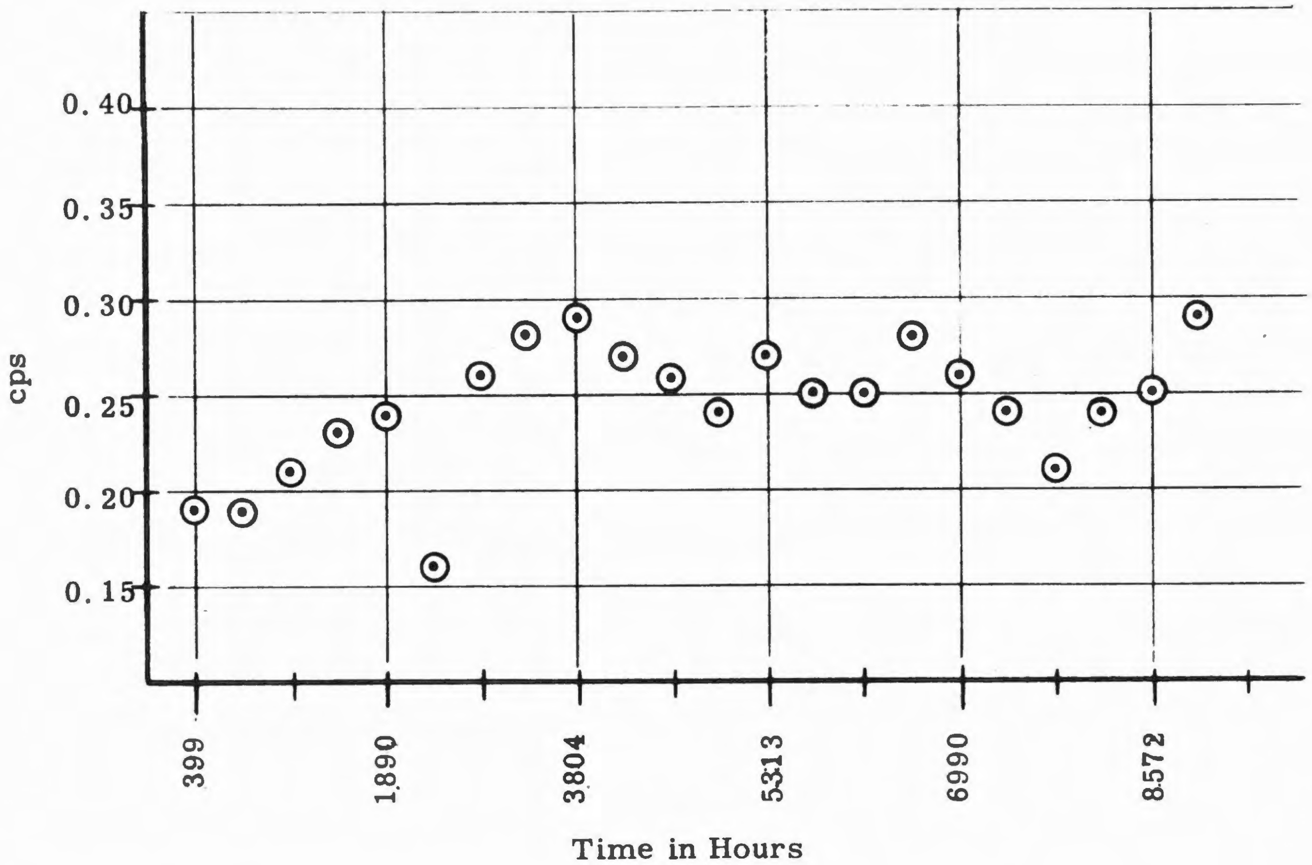


Figure 31. Retainer Beat (243 Hz) Frequency for Wheel CV-92J.

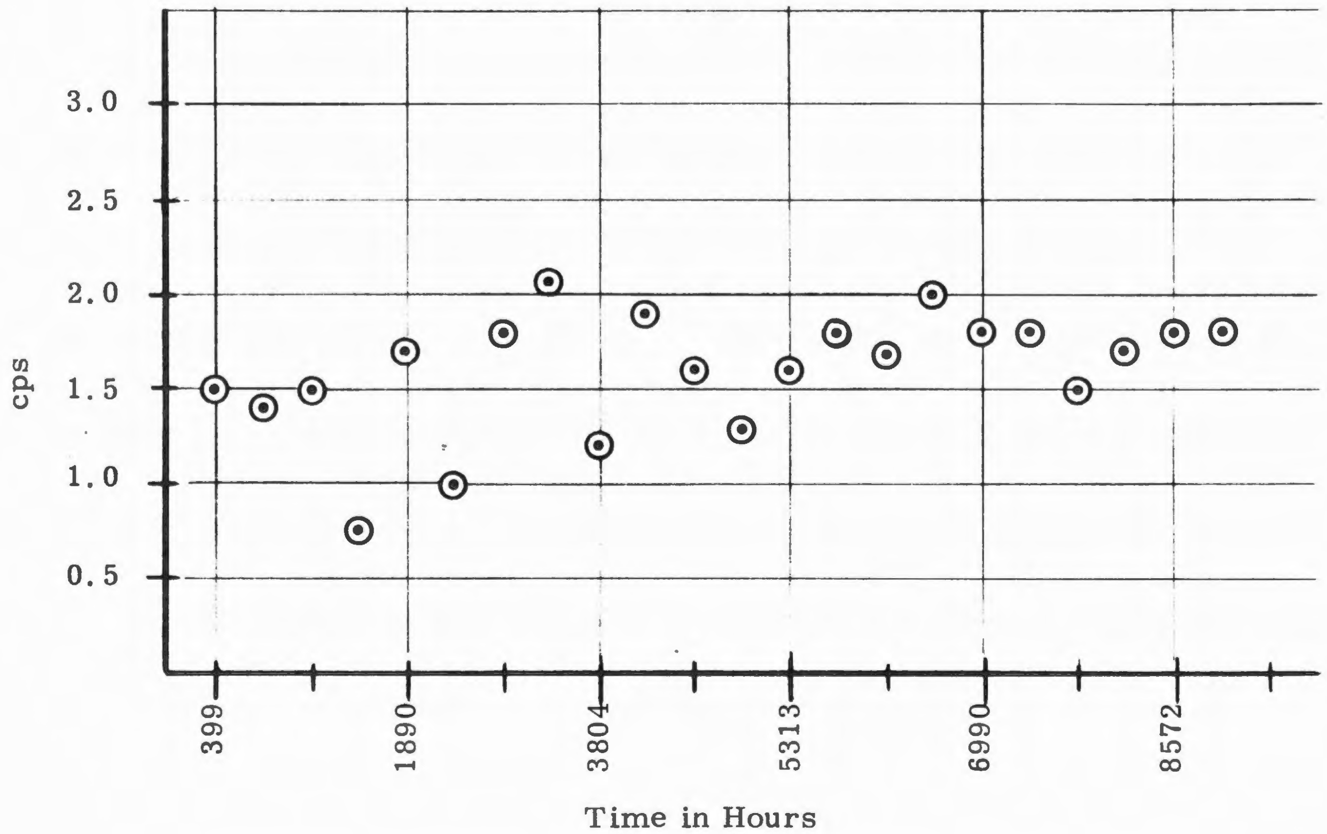


Figure 32. Ball Beat (1701 Hz) Frequency for Wheel CV-92J.

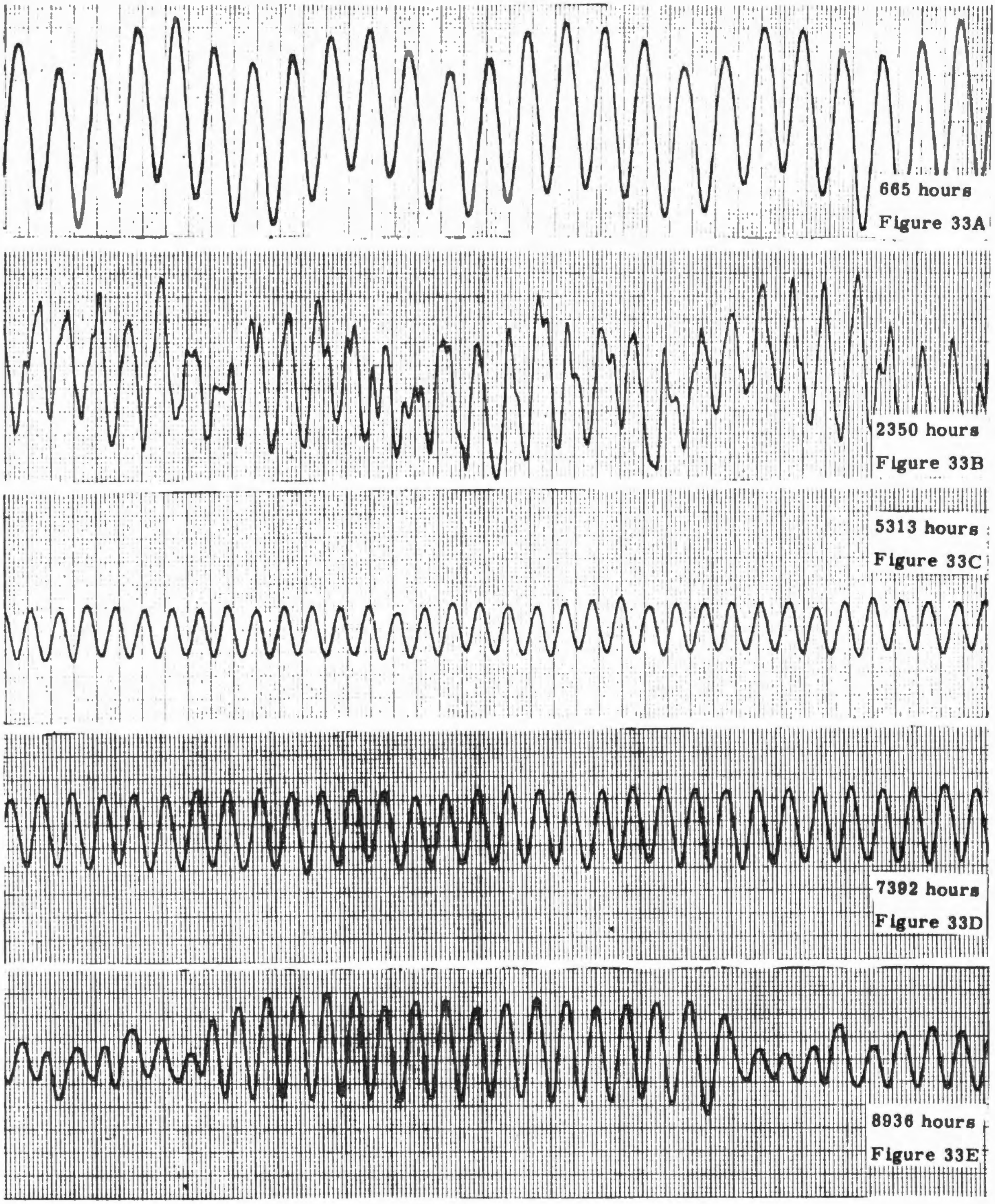


Figure 33. Retainer Beat Frequency Traces for Wheel CV-92J

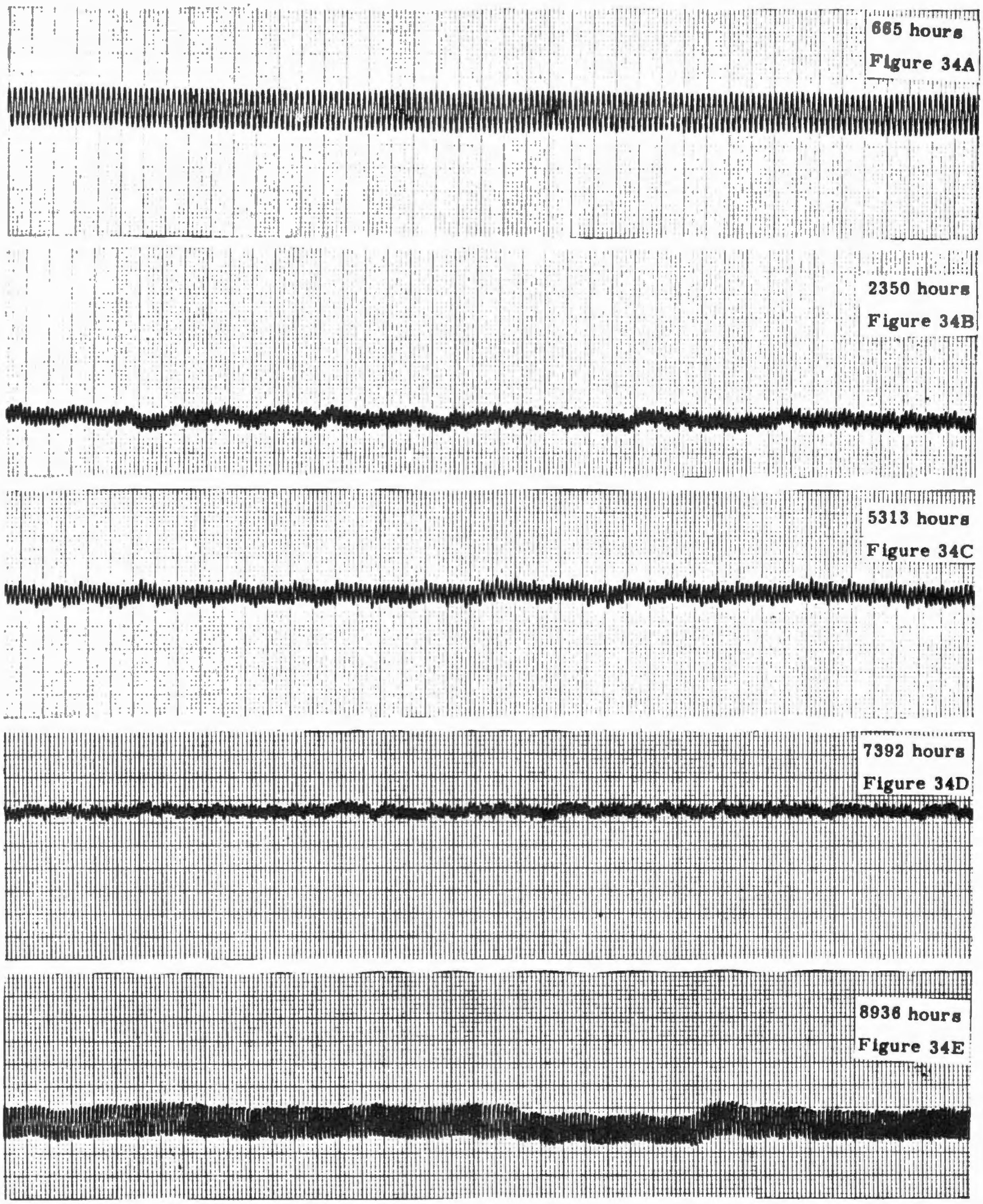


Figure 34. Ball Beat Frequency Traces for Wheel CV-92J

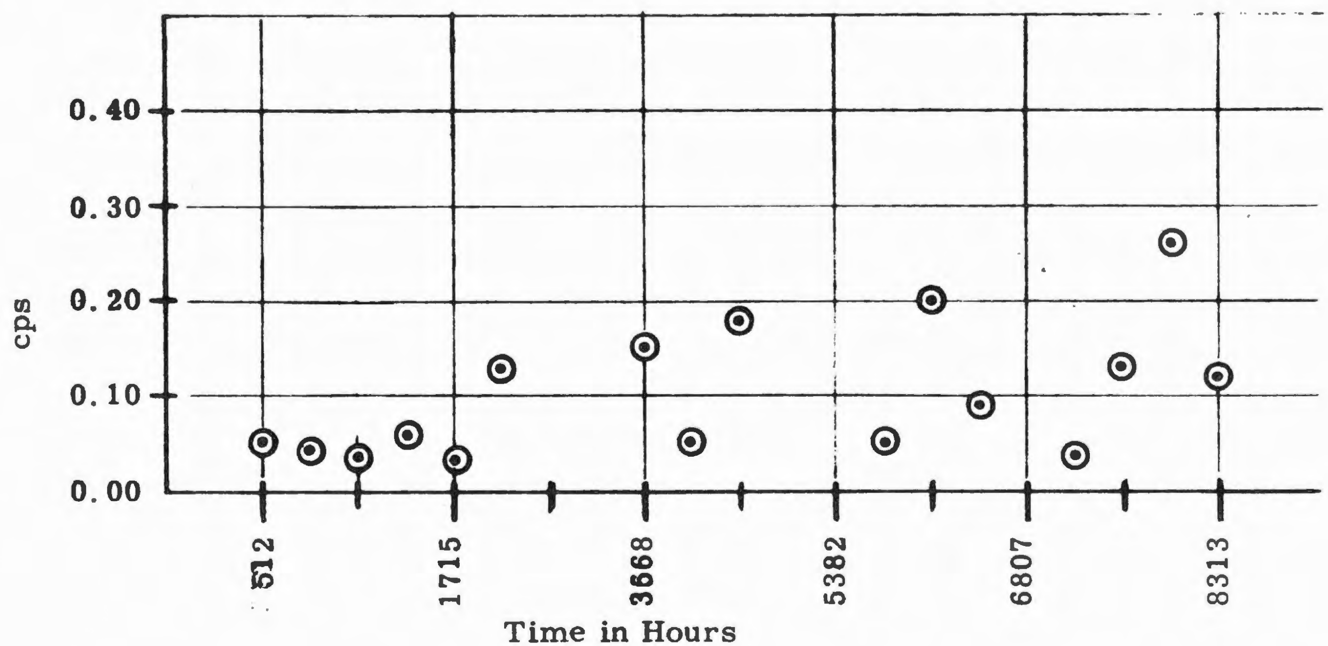


Figure 35. Retainer Beat (243 Hz) Frequency for Wheel CV-123B.

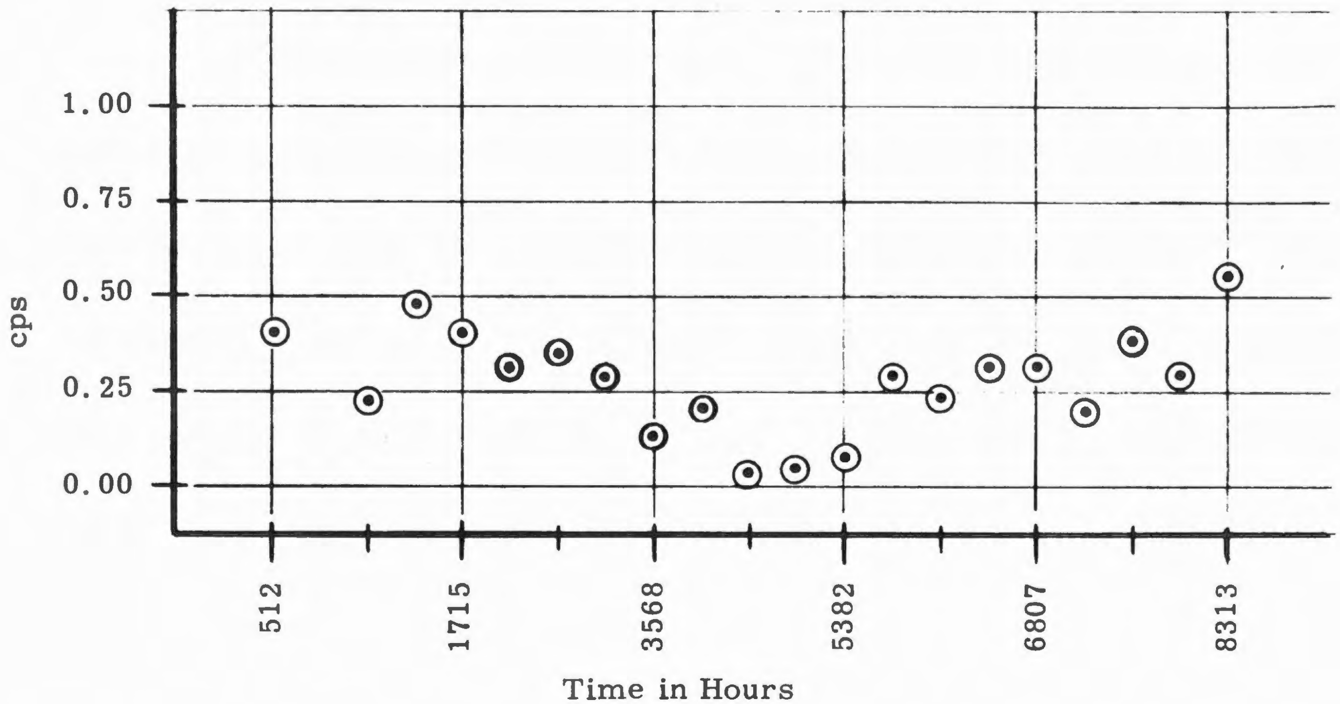


Figure 36. Ball Beat (1701 Hz) Frequency for Wheel CV-123B.

