



**Aerospace
Systems Division**

LSP Timer Overbanking
on the Lunar Surface

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Early in the preliminary design phase of the Lunar Seismic Profiling Experiment (LSP), it was recognized that the environmental conditions to which the timer watch movements would be exposed on the lunar surface would cause an increase in balance wheel amplitude; this could cause "over-banking" and possibly large timing errors in the fast direction. This, in turn, suggested the possibility of LSP timers running out while the astronauts were still on the lunar surface and caused the potential hazard to be categorized as "Safety Catastrophic."

This report presents the results of the tests conducted to acquire a fundamental understanding of the problem in quantitative terms and to reduce the hazard potential to "Safety Negligible" in the flight hardware.

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1.0 BACKGROUND

1.1 Introduction

Early in the preliminary design phase of the Lunar Seismic Profiling Experiment (LSP), it was recognized that the environmental conditions to which the timer watch movements would be exposed on the lunar surface would cause an increase in balance wheel amplitude; this could cause "overbanking" and possibly large timing errors in the fast direction.

Because a numerical value could not be placed on the total effect of the lunar environment on timing accuracy, the problem was identified as "Safety Catastrophic" within the LSP System Safety Program and reported accordingly to the Manned Spacecraft Center. This report reviews the considerable effort expended in acquiring a fundamental understanding of the problem in quantitative terms and in reducing the hazard potential to "Safety Negligible" in the flight Hardware.

This report was originally written as a joint effort of the author and his associates in the investigation, Mr. Charles Sauter of the Bulova Watch Company, and Mr. Rene Besson of Ebauches S.A. Mr. Sauter is responsible for all horological engineering on the LSP timers and Mr. Besson, a visitor from Switzerland at the time, made a most significant contribution to the investigation by performing most of the laboratory tests and by analyzing most of the data.

1.2 Lunar Seismic Profiling (LSP) Experiment

The LSP utilizes artificially induced seismic energy to investigate the physical characteristics of the lunar structure. It is scheduled to be transported to the moon in the descent stage of the Lunar Module (LM) on the Apollo 17 Mission and set out on the lunar surface during the second and third periods of extra-vehicular activity (Figure 1.2.1). Eight packages containing explosive materials ranging from 1/8 to 6 pounds will be set out at distances up to 3.5 kilometers from the ALSEP Central Station. The