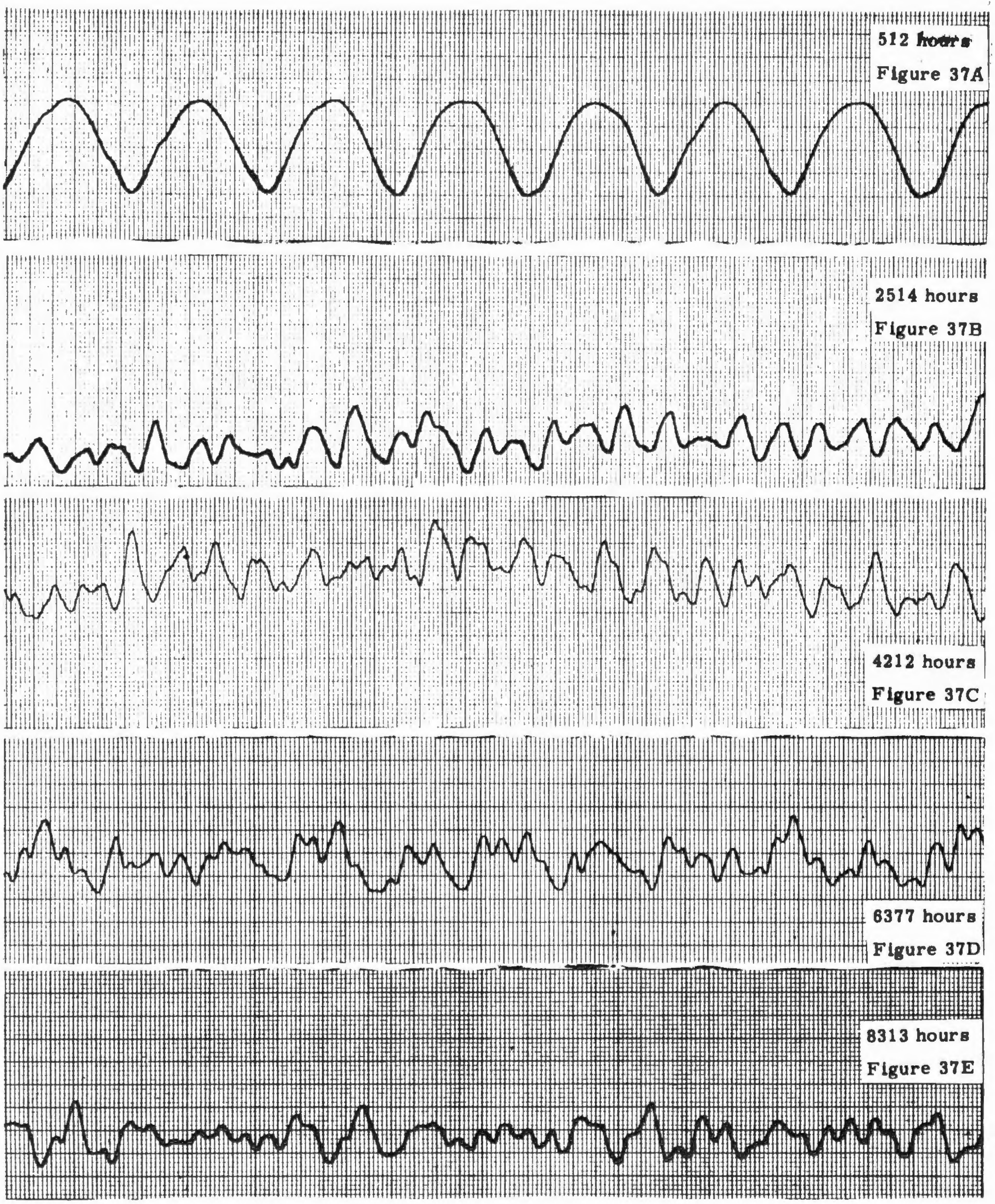


Figure 37. Retainer Beat Frequency Traces for Wheel CV-123B

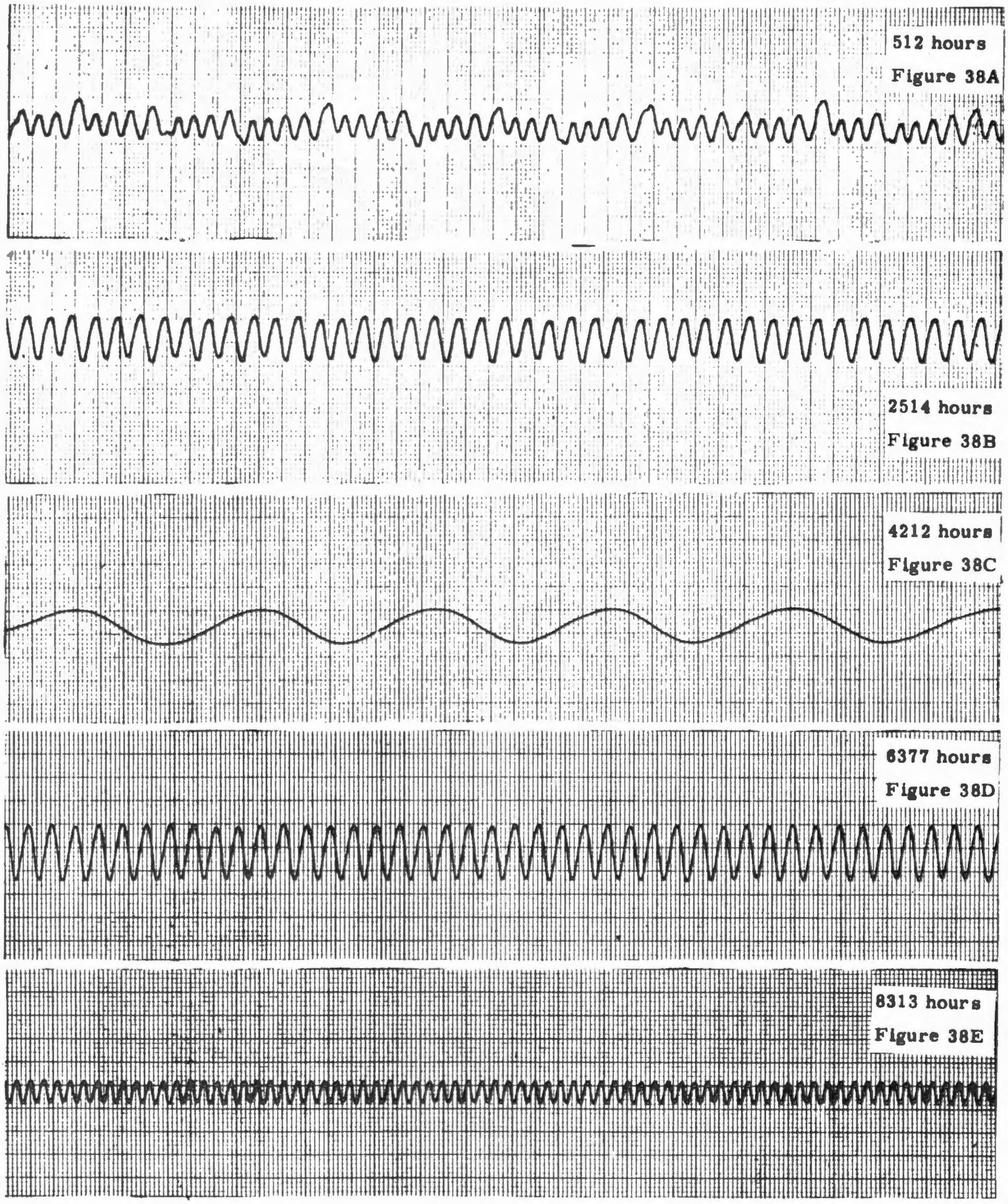


Figure 38. Ball Beat Frequency Traces for Wheel CV-123B

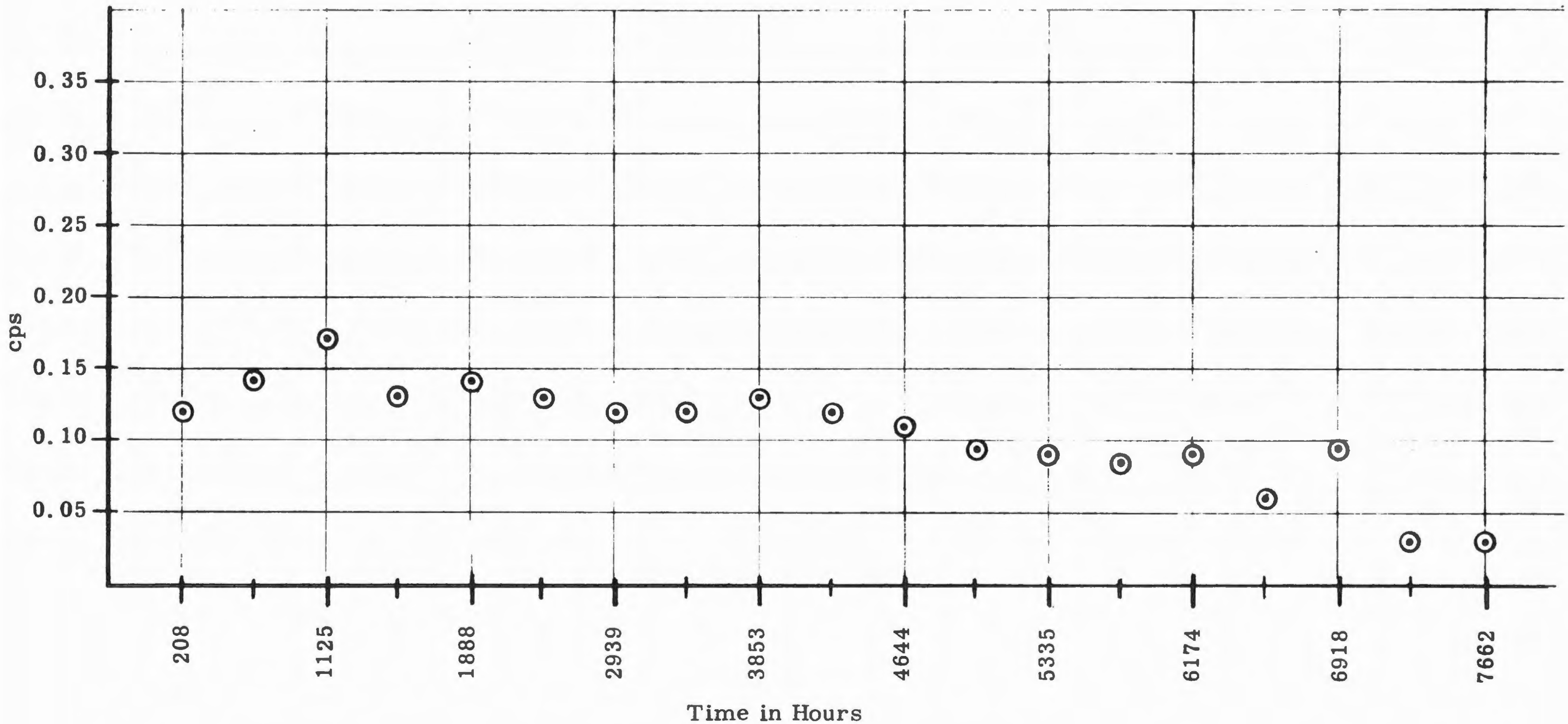


Figure 39. Retainer Beat (243 Hz) Frequency for Wheel CV-121D.

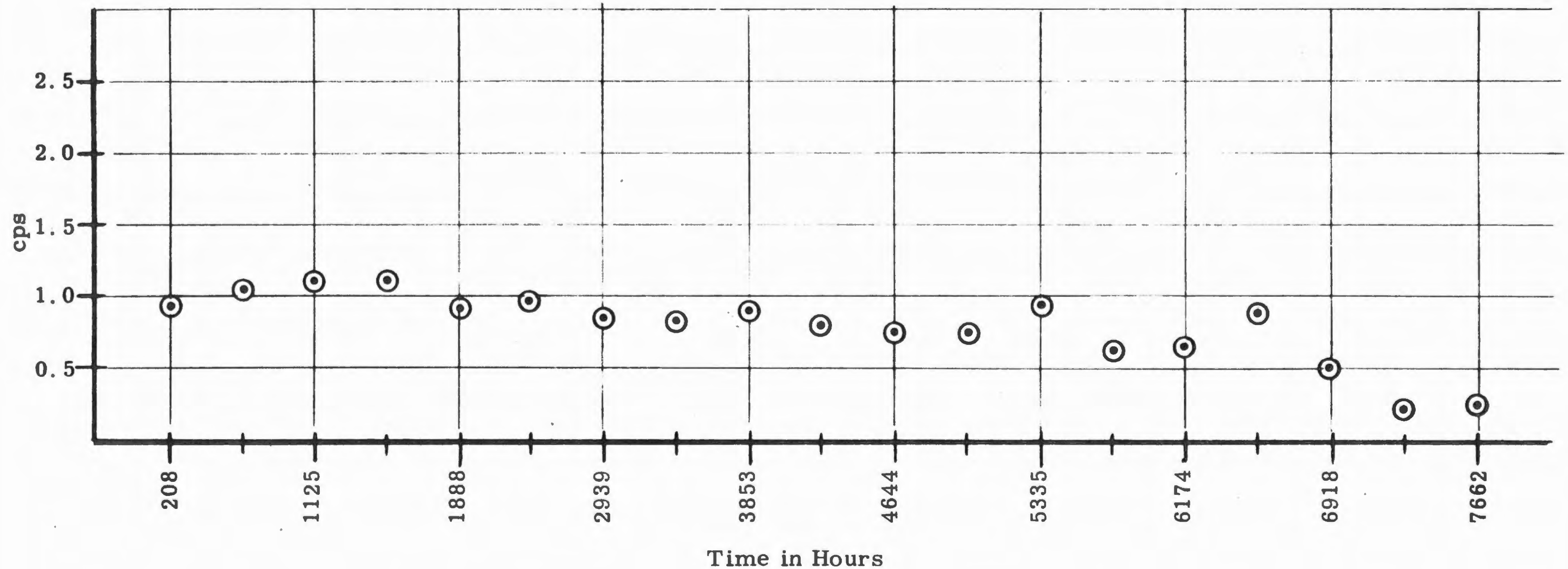


Figure 40. Ball Beat (1701 Hz) Frequency for Wheel CV-121D.

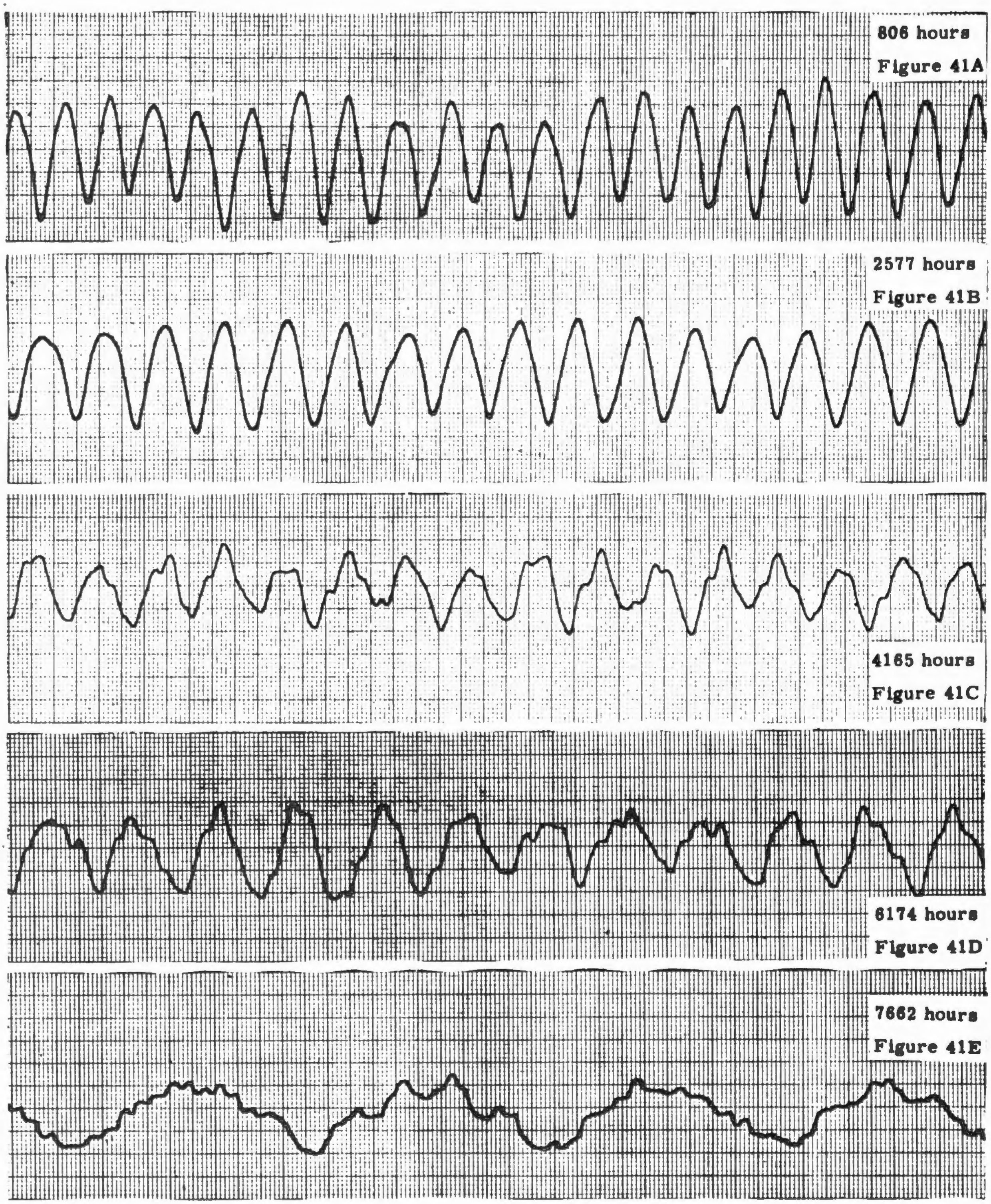


Figure 41. Retainer Beat Frequency Traces for Wheel CV-121D

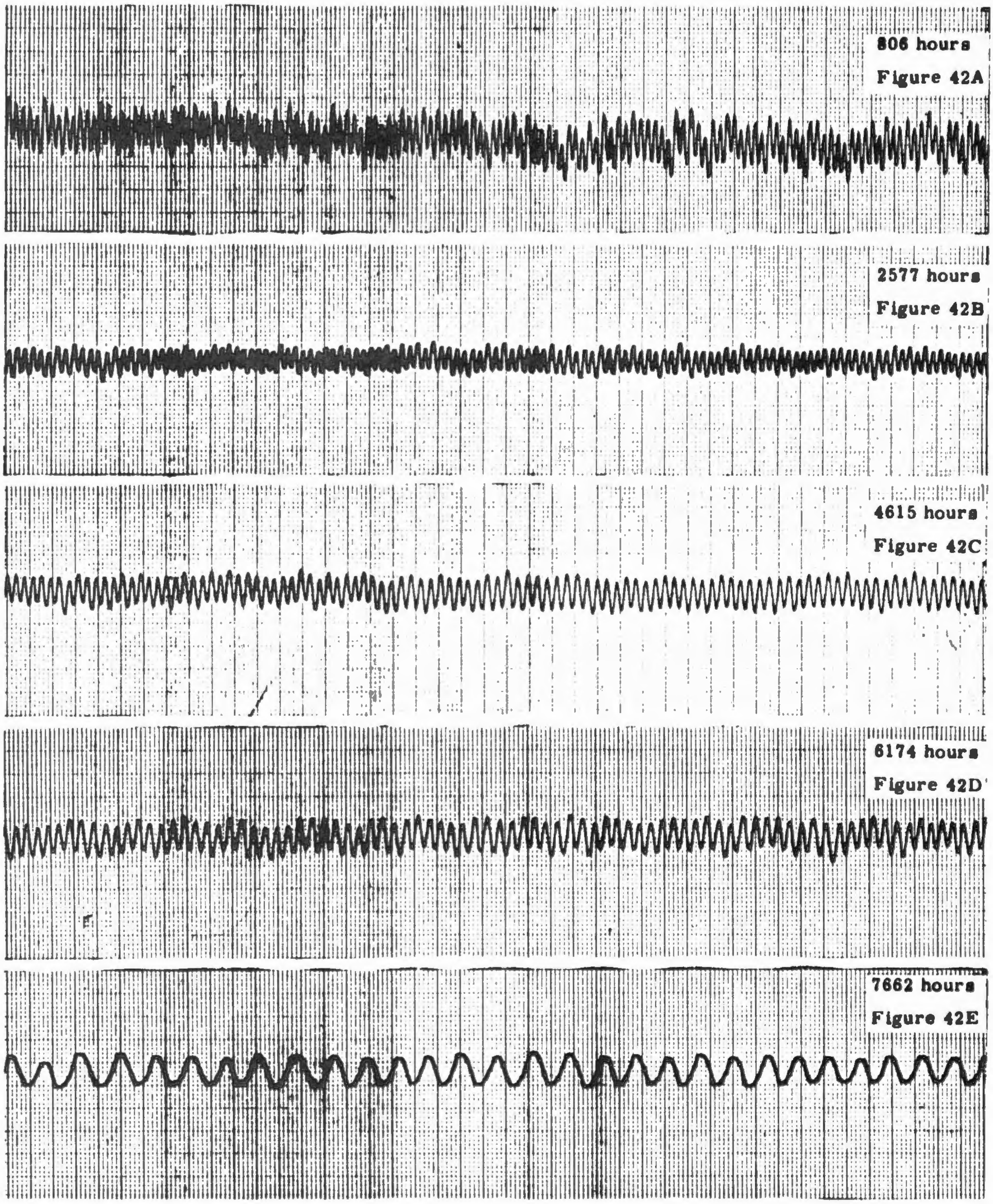


Figure 42. Ball Beat Frequency Traces for Wheel CV-121D

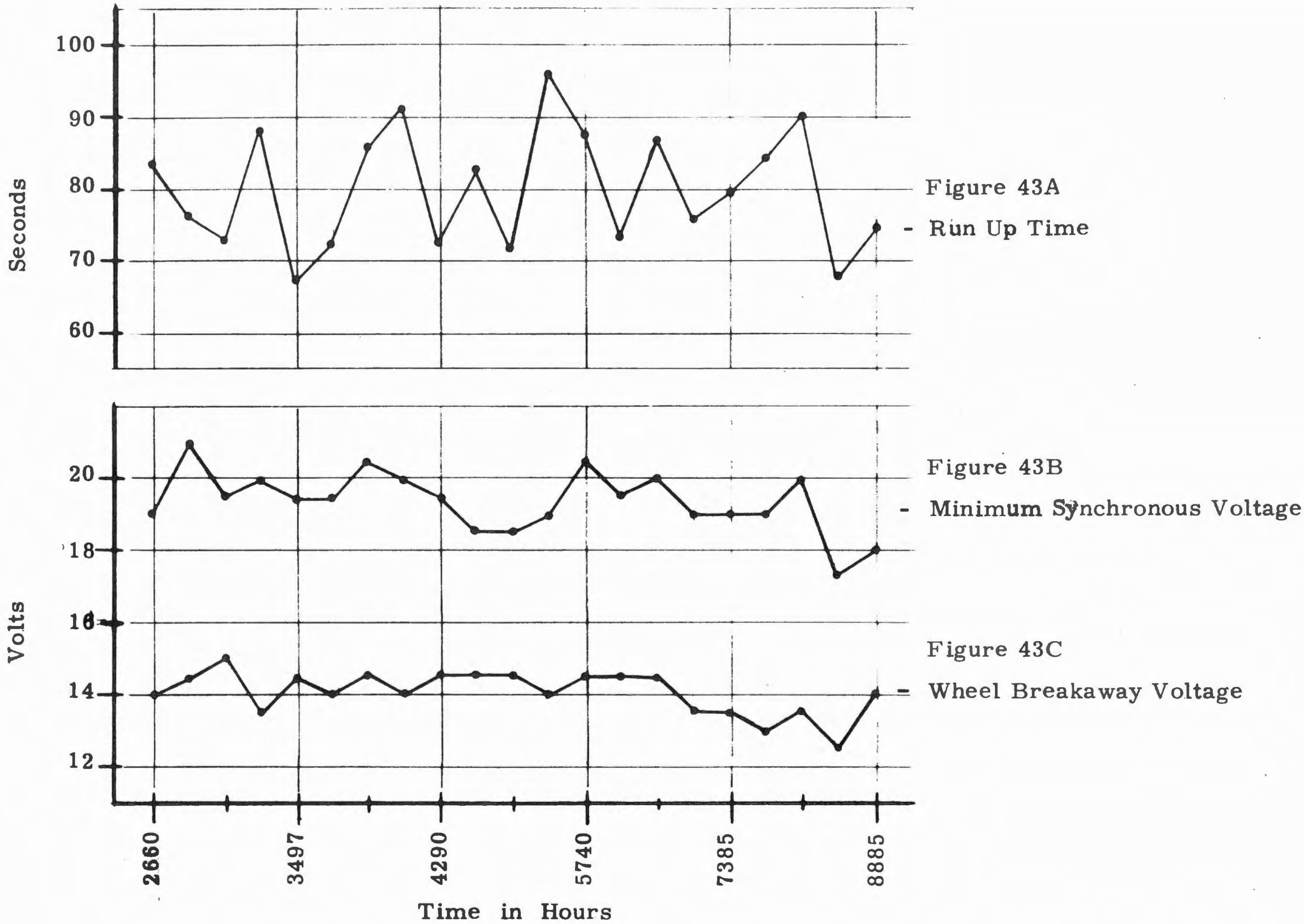


Figure 43. Run Up Time, Minimum Synchronous Voltage, and Wheel Breakaway Voltage Records for Wheel CR-107B.

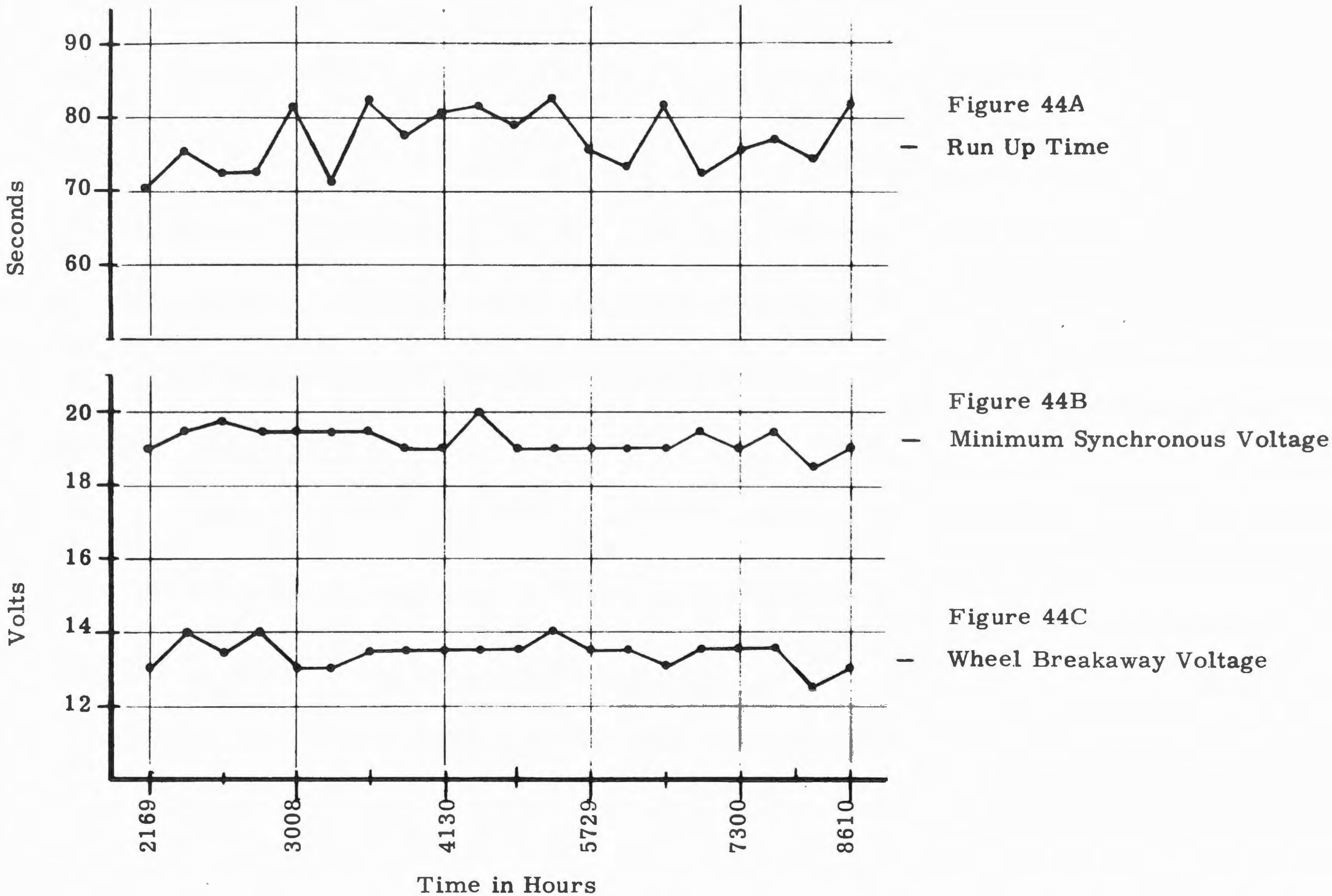


Figure 44. Run Up Time, Minimum Synchronous Voltage, and Wheel Breakaway Voltage Records for Wheel CV-112A.

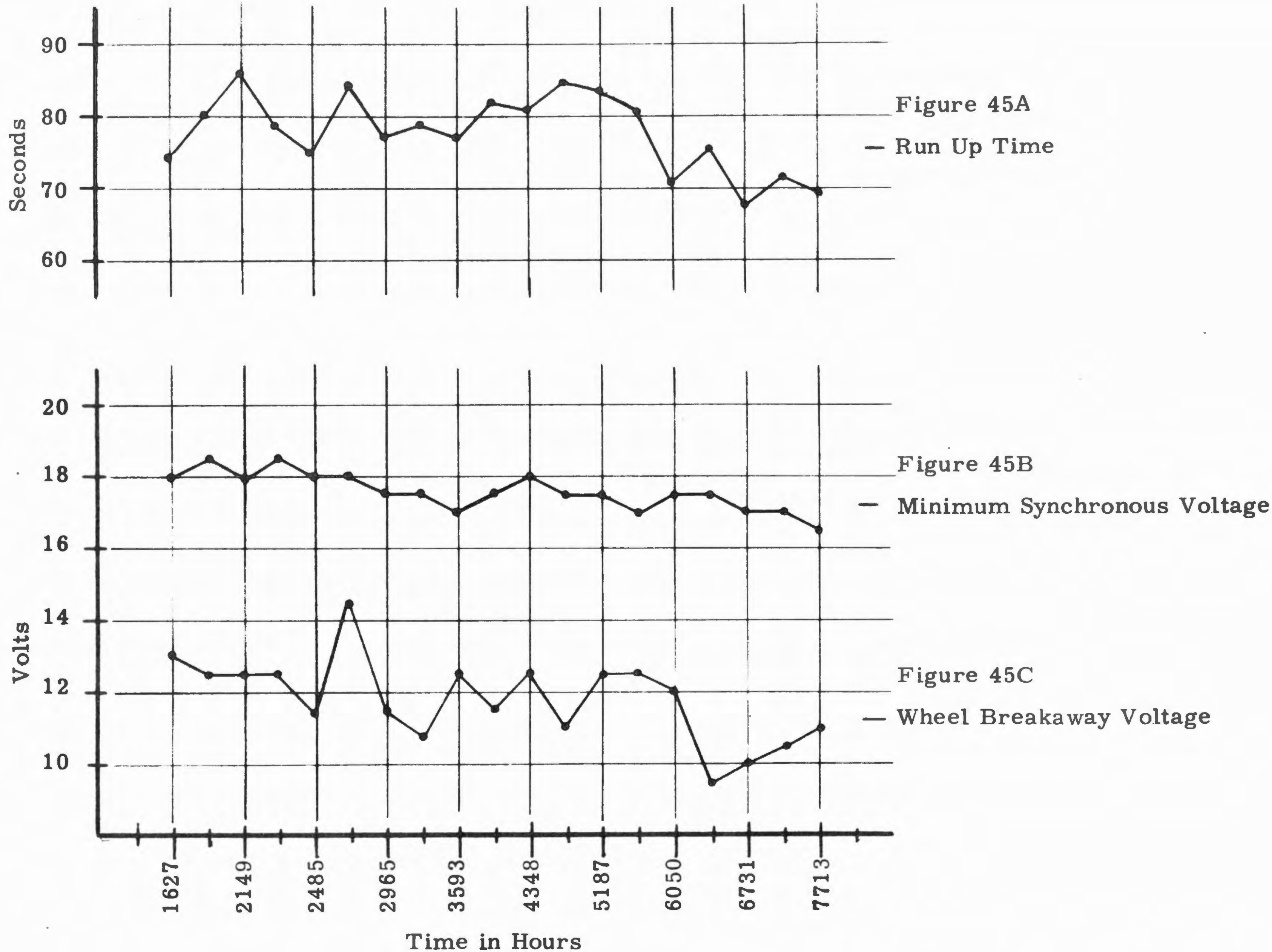


Figure 45. Run Up Time, Minimum Synchronous Voltage, and Wheel Breakaway Voltage Records for Wheel CR-113B.

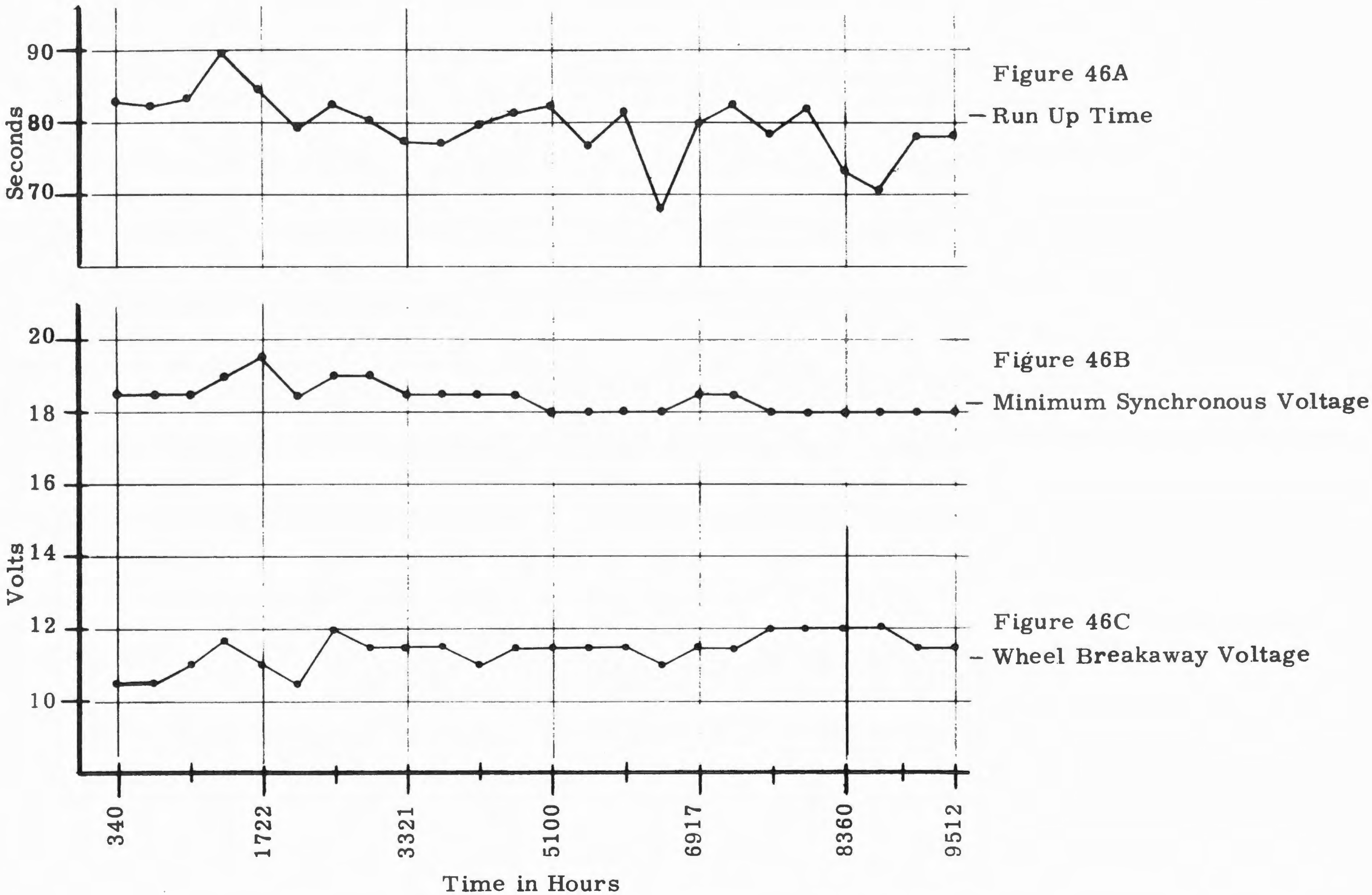


Figure 46. Run Up Time, Minimum Synchronous Voltage, and Wheel Breakaway Voltage Records for Wheel CV-115E.