LSPE DEPLOYED LAYOUT

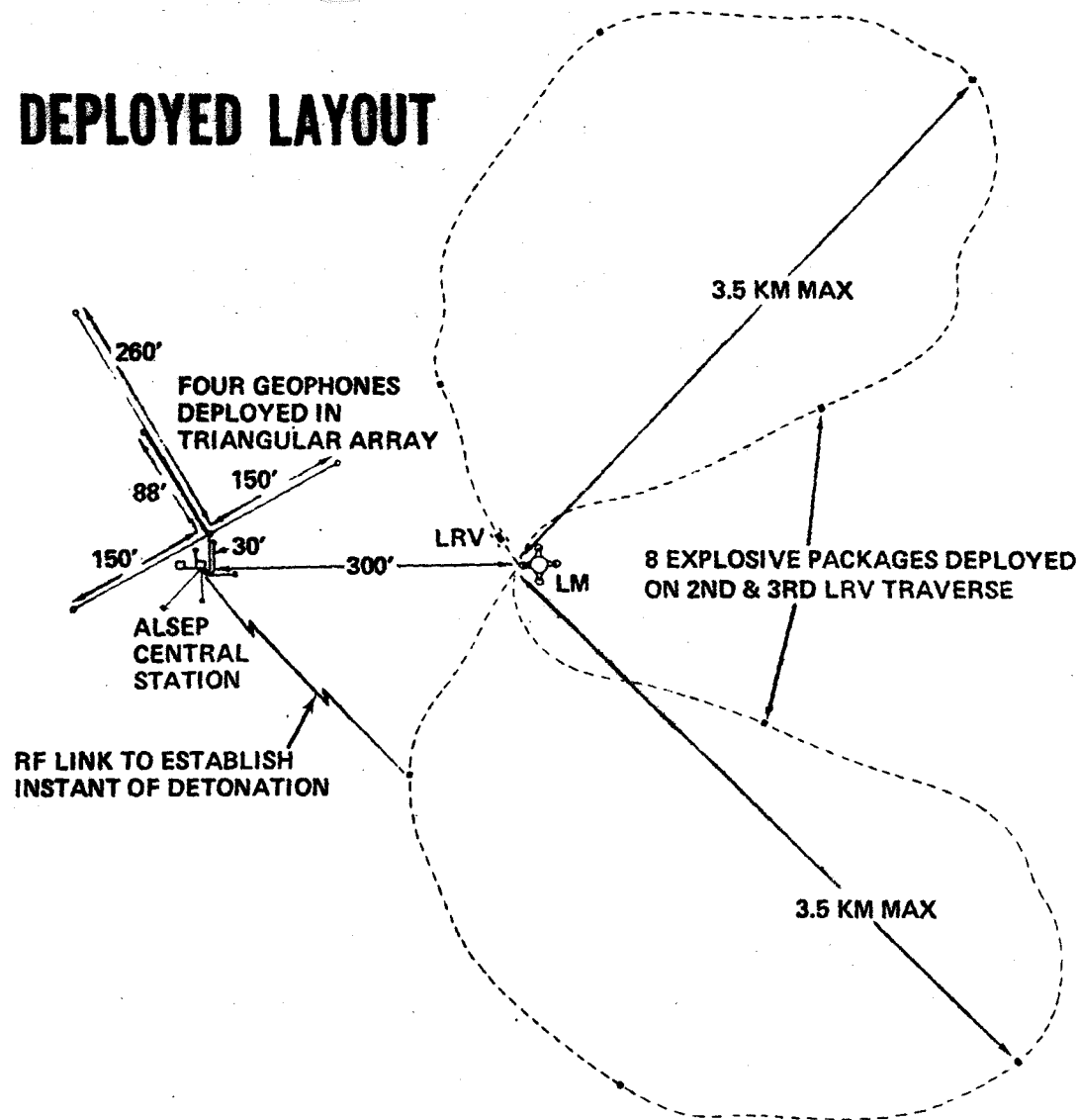


FIGURE 1.2.1



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packages are activated by the astronauts as they are set out by removing pull pins which initiate internal timing functions (Figure 1.2.2). The timing functions establish two of the three conditions required to detonate the packages after departure of the astronauts from the lunar surface, the third condition being the reception and successful decoding of a command signal transmitted from the ALSEP Central Station (Figure 1.2.3). Identification of the seismic output of each package is maintained by staggering the timing functions of the packages to establish a discrete firing time window for each.