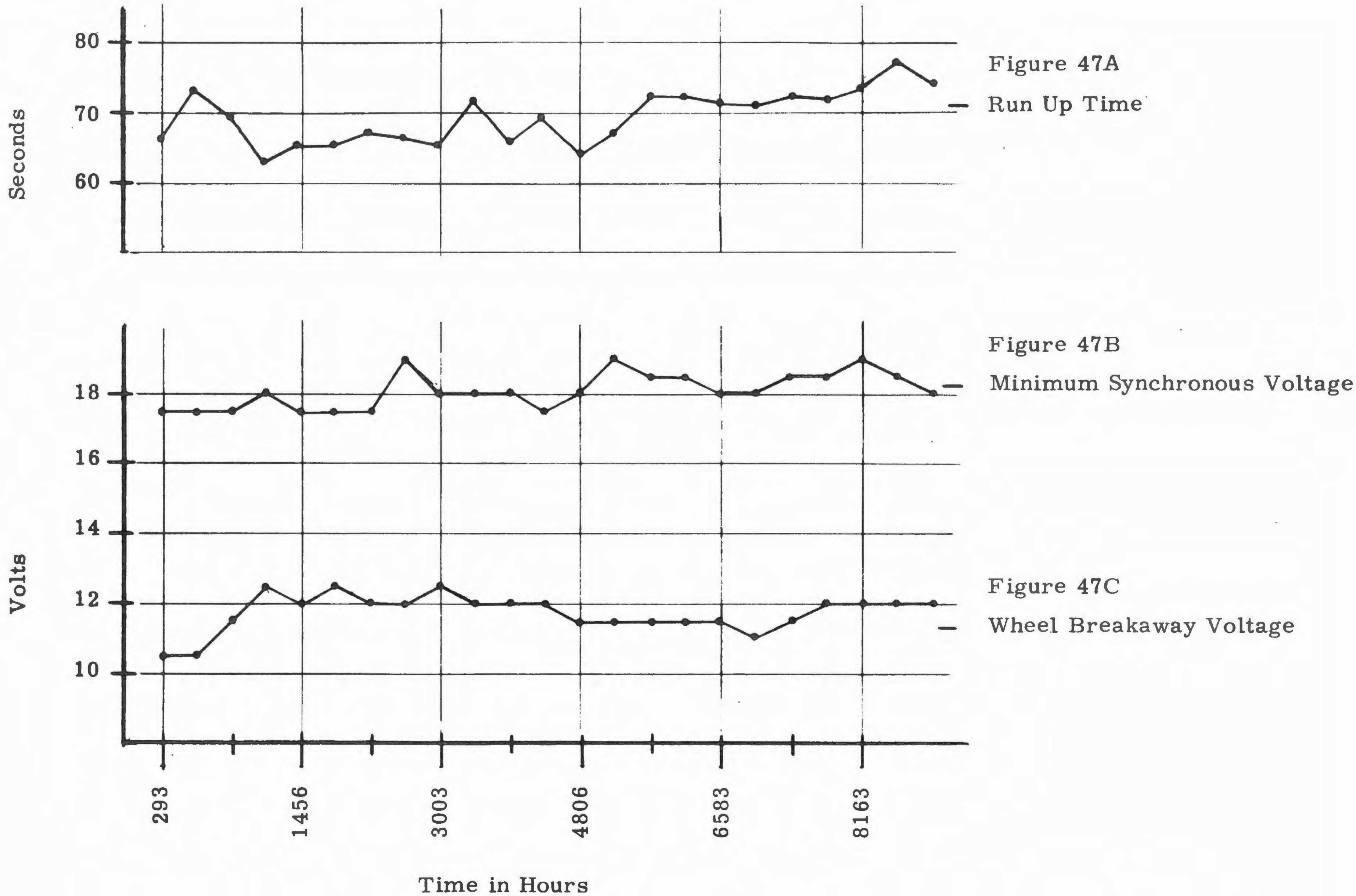


Figure 47. Run Up Time, Minimum Synchronous Voltage, and Wheel Breakaway Voltage Records for Wheel CV-92J.

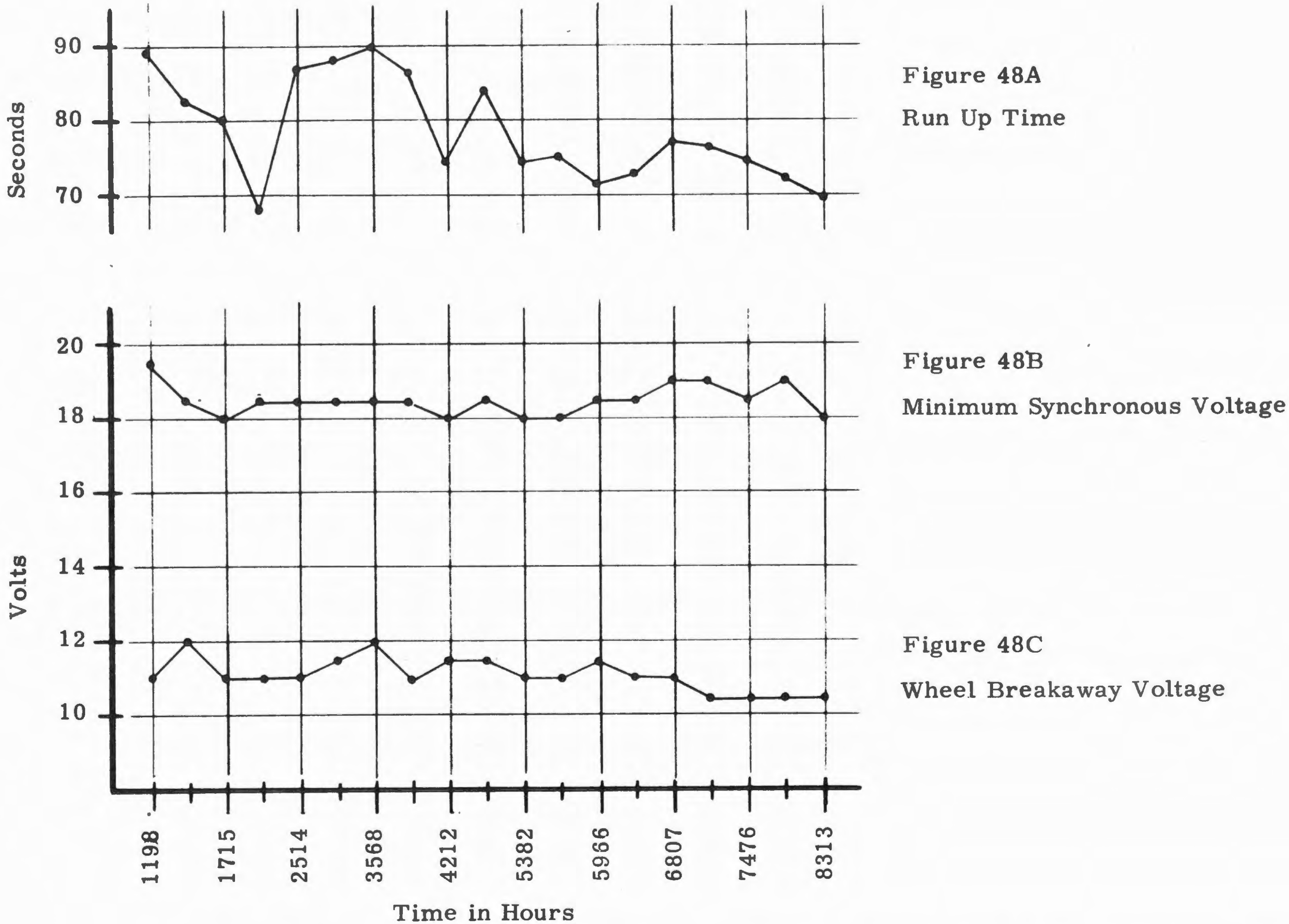


Figure 48. Run Up Time, Minimum Synchronous Voltage, and Wheel Breakaway Voltage Records for Wheel CV-123B.

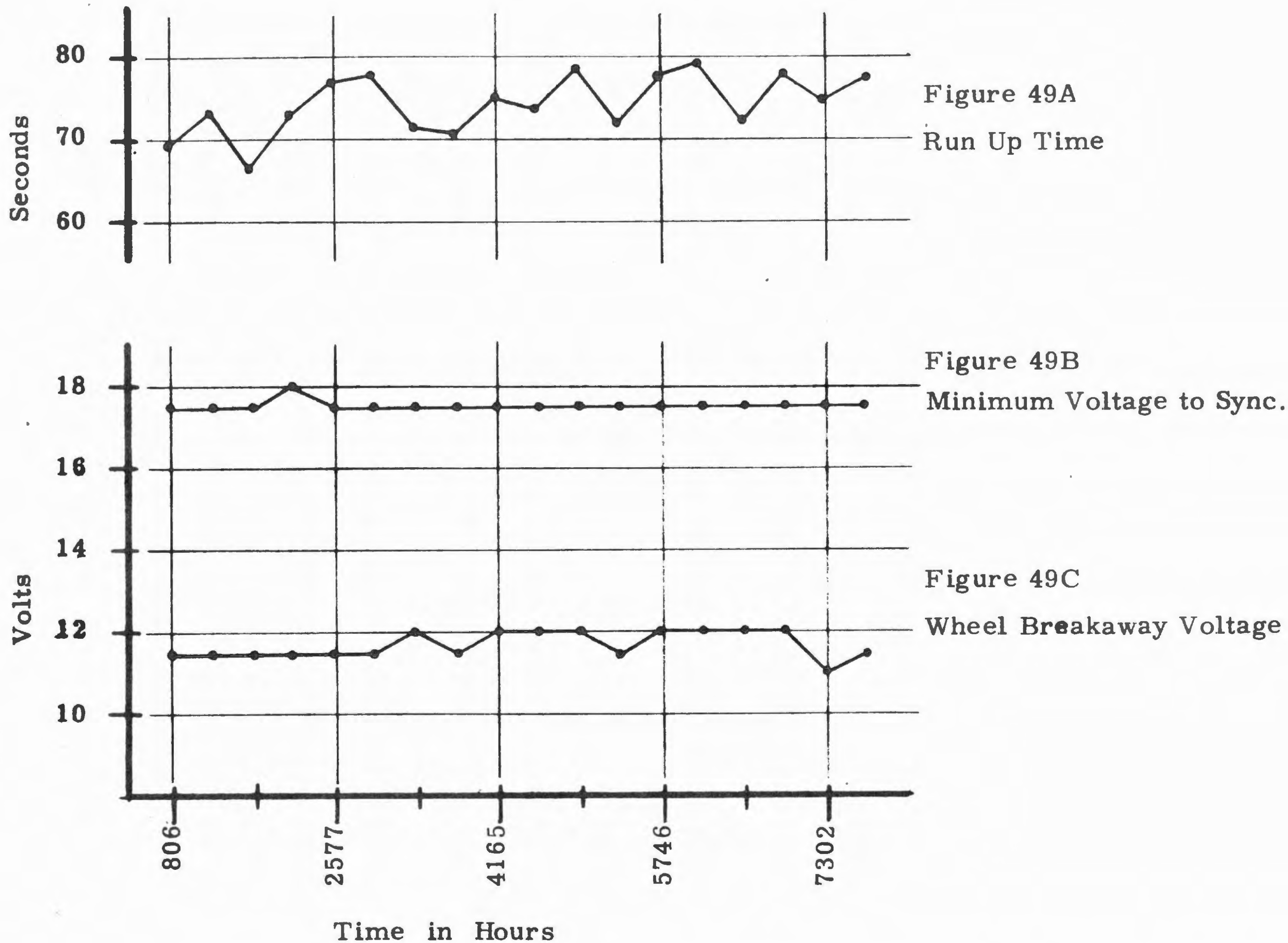
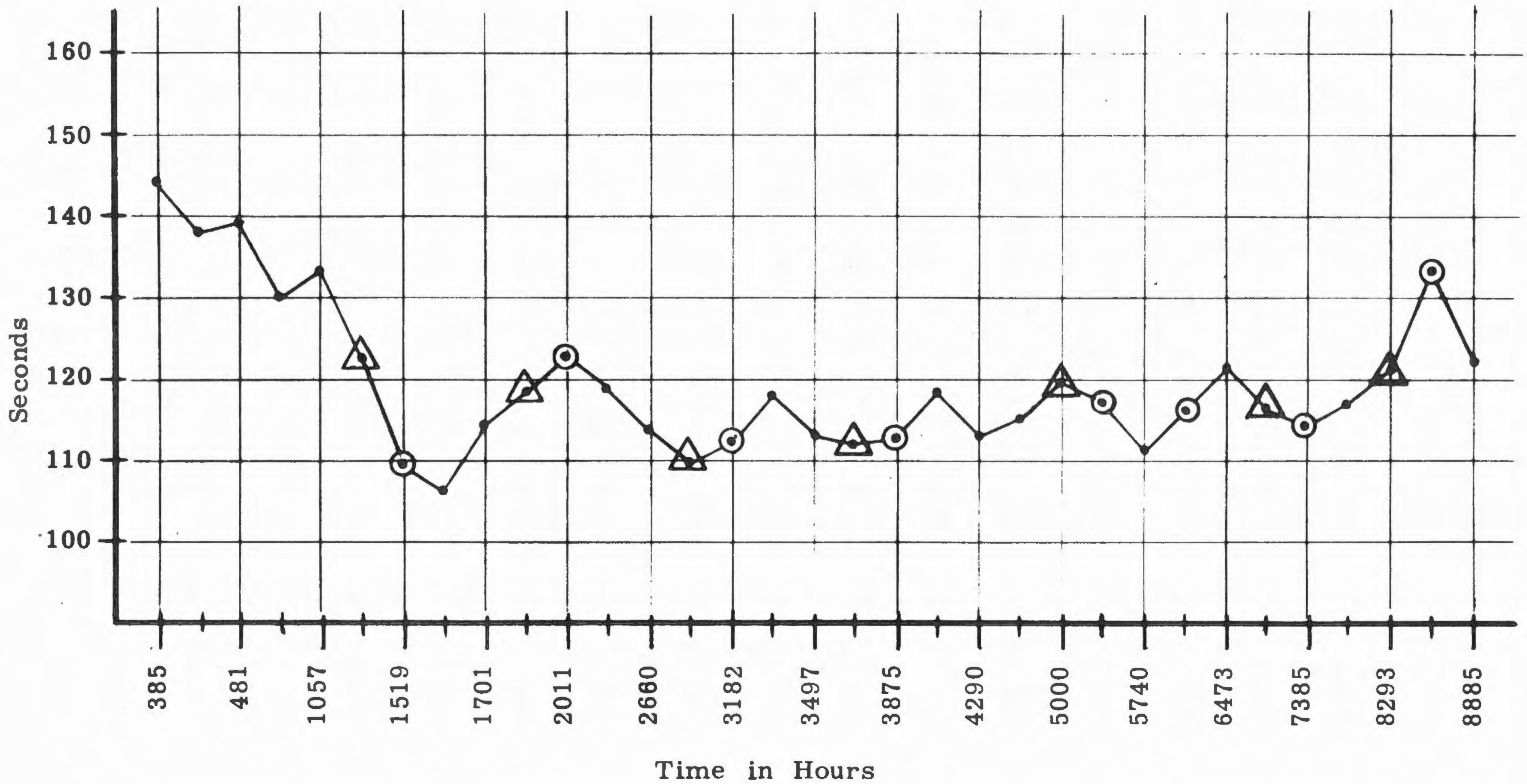


Figure 49. Run Up Time, Minimum Synchronous Voltage, and Wheel Breakaway Voltage Records for Wheel CV-121D.

RUNDOWN TIMES FOR CR-107B
(24,000 RPM to 6,000 RPM)



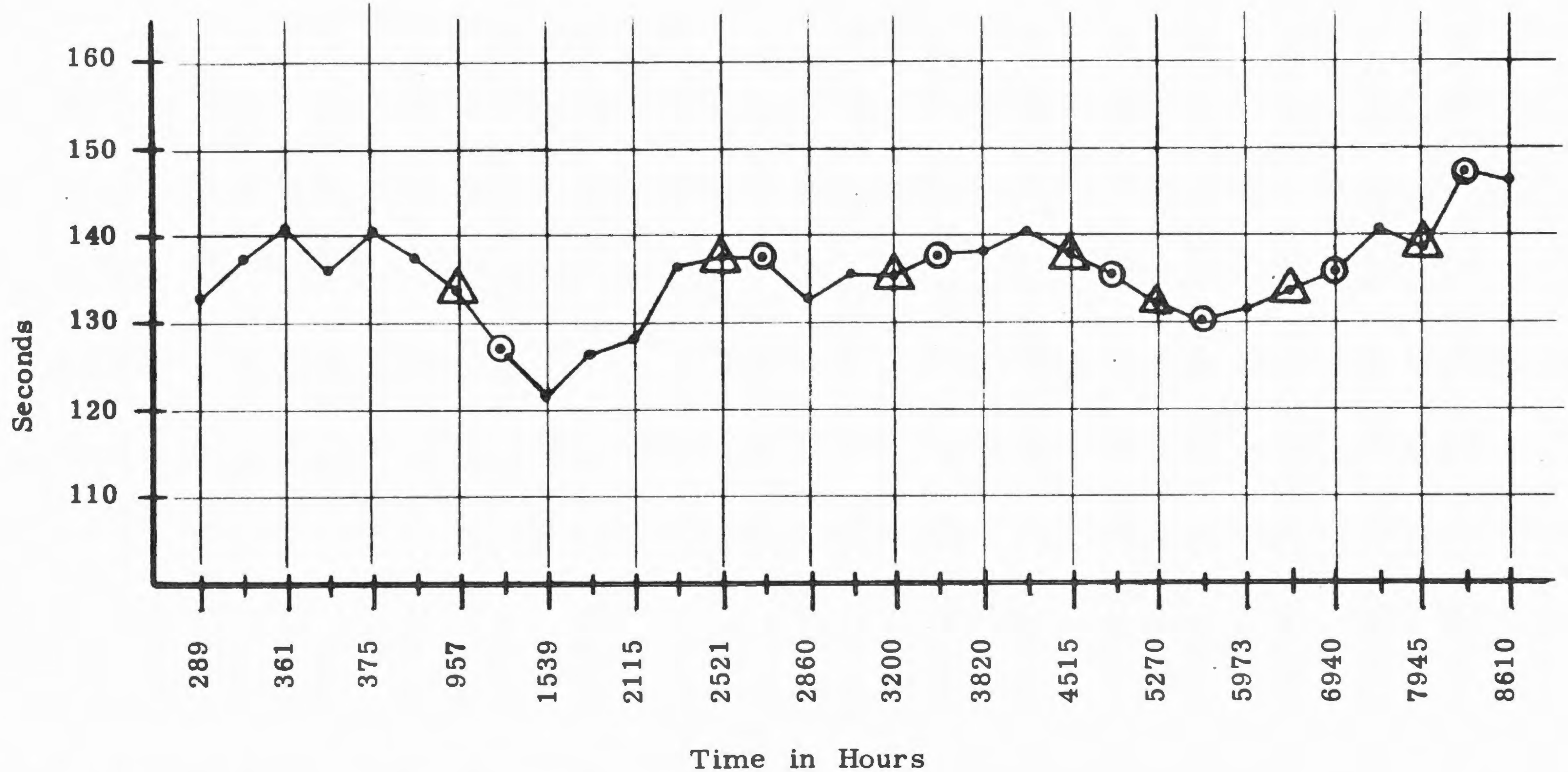
⊙ Rundown time taken following wheel assembly to fixture after visual examination.

△ Wheel was removed after rundown time was taken.

Figure 50. Wheel Run Down Time Record for Wheel CR-107B.

RUNDOWN TIMES FOR CV-112A

(24,000 RPM to 6,000 RPM)



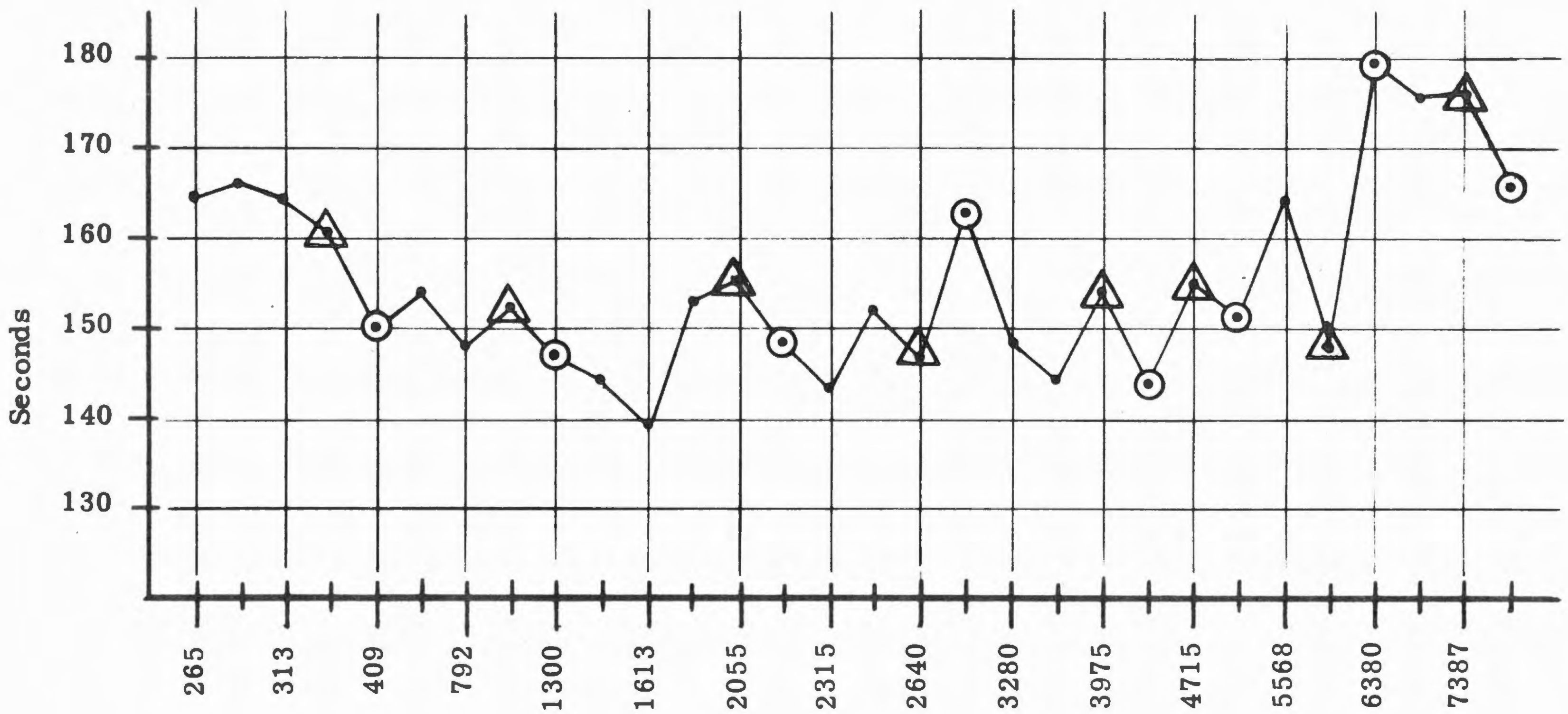
△ Wheel was removed after rundown time was taken.

⊙ Rundown time taken following wheel assembly to fixture after visual examination.

Figure 51. Wheel Run Down Time Record for Wheel CV-112A.

RUNDOWN TIMES FOR CR-113B

(24,000 RPM to 6,000 RPM)



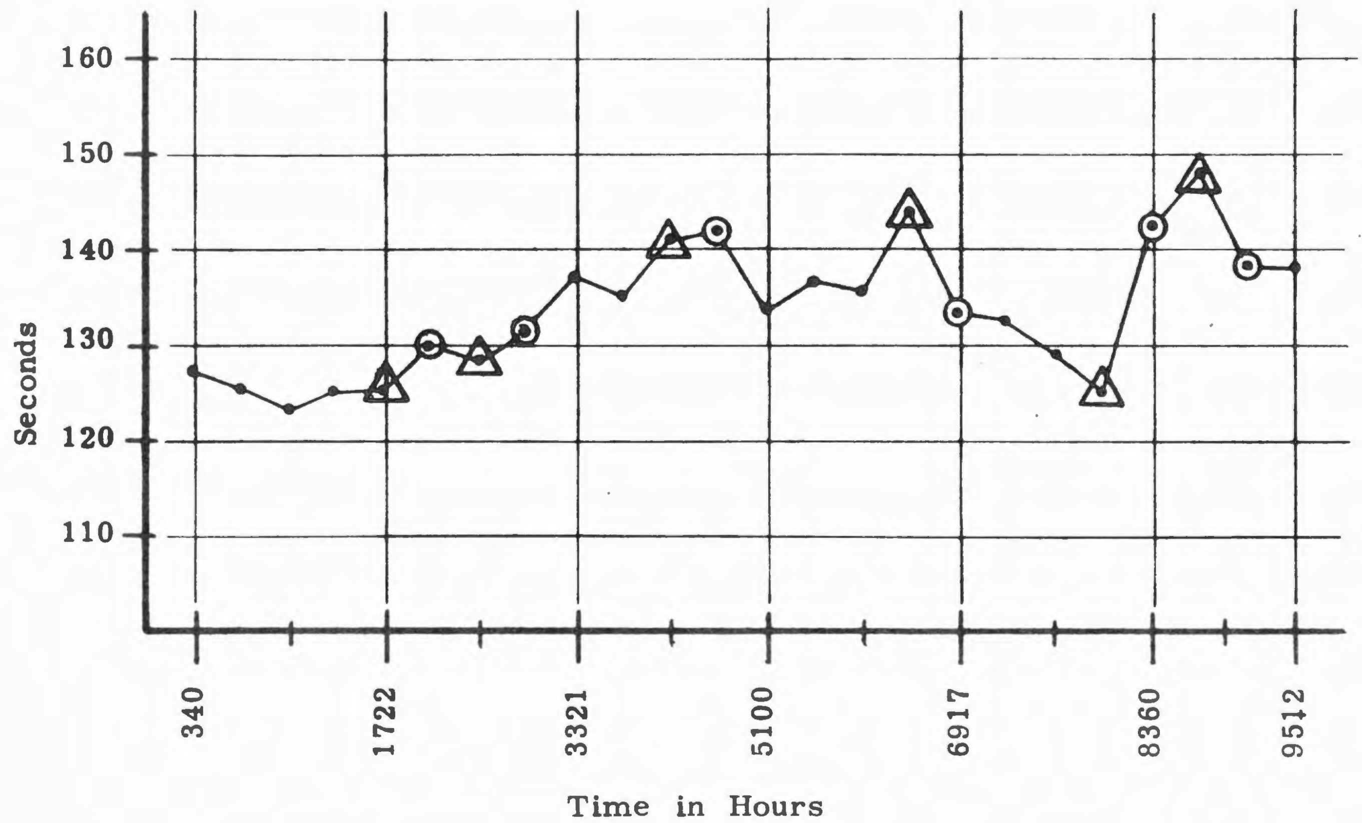
⊙ Rundown time taken following wheel assembly to fixture after visual examination.

△ Wheel was removed after rundown time was taken.

Figure 52. Wheel Run Down Time Record for Wheel CR-113B.

RUNDOWN TIMES FOR CV-115E

(24,000 RPM to 6,000 RPM)

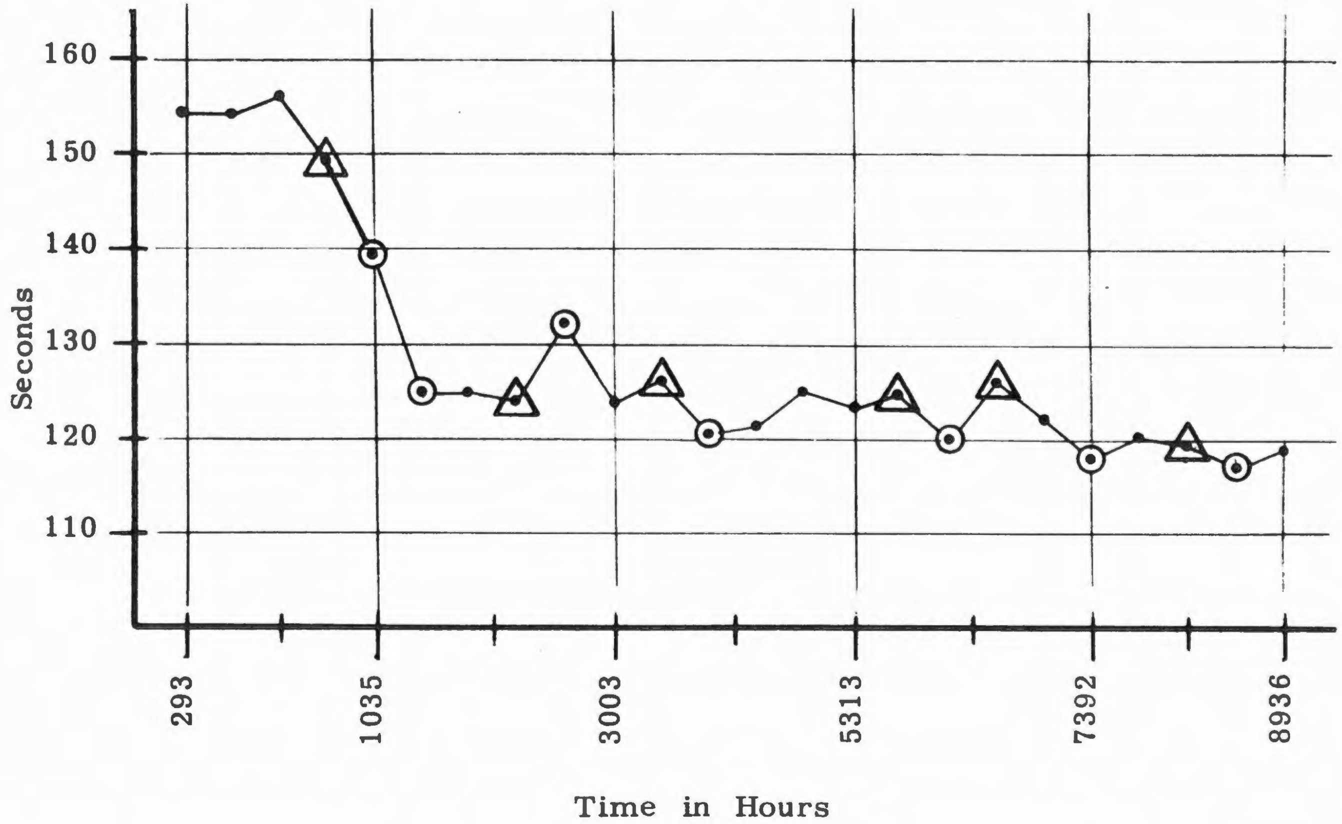


△ Wheel was removed after rundown time was taken.

⊙ Rundown time taken following wheel assembly to fixture after visual examination.

Figure 53. Wheel Run Down Time Record for Wheel CV-115E.

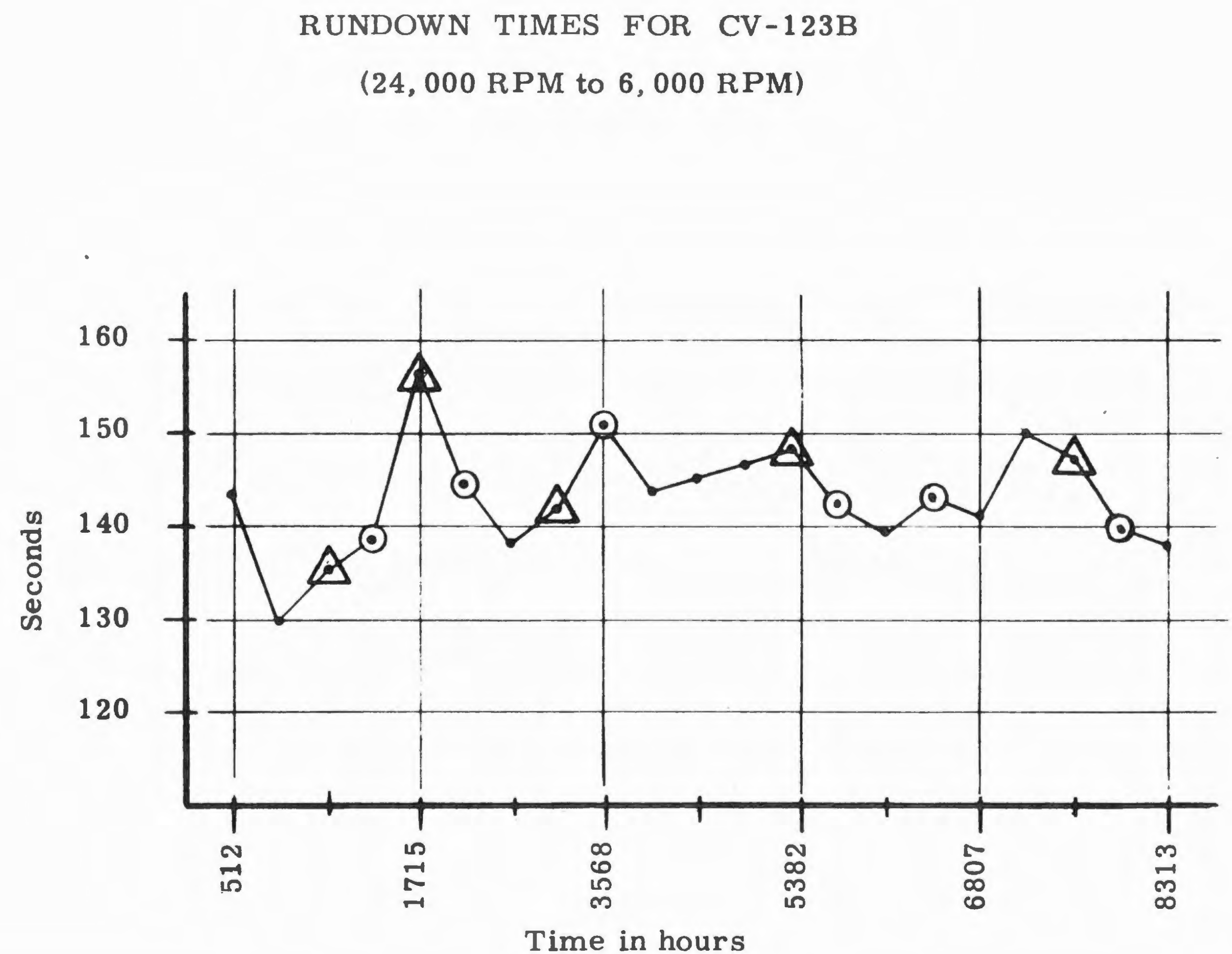
RUNDOWN TIMES FOR CV-92J
(24,000 RPM to 6,000 RPM)



⊙ Rundown time taken following wheel assembly to fixture after visual examination.

△ Wheel was removed after rundown time was taken.

Figure 54. Wheel Run Down Time Record for Wheel CV-92J.



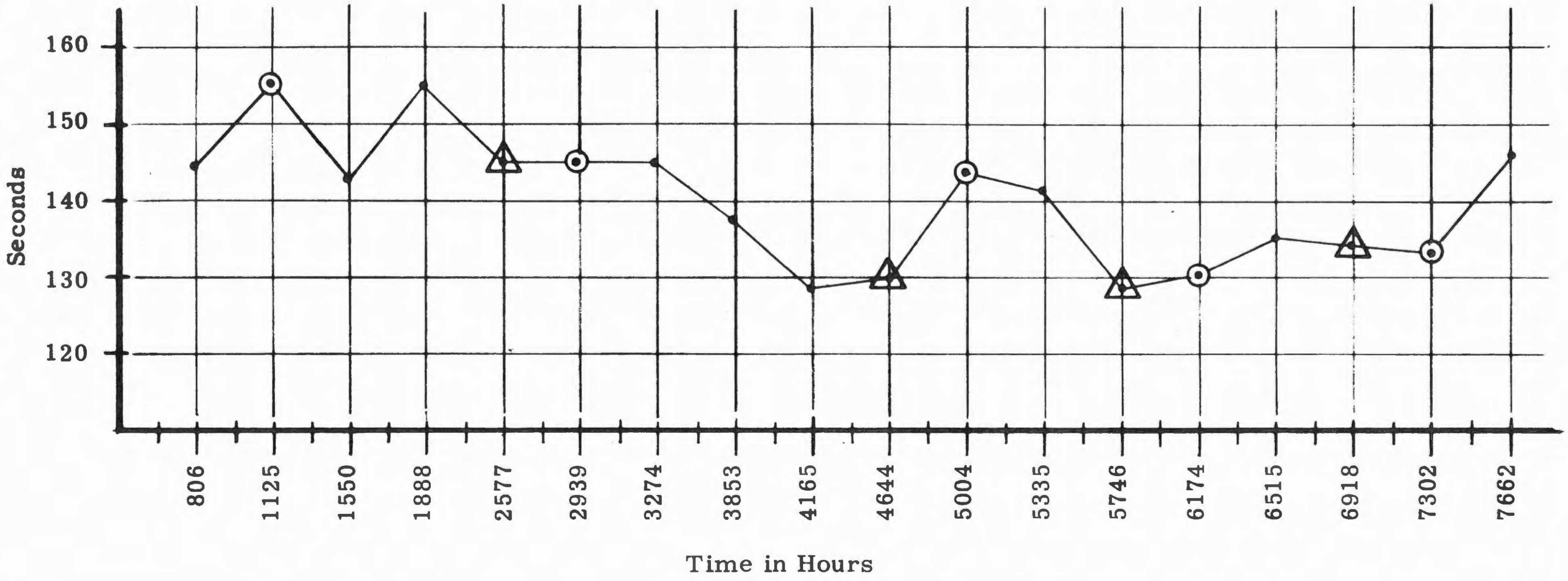
⊙ Rundown time taken following wheel assembly to fixture after visual examination.

△ Wheel was removed after run down time was taken.

Figure 55. Wheel Run Down Time Record for Wheel CV-123B.

RUNDOWN TIMES FOR CV-121D

(24,000 RPM to 6,000 RPM)



⊙ Rundown time taken following wheel assembly to fixture after visual examination.

△ Wheel was removed after rundown time was taken.

Figure 56. Wheel Run Down Time Record for Wheel CV-121D.

071 CONFIGURATION		
Wheel No.	Hours at 12-11-69	Hours at 6-30-70
CR-107B	9,125	13,956
CV-112A	8,634	13,464
CR-113B*	8,073	12,905

081 CONFIGURATION	
Wheel No.	Hours at 6-30-70
CV-115E**	9,818
CV-92J**	9,194
CV-123B	8,582
CV-121D	7,962

* Wheel classified as a failure after 3,975 hours running time.

** Wheel is in SRA vertical position.

Figure 57. MIT Wheel Life Test Hours.

071 CONFIGURATION		
Wheel No.	Hours at 12-11-69	Hours at 6-30-70
S 225	9,525	12,585
VA 7	7,912	10,972
S 40	5,878	8,938
VA 37*	6,765	-----

081 CONFIGURATION	
Wheel No.	Hours at 6-30-70
VA 23	7,675
VA 233**	7,254
V 232	6,795
V 234**	6,786
V 235	6,646
V 236	6,550

* Running hours when wheel failed on 10-27-69.

** Wheel is in SRA vertical position.

Figure 58. Bendix Wheel Life Test Hours.

	Total Hours	One-Sided Confidence Level
MIT Wheels	57,290	97.8 %
Bendix Wheels	71,786	99.3 %
MIT & Bendix Wheels Combined	129,076	99.9 %

Figure 59. 10,000 Hour MTBF Confidence Levels.

REFERENCES

1. Feldman, Julius. MIT Draper Lab ISS Memo No. 743, Rev. E, Subject: "Apollo II IRIG Wheel Design Verification Test Plan," dated August 28, 1969.

2. Miller, John E. and Feldman, Julius. "Gyro Reliability in the Apollo Guidance, Navigation, and Control System," JOURNAL OF SPACECRAFT AND ROCKETS, Vol. 5, No. 6, June 1968, pp. 638-643.

3. Feldman, Julius. MIT Draper Lab ISS Memo No. 739, Rev. D, Subject: "Proposed Failure Guide Lines for Bearing Verification Test Program," dated September 8, 1969.

APPENDIX A

1. INTRODUCTION

It is the endeavor of this appended report to further the understanding of bearing performance and evaluation by making available the findings of two DVTP life test wheel disassemblies. The wheels which have been selected for teardown analysis represent each of the design configurations under study in this life test program.

The visual studies were made under 40 power magnification with an American Optical Binocular Microscope. All metal parts were illuminated for examination with both incandescent and fluorescent light sources. Each component was inspected and photographed before and after cleaning. The observations, measurements, and photographs are presented in this appendix.

The selection of these particular wheels for teardown was determined for the following reasons:

a) 071 Configuration

Wheel CR-113B, with 13,769 hours of running time, was selected because it was the only wheel in the life test program classified as a "predicted failure."

b) 081 Configuration

Wheel CV-115E, with 10,681 hours of running time, was selected because, in addition to being the oldest member of the 081 group, it was one of the two life test subjects which had been run exclusively in the SRA vertical position.

2. TEARDOWN ANALYSIS REPCRT FOR WHEEL CR-113B

Wheel Bearing Disassembly

-SRA End 1 (Before cleaning).

Retainer (See Figure A-1).