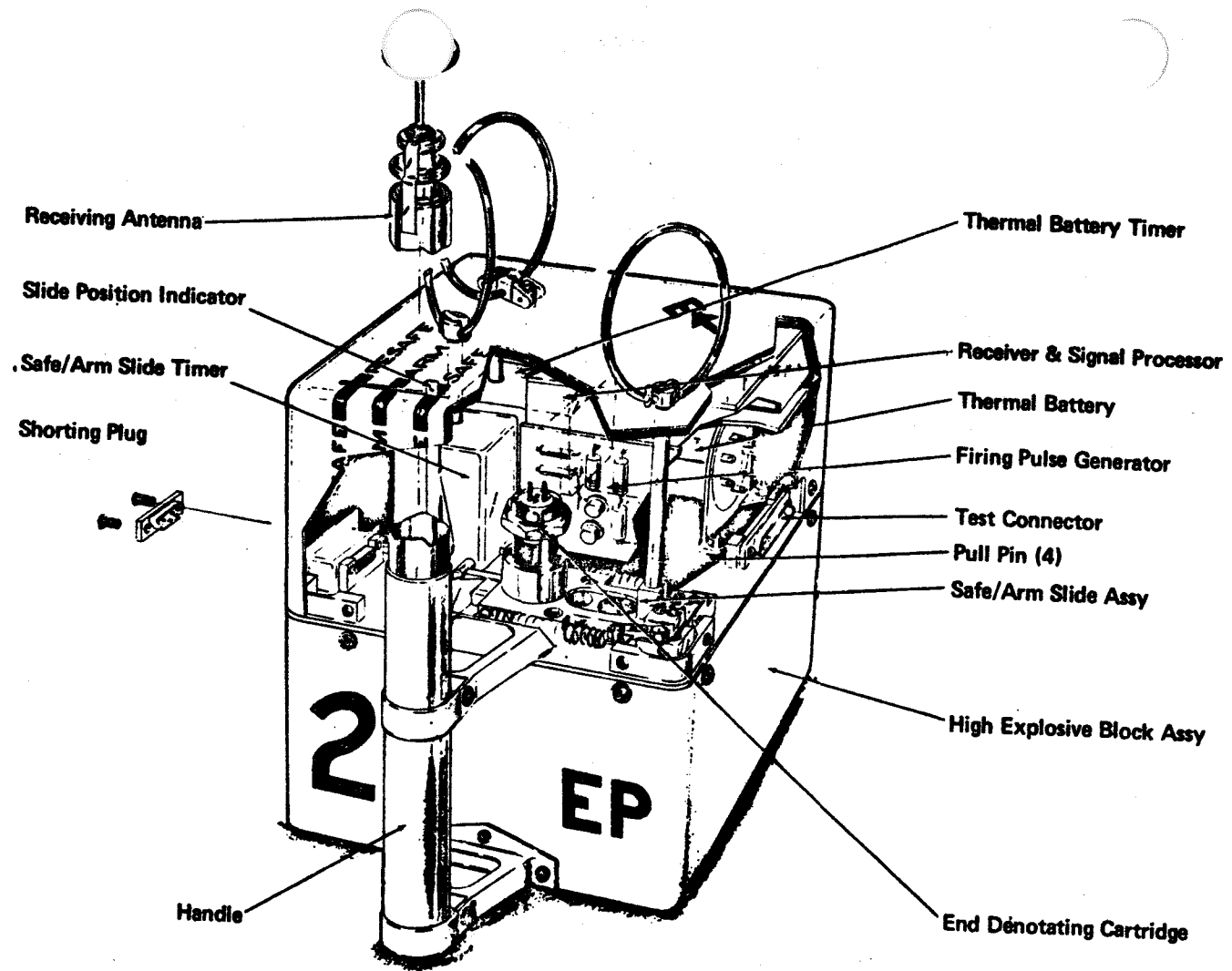
Seismic signals are detected by geophones, processed through the LSP Central Electronics in the ALSEP Central Station, and telemetered back to earth through the ALSEP Central Station along with critical timing data.

Subsequent to operation with the explosive packages, the LSP may also be used to detect high-frequency natural lunar surface activity during commanded intermittent listening periods.