The ball pockets were heavily stained with blackened varnish deposits. There was varnish spill-over from the ball pockets onto the outside diameter of the retainer, which was smeared completely around the circumference. The inside diameter and sides of the retainer were free of stain.

Inner Race (See Figure A-2).

The raceway surface was mostly obscured by heavy deposits of oil breakdown residue and fragments of black gummy varnish. Silver gray metal-like particles were profusely sprinkled over the whole race area. A dull orange discoloration was discernible in the ball track.

Outer Race (See Figure A-2).

The physical condition of this race was identical to that of the inner race.

Balls (See Figure A-3).

There were multiple criss-cross bands on the balls. Some bands were of gray matte finish while others dark orange. Black lubricant sludge was smeared on the balls. Silver gray particles adhered to the ball surfaces.

+SRA End 2 (Before cleaning).

Retainer (See Figure A-4).

The ball pockets were heavily stained with blackened varnish deposits. There was varnish spill-over from the ball pockets onto the outside diameter of the retainer, which was smeared completely around the circumference. This inside diameter and sides of the retainer were free of stain.

Inner Race (See Figure A-5).

Oil breakdown residue was caked on the upper portion of the raceway. There was a heavy varnish deposit opposite the load side of the raceway. The ball track had a deep gray matte finish with an "orange peel" discoloration line running along its center. Numerous silver gray particles were sprinkled about the raceway area.

Outer Race (See Figure A-5).

The physical condition of this race was identical to that of the inner race.

Balls (See Figure A-6).

All balls had multiple dull orange discoloration bands. Black gummy sludge was smeared on the balls. Silver gray particles clung to the ball surfaces.

-SRA End 1 (After cleaning).

Inner Race (See Figure A-7).

The ball track had a deep gray matte finish with an "orange peel" discoloration line running along its center. There was a lateral waviness to the ball path. Thirty-one "brinell" marks were seen on the maximum load side of the sinuate track. See Figure A-8.

Outer Race (See Figure A-7).

The ball track had a deep gray matte finish and edged on the load side by a pronounced "orange peel" discoloration line. This raceway did not have the same abnormalities as the inner raceway.

Balls (See Figure A-9).

The cleaning did not uncover any further information. Ball sizes and sphericity checks compared favorably to the original measurements.

+SRA End 2 (After cleaning).

Inner Race (See Figure A-10).

The ball track was a pronounced gray matte finish with a fine "orange peel" discoloration line running along its center. Three ball brinells were noted on the load side of the raceway, partially within the matte finish of the track. Two brinells were along side each other while the third one was approximately 30° away.

Outer Race (See Figure A-10).

There was a heavy "orange peel" discoloration line within the pronounced gray matte ball track. There were numerable pits and dirt dents within the discolored band. The ball track appeared slightly frosty on the load side in some areas.

Balls (See Figure A-11).

There was multiple bronze-color banding of varying widths. One ball had a bad scratch mark. The ball sizes and sphericity checks compared favorably to the original measurements.

Remarks

The bearing components of wheel CR-113B were marred by metal damage in the form of ball and raceway discoloration, brinelling, and wear lapping.

The wear lapping between ball and raceway surfaces was confirmed by the increase in the wheel compliance measurements. The original axial mechanical compliance was 11.5 microinches per pound, while after 13,769 hours of running time, the axial mechanical compliance measurement had increased to 16.0 microinches per pound. The significant amount of wear was also reflected in the increase of the contact angle measurements.* Since the ball sizes and sphericity checks compared favorably with the original measurements, it can be assumed that the wear lapping took place on the raceways.

The unusual "brinell" formations that were present only on the -SRA inner race indicates that they were probably not caused during assembly. This wheel has never been subjected to vibration test. It is difficult to speculate as to the possible cause of this unusual phenomenon.

All fluid lubrication had been depleted in both bearings. Sludge and varnish was all that remained.

It is interesting to note that, despite the advanced degradation of the bearings and the lubricant, this wheel was able to maintain synchronous speed at 18.0 volts. Its total power consumption at 28 volts was 2.84 watts. The differential power trace showed excellent stability over long periods of time. The beat frequency recordings, however, were erratic.

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* The original measurements of 31°14' and 31°44' increased to 32°50' and 34°17', respectively.

3. TEARDOWN ANALYSIS REPORT FOR WHEEL CV-115E

Wheel Bearing Disassembly

-SRA End 1 (Before cleaning).

Retainer (See Figure A-12).

The inside of all ball pockets were ringed with dark stain, which spilled over onto the outer circumference of the retainer, adjacent to the pockets. The inside circumference and sides of the retainer were free of stain. No metal contamination was found.

Inner Race (See Figure A-13).

An evenly distributed oil film with typical color patterns covered the raceway. Oil film and oil droplets were seen on the main body of the shaft. Small oil soaked nylasint particles were scattered about the race area. No oil breakdown residue accumulations were found on the inner race. The ball path showed a pronounced gray wear track. No burn discoloration was evident.

Outer Race (See Figure A-13).

Both the land and race curvature were wetted with an adequate oil film displaying typical color patterns. Occasional oil droplets were also noted. No oil breakdown residue was found on the outer race. Scattered oil soaked nylasint particles were seen on the raceway area. The ball path showed a pronounced gray wear track. No burn discoloration was detected on the raceway.

Balls (See Figure A-14).

The balls were coated with an film of oil. A small oil meniscus was present under each ball prior to bearing disassembly. There were no ball bands. The balls had a light matte finish which had been noted at assembly time.

+SRA End 2 (Before cleaning).

Retainer (See Figure A-15).

The inside of all ball pockets were ringed with dark stain, which spilled over onto the outer circumference of the retainer, adjacent to the pockets. The inside circumference and sides of the retainer were free of stain. No metal contamination was found.

Inner Race (See Figure A-16).

An evenly distributed oil film with typical color patterns covered the raceway. Oil film and oil droplets were seen on the main body of the shaft. Small oil soaked nylasint particles were scattered about the raceway area. No oil breakdown residue accumulations were found on the inner race. The ball path showed a pronounced gray wear track. No burn discoloration was detected on the raceway.

Outer Race (See Figure A-16).

Both the land and race curvature were wetted with an adequate oil film displaying typical color patterns. Occasional oil droplets were also noted. No oil breakdown residue was found on the outer race. Scattered oil soaked particles were in the raceway area. The ball path showed a pronounced gray wear track. No burn discoloration was detected on the raceway.

Balls (See Figure A-17).

The balls were coated with a clean film of oil. A small oil meniscus was present under each ball prior to bearing disassembly. There were no ball bands. The balls had a somewhat heavier matte finish than the balls of the -SRA end. This condition was noted at assembly time.

-SRA End 1 (After cleaning).

Inner Race (See Figure A-18).

The ball track had a deep gray matte finish edged with a partially frosted fringe. Two very minute dirt dents were detected in the ball track. There was no burn discoloration on the raceway. No brinell marks were present on the inner race.

Outer Race (See Figure A-18).

The physical condition of this race was essentially the same as the inner race with the exception that a few more small dirt dents were in evidence.

Balls (See Figure A-19).

The cleaning substantiated the initial findings. Ball sizes and sphericity checks compared favorably to the original measurements.

+SRA End 2 (After cleaning).

Inner Race (See Figure A-20).

The ball track had a deep gray matte finish. There was no burn discoloration on the raceway. No brinell marks were present on the inner race.

Outer Race (See Figure A-20).

The physical condition of this race was identical to that of the inner race.

Balls (See Figure A-21).

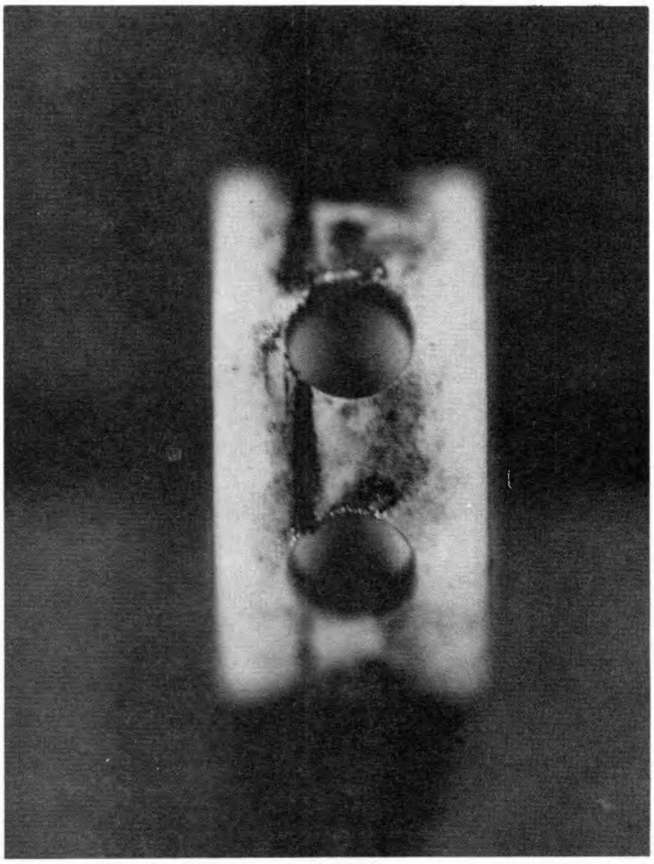
The cleaning substantiated the initial findings. Ball sizes and sphericity checks compared favorably to the original measurements.

Remarks

No significant metal damage or burn discoloration was found on any of the bearing components for wheel CV-115E.

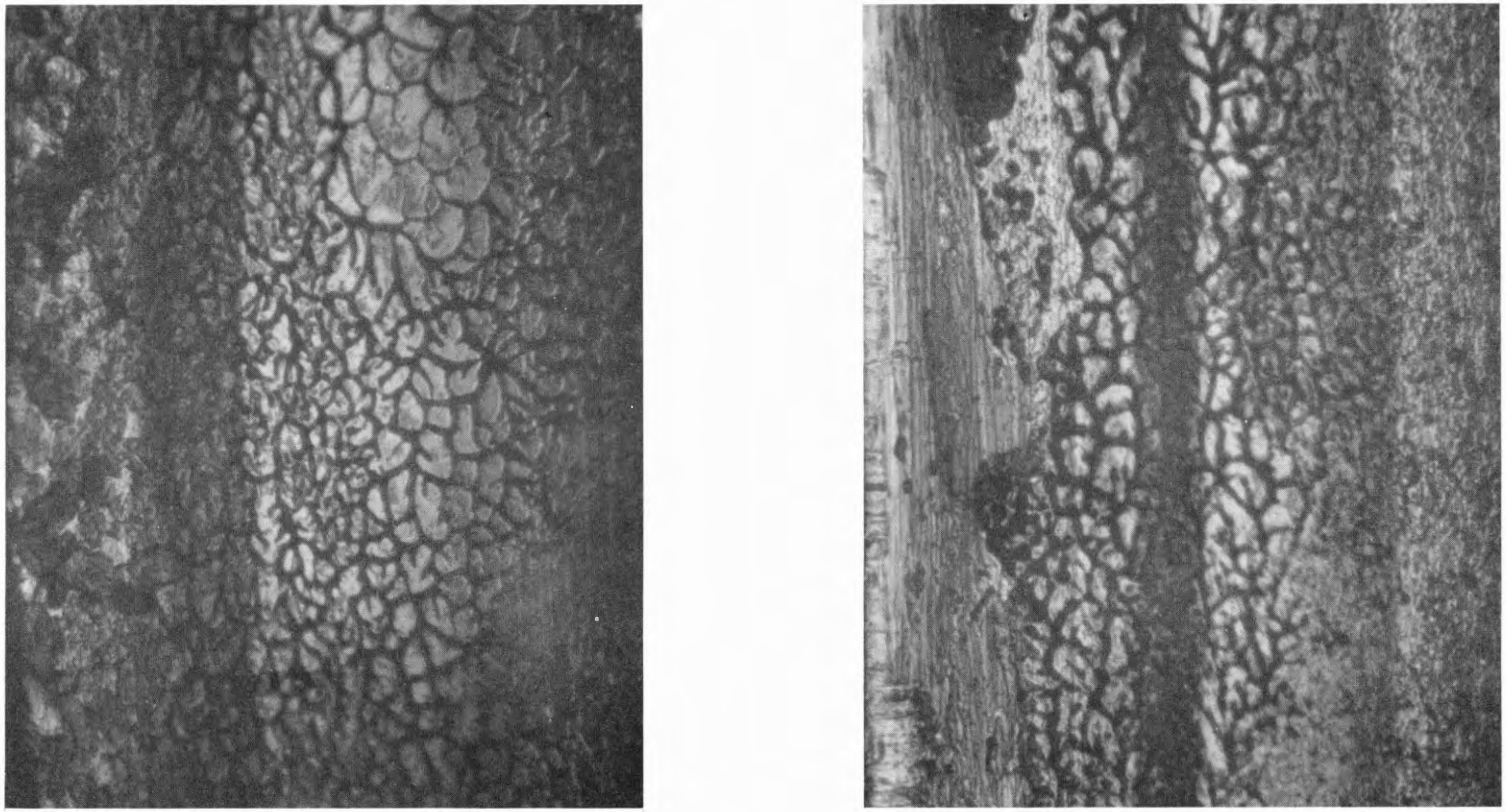
There was no significant change in the axial mechanical compliance, or in the contact angle measurements at the conclusion of the life test run.

Adequate lubrication was still in evidence after 10,681 hours of running time. The life test of this wheel was conducted wholly in the SRA vertical position. There was no visual evidence of gravity-oriented oil migration.



WHEEL # CR - 113 B

Figure # A-1 Retainer from the - SRA bearing, end 1 (10X).



INNER RACE

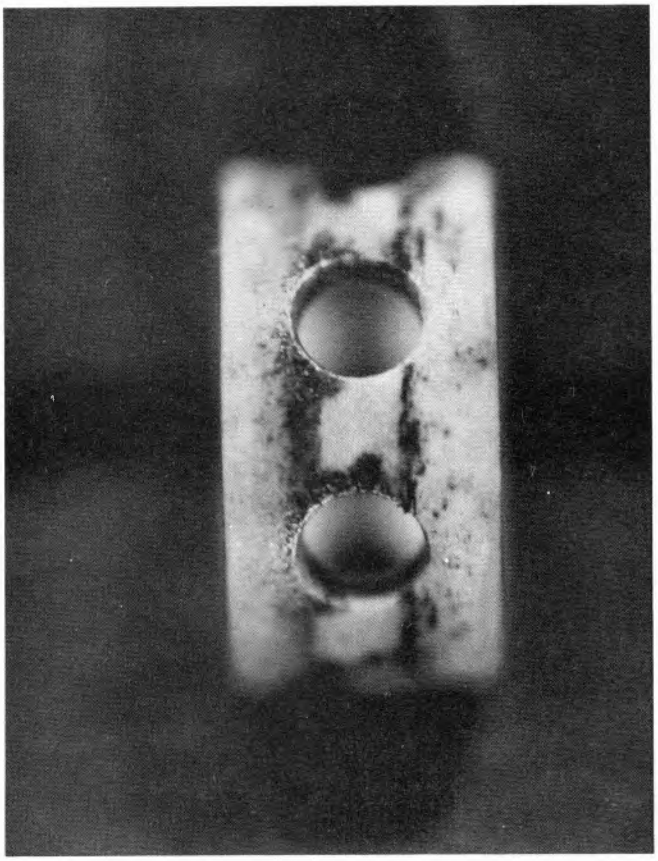
OUTER RACE

WHEEL # CR-113 B

Figure # A-2 Uncleaned races from the - SRA bearing, end 1 (160 X)

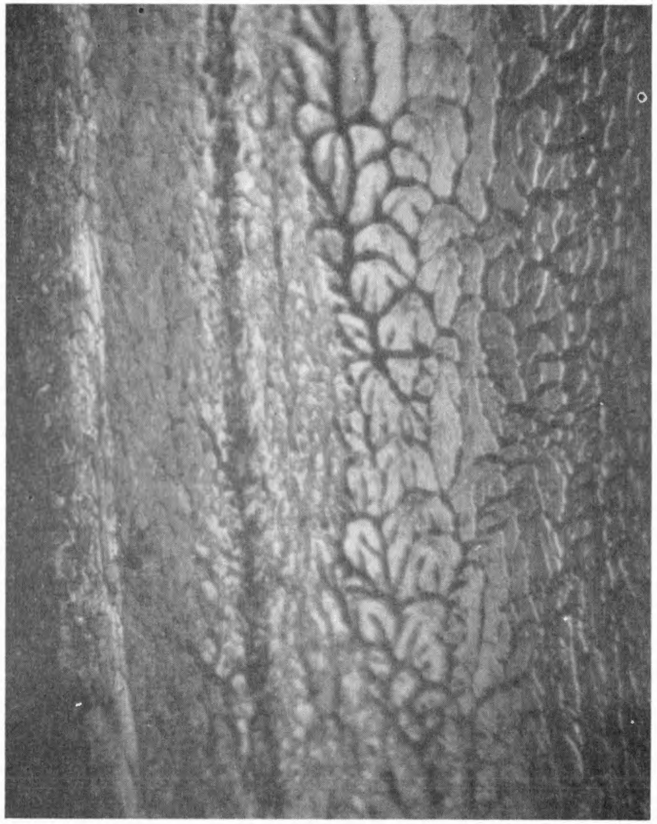
WHEEL # CR-113 B

Figure # A-3 Uncleaned ball from the - SRA bearing, end 1 (160 X).

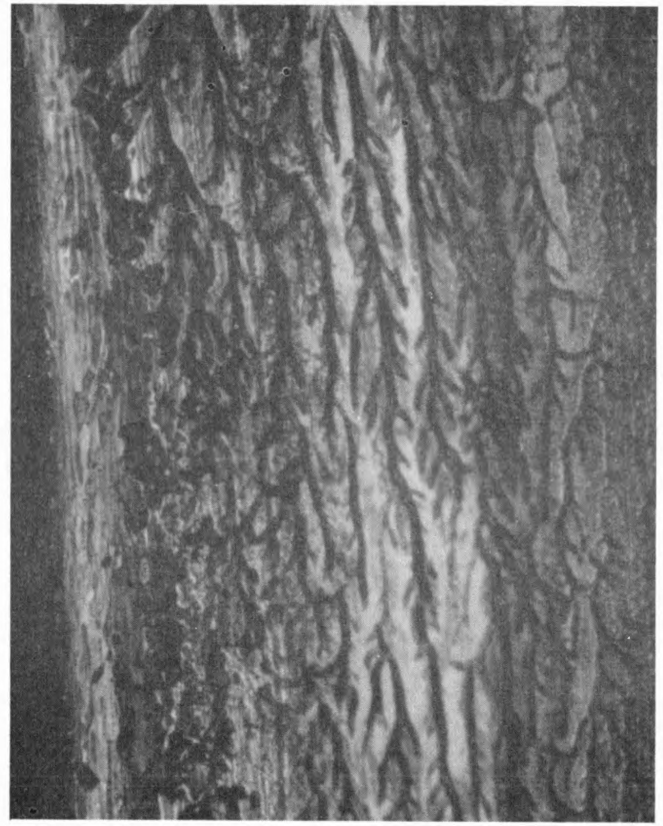


WHEEL # CR-113 B

Figure # A-4 Retainer from the + SRA bearing, end 2 (10 X).