1.3 LSP Timers

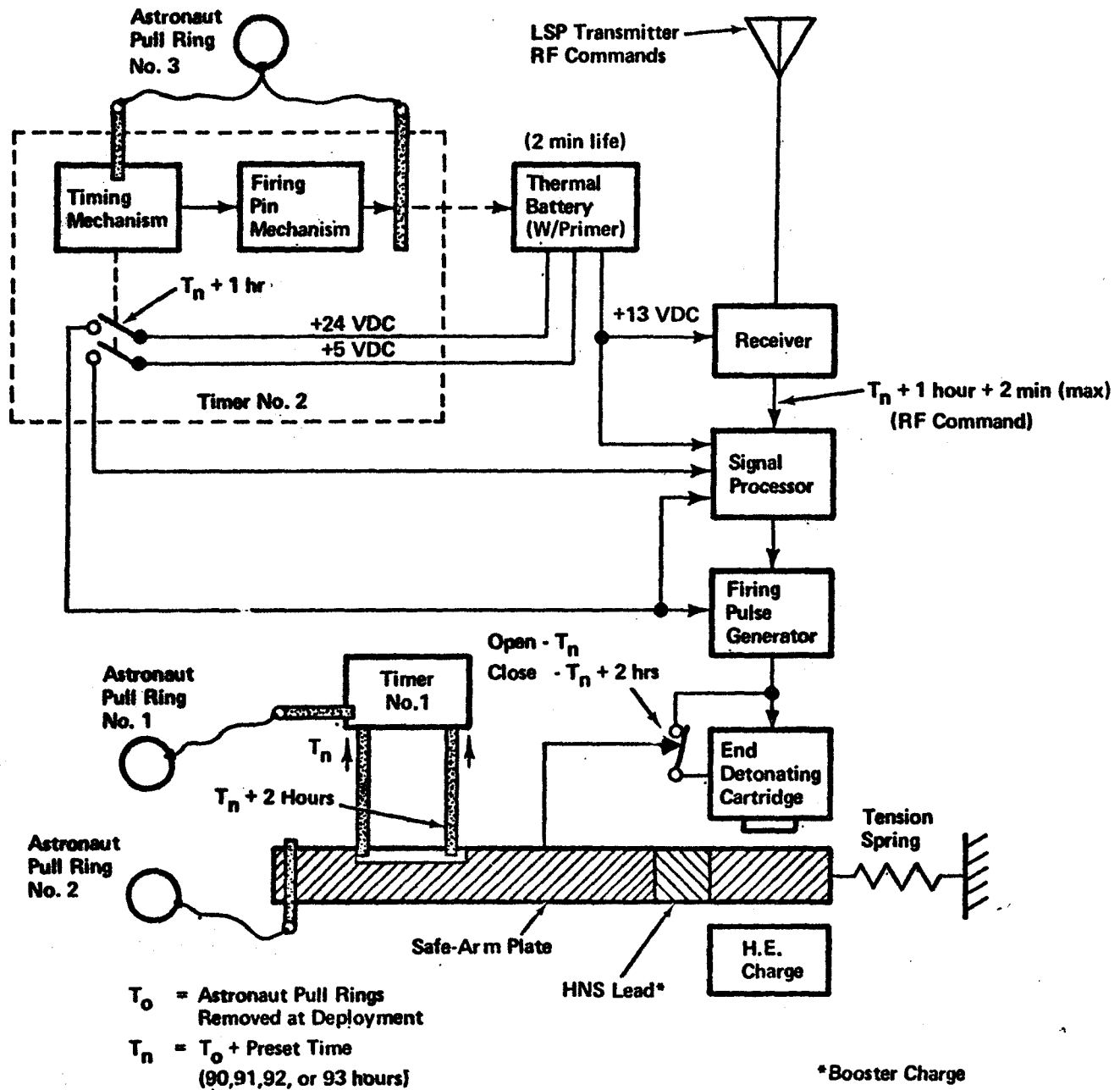
From a safety viewpoint, the key components of each explosive package are the timers, two per package, which establish the conditions permitting the conversion of the firing command from the Central Station into the detonation of an explosive package after departure of the astronauts from the lunar surface. The timers are completely mechanical, relying on a modified military "hack" wrist watch movement to provide the time regulation to advance a timing drum to a position where the output function is initiated. The timers are preset at the time of manufacture and there are no controls or adjustments to be made after that point is passed. It only remains for the astronauts to remove the pull pins which start the watch movements and which remove the mechanical, redundant in-flight safety features when the packages are in position on the lunar surface.

The safe/arm timer moves a slide from a position in which it provides complete physical isolation of the end detonating cartridge (EDC) from the explosive block to the "arm" position in which an explosive train, or "lead," in the slide lines up between the explosive block and the EDC. If for any reason detonation does not occur and the package is still intact after two hours, the timer will cause the lead to move beyond the position of alignment, thereby permanently isolating the EDC from the explosive block.



Explosive Package

FIGURE 1.2.2



BLOCK DIAGRAM OF EXPLOSIVE PACKAGE

FIGURE 1.2.3



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One hour after the safe/arm timer opens the firing time window, the battery timer releases a firing pin which strikes a percussion primer in a thermal battery. The heat generated within the battery as a result of this action liquifies a normally solid material, creating an electrolyte which activates the battery for a period of approximately three minutes. With power applied to the receiver, decoder, and capacitive firing circuits, the explosive package is capable of responding to a firing command from the Central Station.