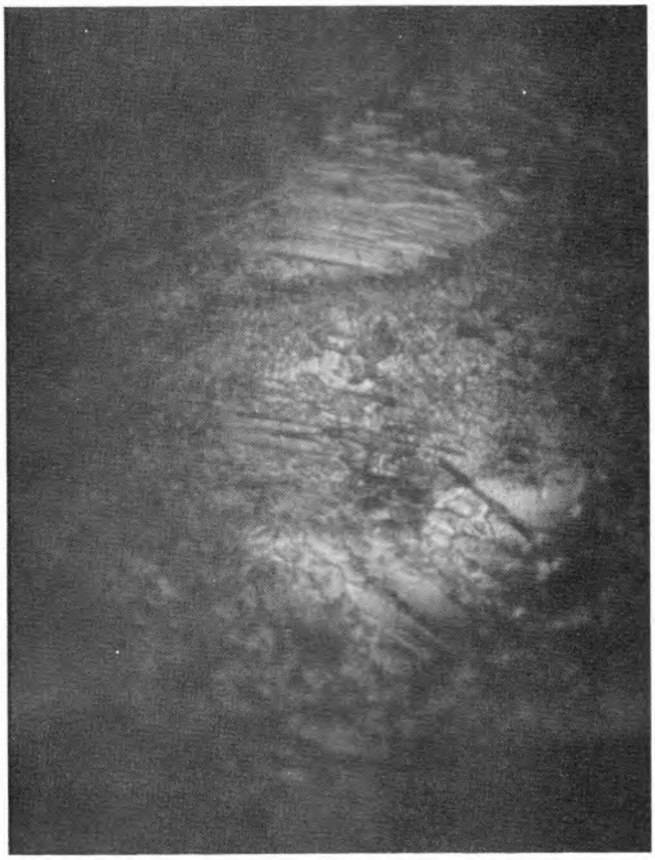
INNER RACE



OUTER RACE

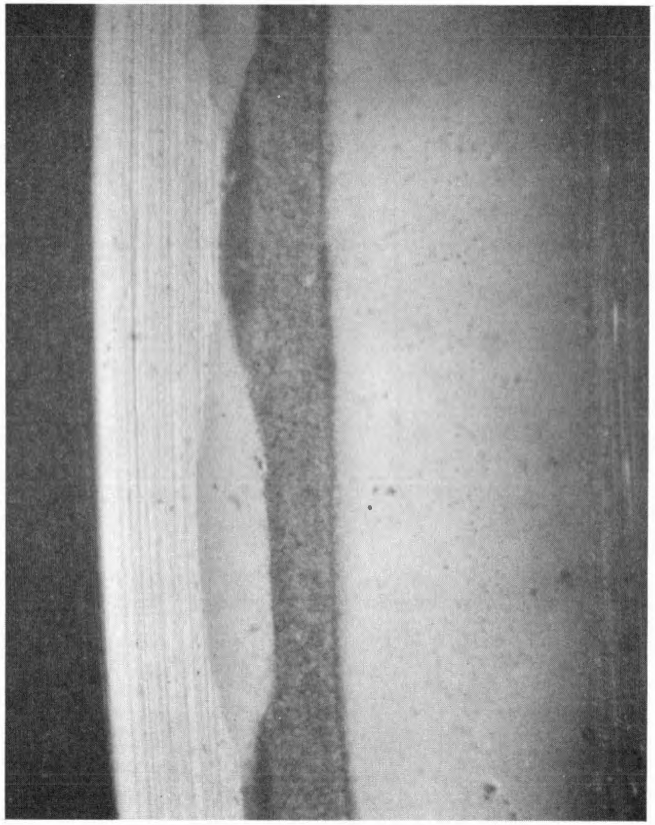
WHEEL # CR-113 B

Figure # A-5 Uncleaned races from the +SRA bearing, end 2 (160X).

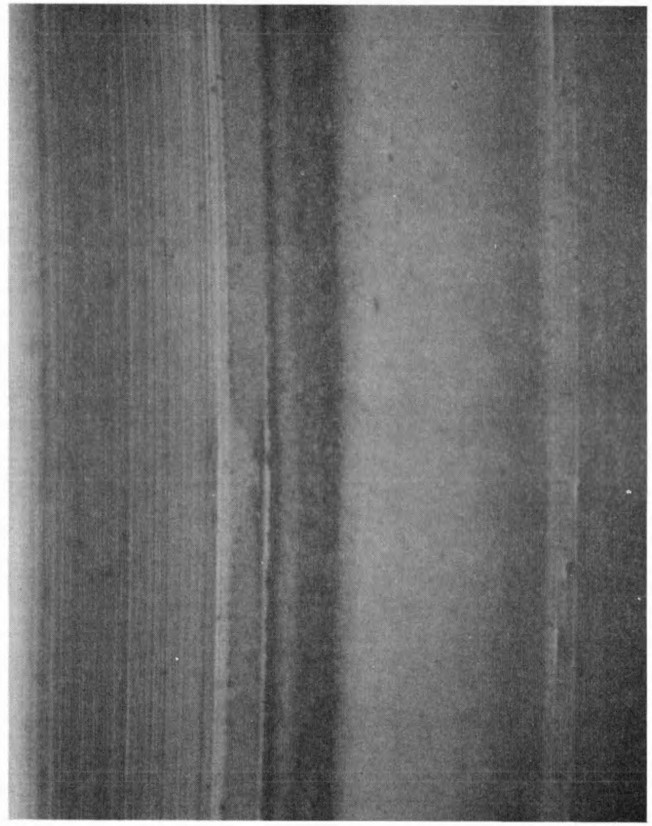


WHEEL # CR-113 B

Figure # A-6 Uncleaned ball from the + SRA bearing, end 2 (160 X).



INNER RACE



OUTER RACE

WHEEL # CR-113 B

Figure #A-7 Cleaned Races from the -SRA bearing, end 1 (160X).

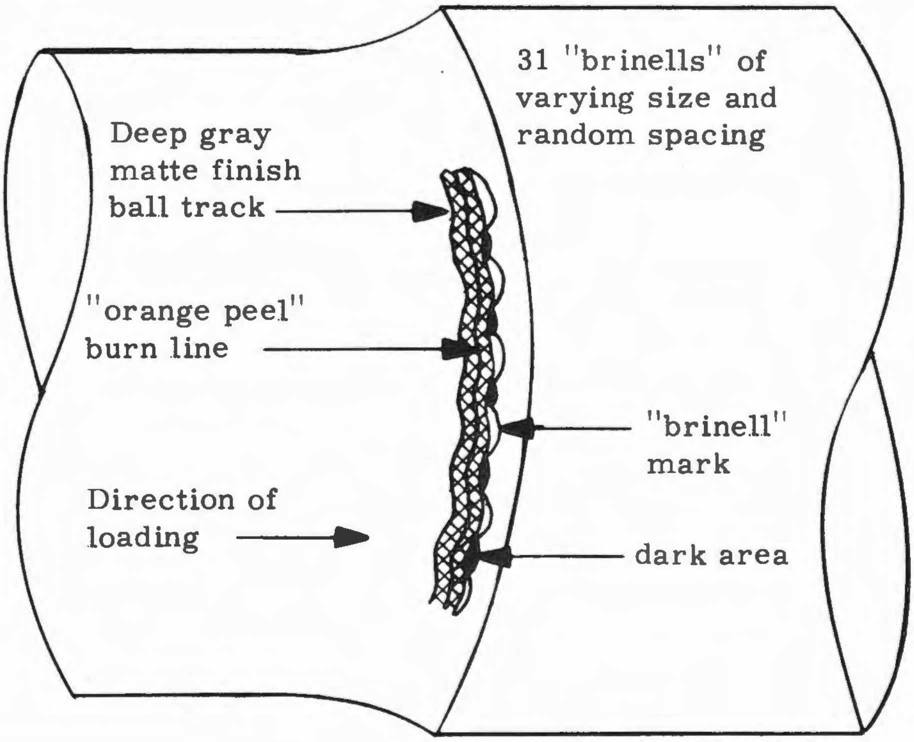
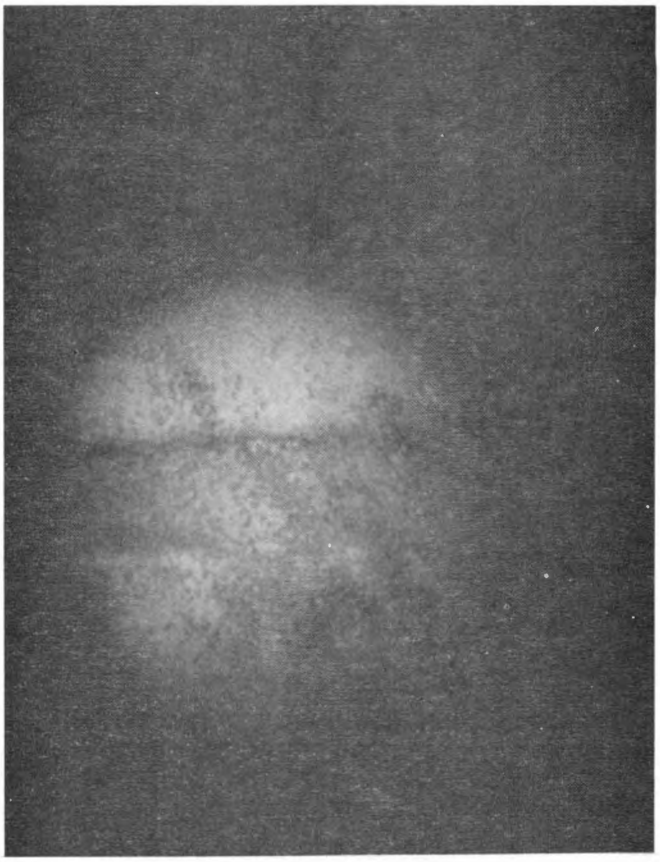
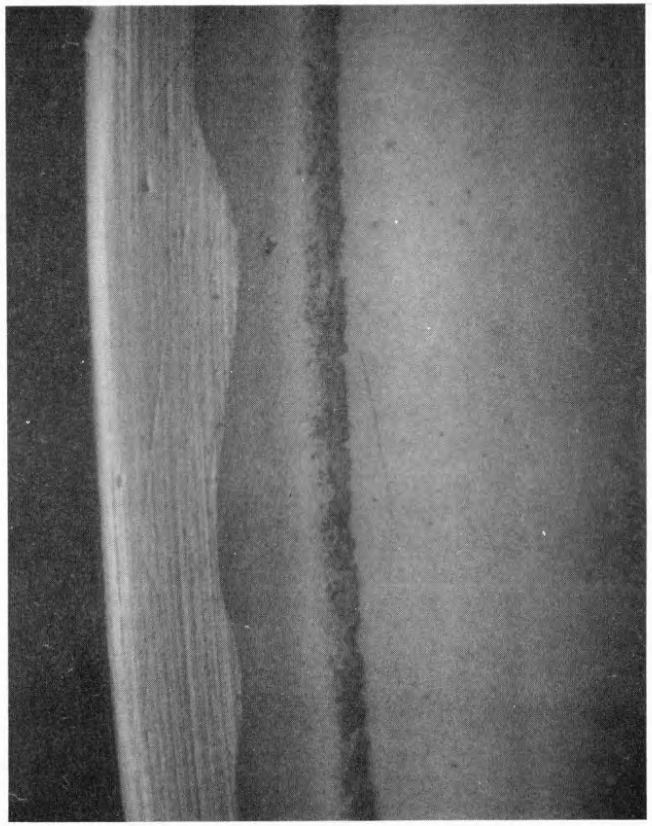


Figure A-8. Portion of -SRA Inner Race Ball Track of Wheel CR-113B.

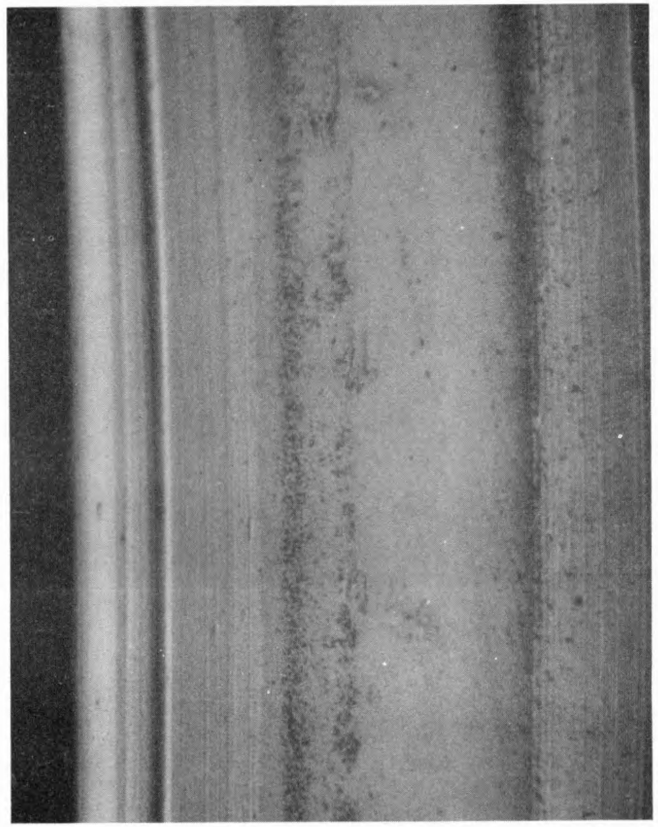


WHEEL # CR-113 B

Figure # A-9 Cleaned ball from the - SRA bearing, end 1 (160X).



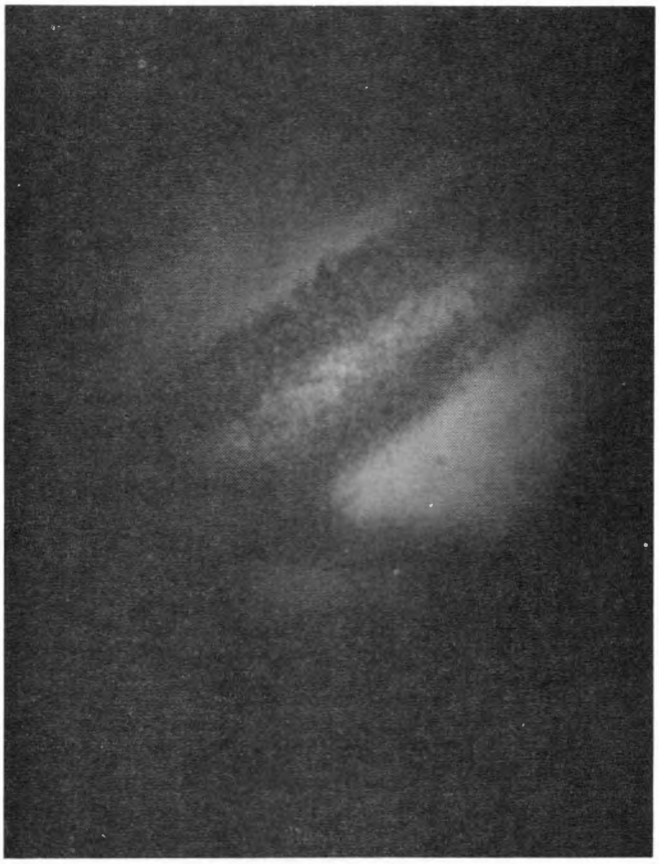
INNER RACE



OUTER RACE

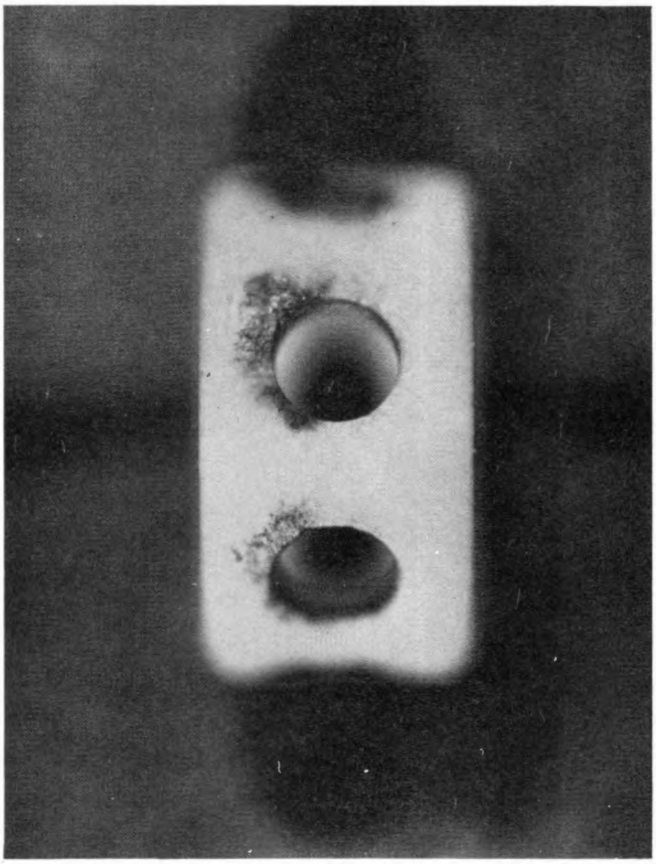
WHEEL # CR-113 B

Figure # A-10 Cleaned races from the + SRA bearing, end 2 (160 X).



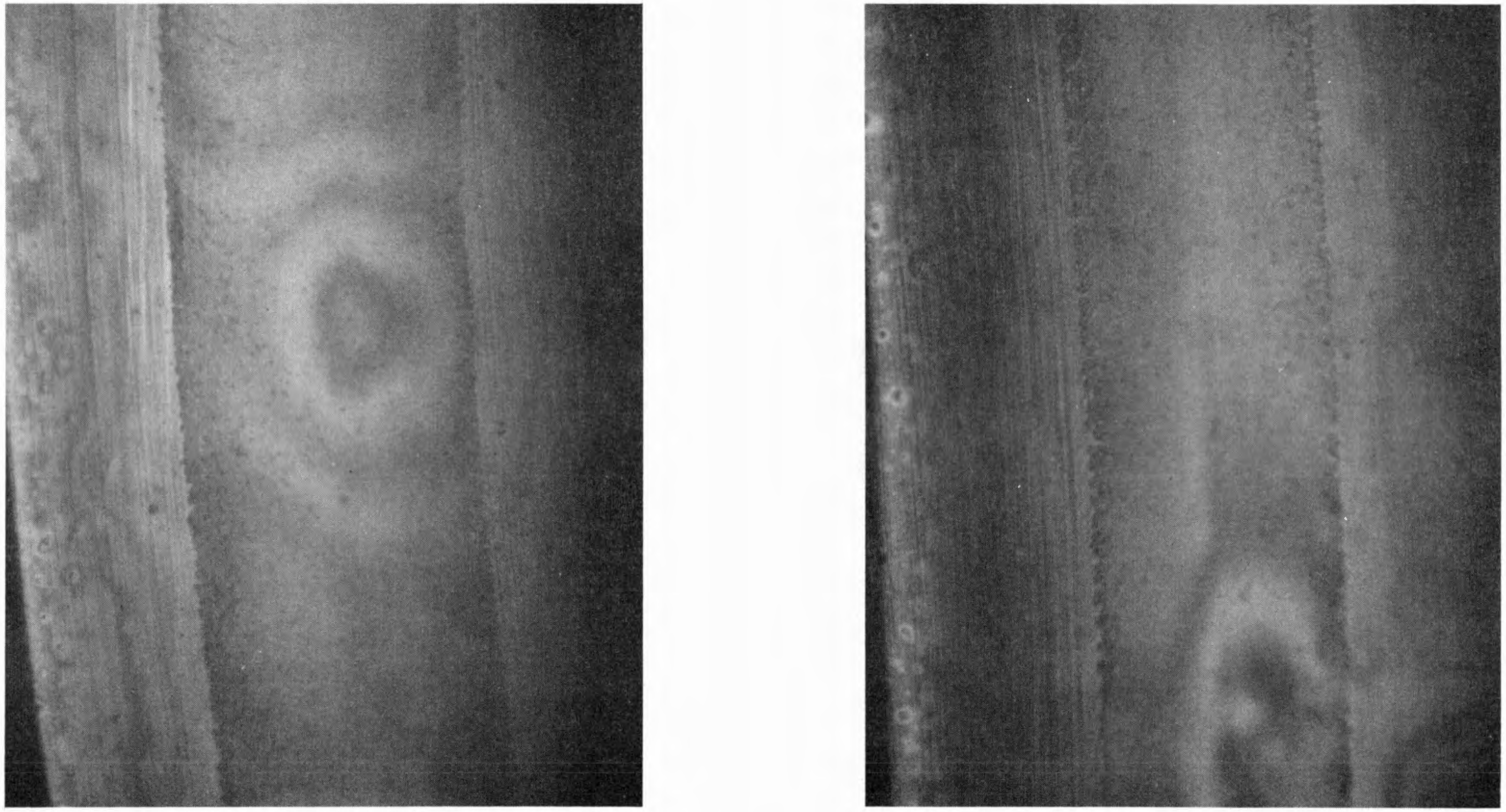
WHEEL # CR-113 B

Figure # A-11 Cleaned ball from the + SRA bearing, end 2 (160 X).