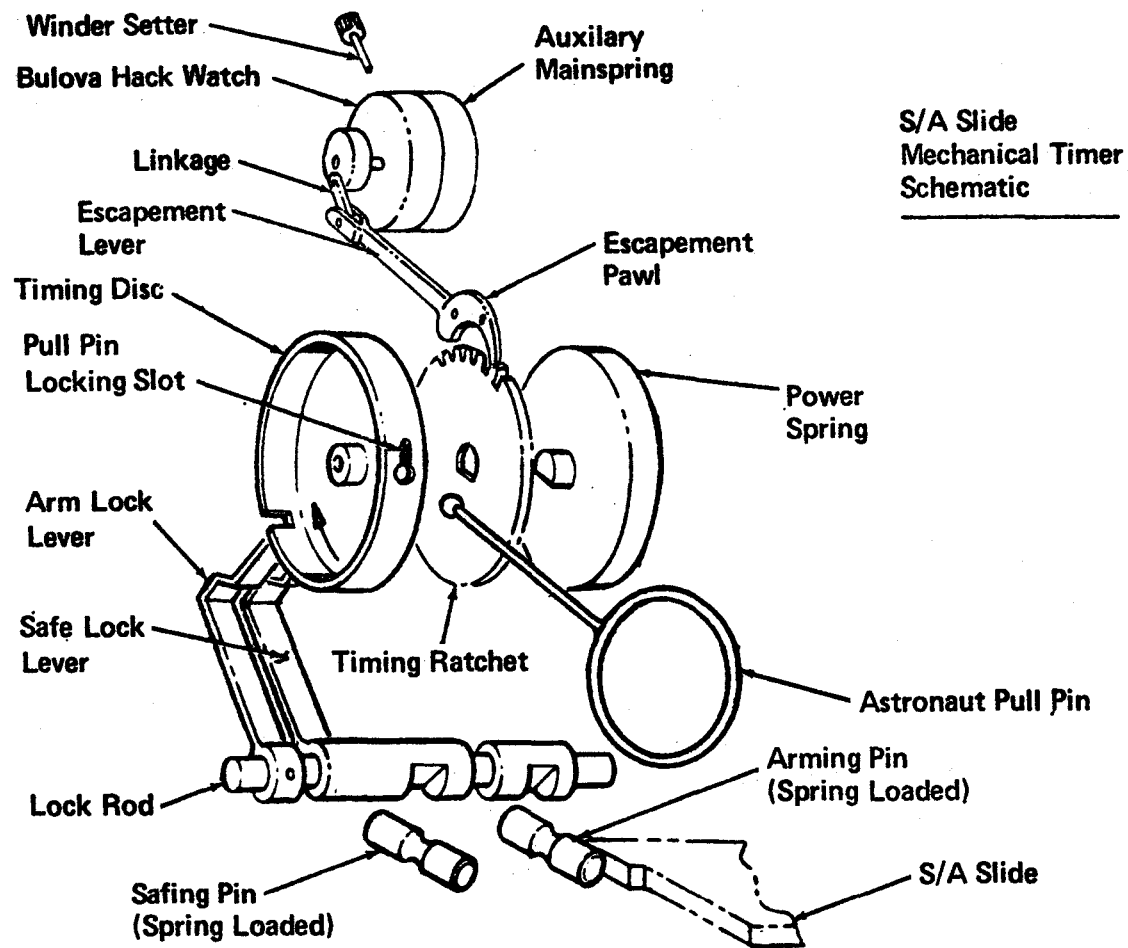
Although the safe/arm and battery timers provide different output functions, the time regulation and timing drum components are essentially the same (Figures 1.3.1 and 1.3.2, respectively). As related to the problem discussed in this report, they may be considered to be identical.

1.4 The Hack Watch Movement

The Bulova hack watch movement is produced in large numbers for use in military wrist watches and conforms to MIL-W-3818 (superseded by Federal Specification GG-W-113a). It has a jewelled pallet, detached lever, mechanical escapement movement, and an overcoiled hairspring. It is ruggedized for military service but is otherwise typical of high quality horological practice. The term "hack watch" derives from the design feature which stops the movement when the winding stem is pulled out and starts it again when the stem is depressed. A group of watches can thus be precisely set or "hacked" to a common time base and started simultaneously. In the LSP Timer, the timer pull pin "wipes" a mechanical linkage as it is extracted. This action depresses the stem and starts the prewound and preset watch movement.