WHEEL # CV-115 E

Figure # A-12 Retainer from the - SRA bearing, end 1 (10 X).

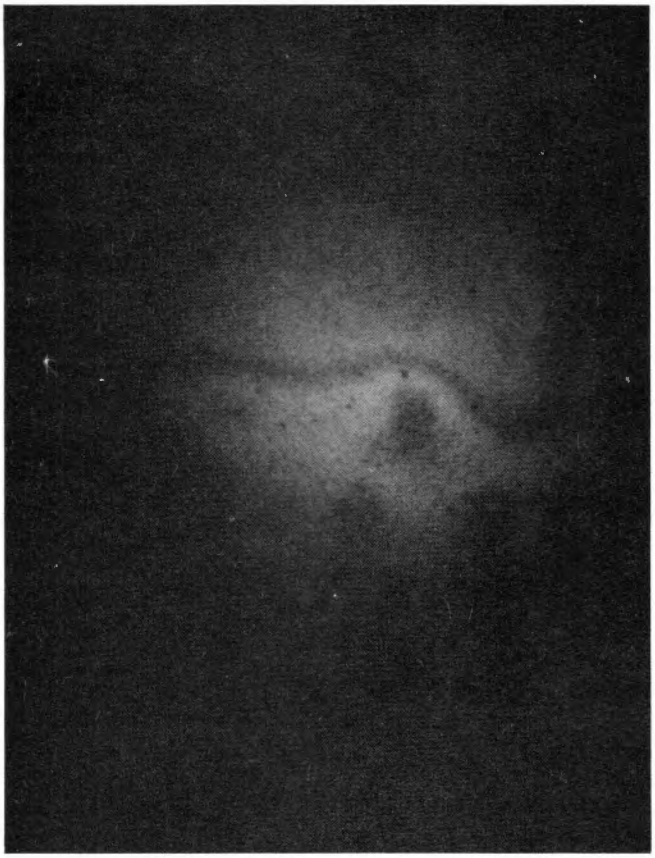


INNER RACE

OUTER RACE

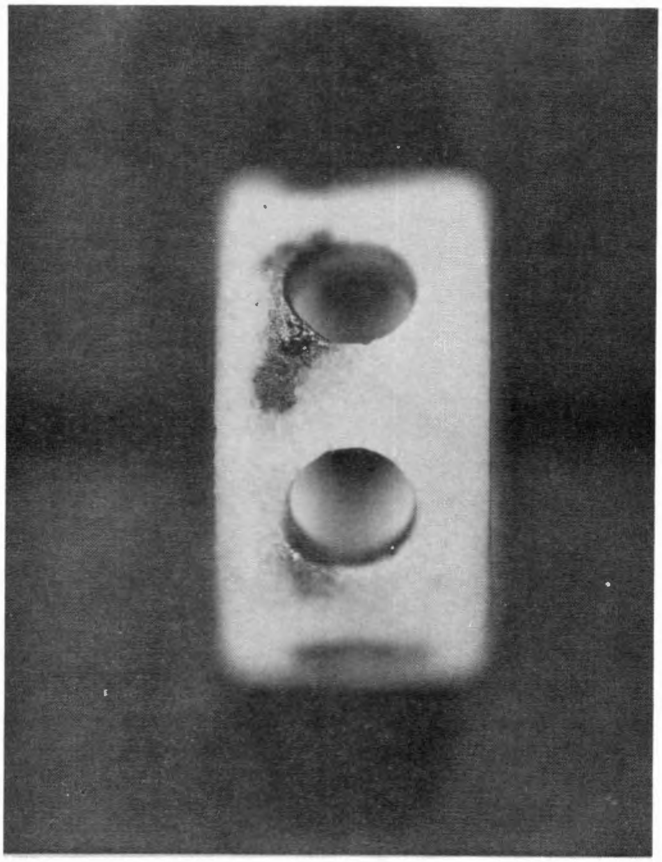
WHEEL # CV-115 E

Figure #A-13 Uncleaned races from the - SRA bearing, end 1 (160 X)



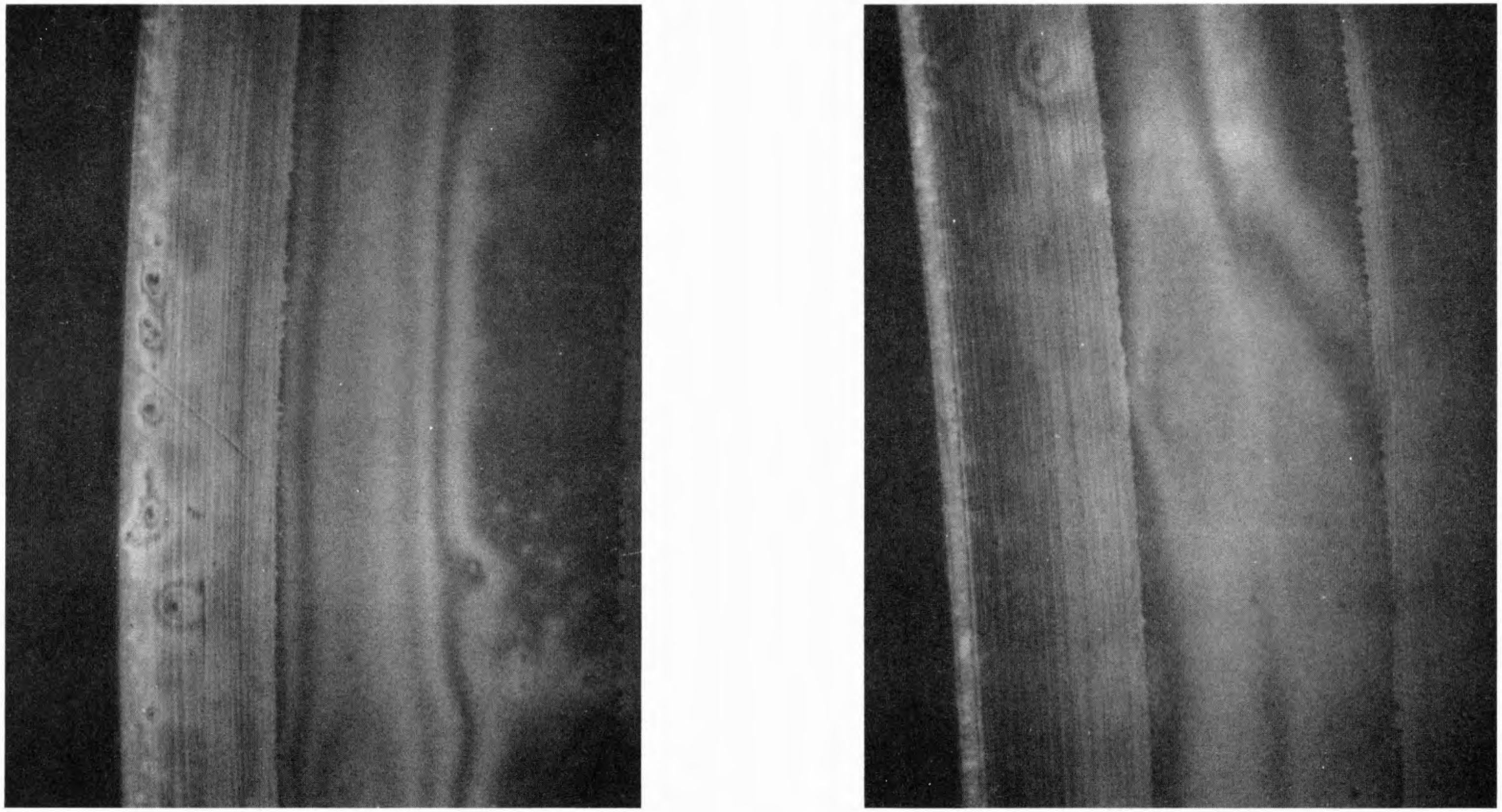
WHEEL # CV-115 E

Figure # A-14 Uncleaned ball from the - SRA bearing, end 1 (160 X).



WHEEL # CV-115 E

Figure # A-15 Retainer from the + SRA bearing, end 2 (10X).



INNER RACE

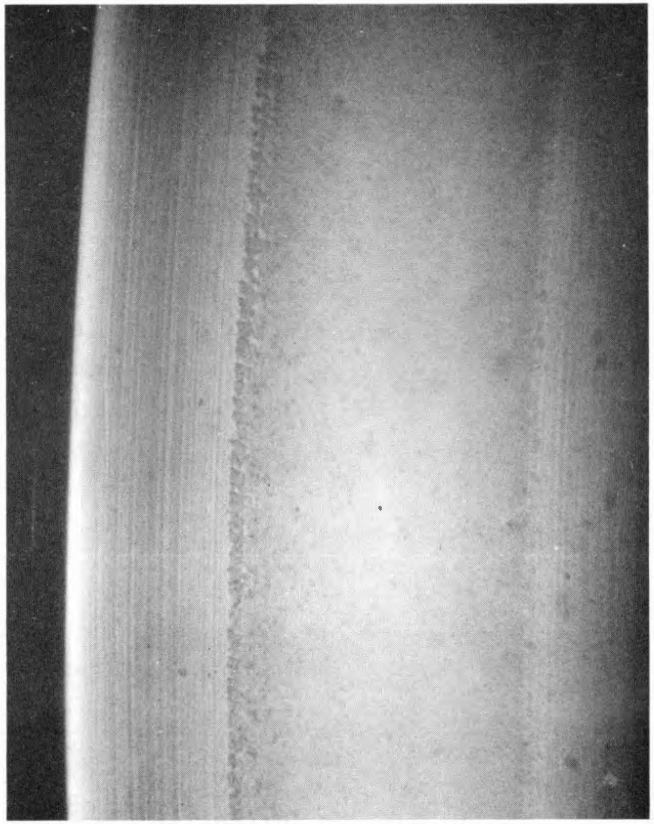
OUTER RACE

WHEEL # CV-115 E

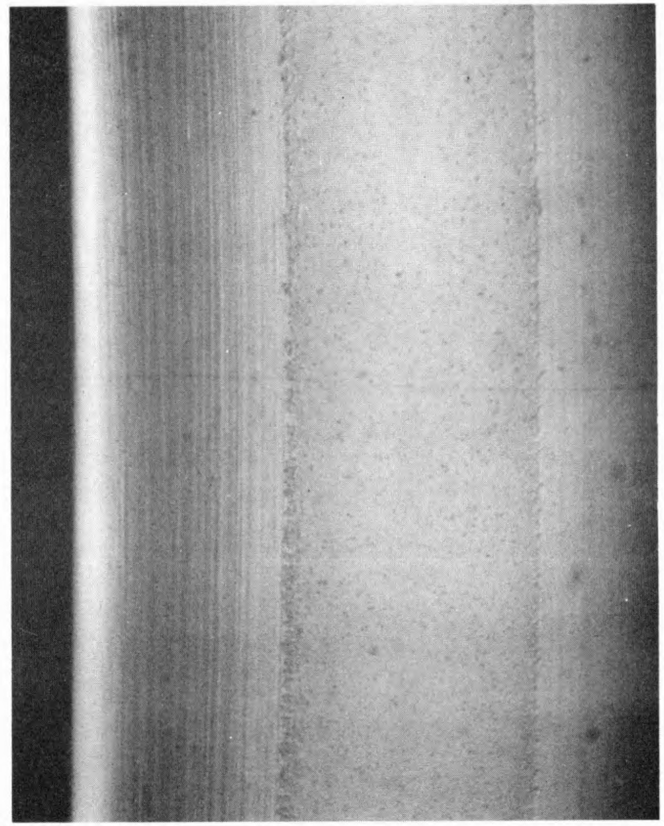
Figure # A-16 Uncleaned races from the + SRA bearing, end 2 (160 X).

WHEEL # CV-115 E

Figure # A-17 Uncleaned ball from the + SRA bearing, end 2 (160 X).



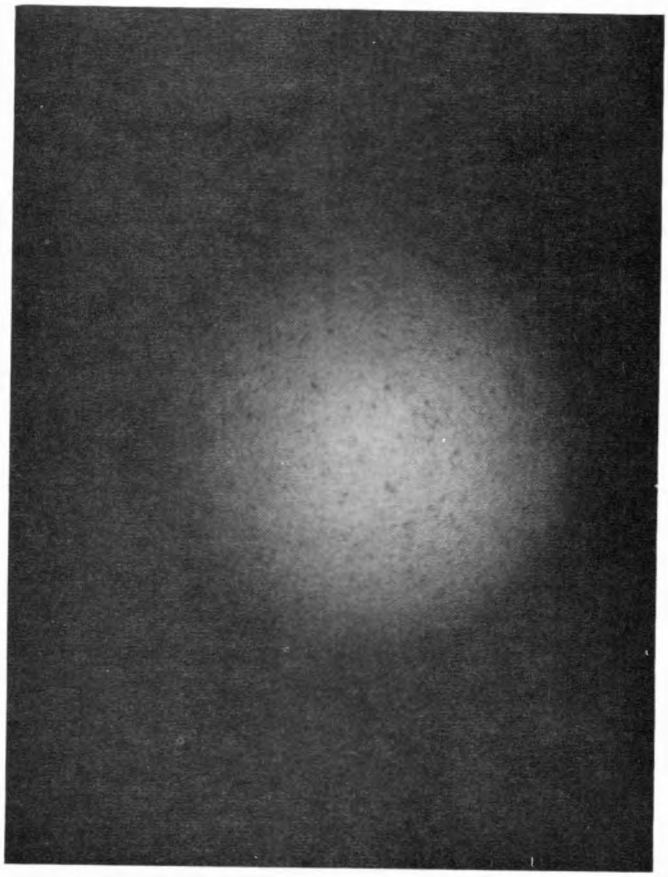
INNER RACE



OUTER RACE

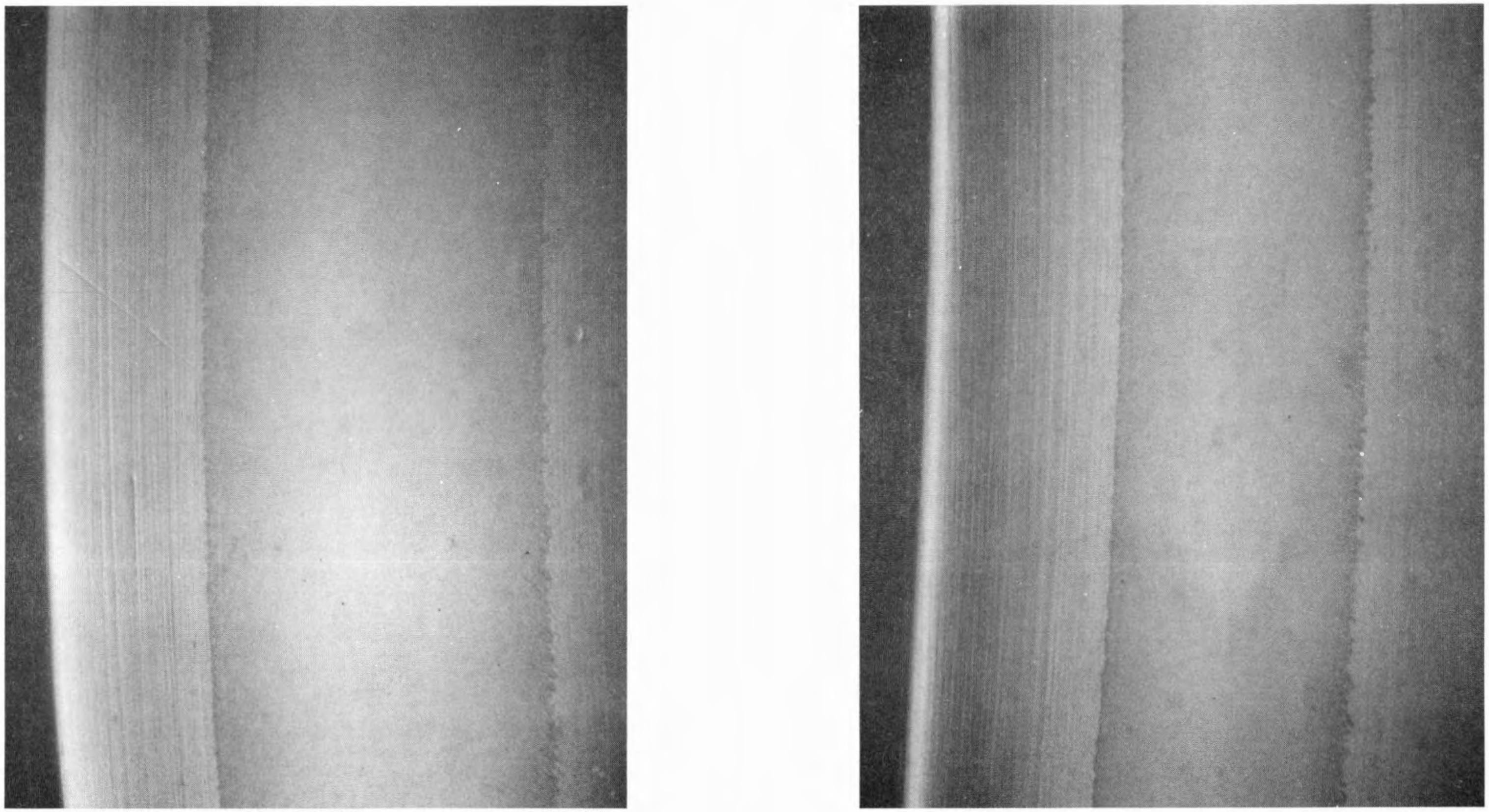
WHEEL # CV-115 E

Figure # A-18 Cleaned races from the - SRA bearing, end 1 (160 X).



WHEEL # CV-115 E

Figure # A-19 Cleaned ball from the -SRA bearing, end 1 (160 X).

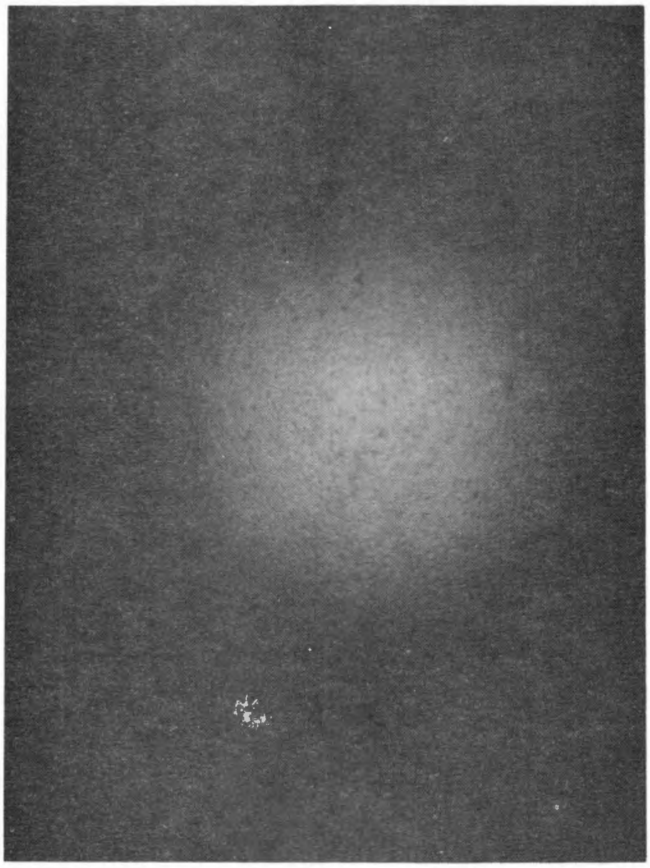


INNER RACE

OUTER RACE

WHEEL #CV-115E

Figure # A-20 Cleaned races from the +SRA bearing, end 2(160X)



WHEEL # CV-115 E

Figure # A-21 Cleaned ball from the + SRA bearing, end 2 (160 X).

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