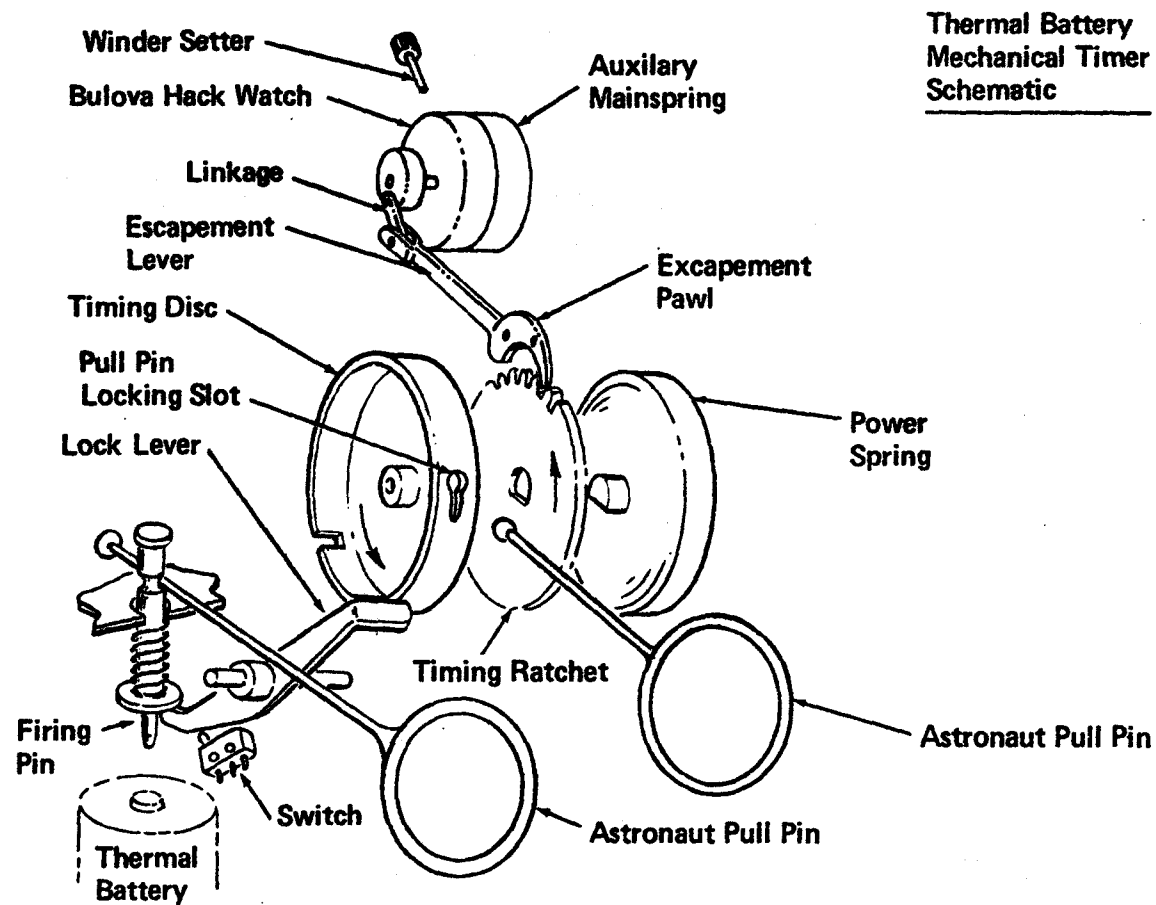
Timekeeping in a watch movement is actually performed by controlling the rate of dissipation of energy from the coiled mainspring. The control function is provided by the balance wheel and hairspring assembly which, when properly adjusted, oscillates in simple harmonic motion. The Bulova hack watch, per common practice, oscillates at a beat rate of five times per second. The principal components of a typical mechanical escapement watch are illustrated in Figure 1.4.1.

The measurement of angular displacement of a point on the rim of the balance wheel as it oscillates is the "amplitude" and is measured in "turns." A skilled horologist can visually determine the amplitude of an oscillating balance wheel to an eighth of a turn. The characteristic amplitude is a function of torque of a given mainspring and is adjustable only by substituting mainsprings of different torque characteristics. The

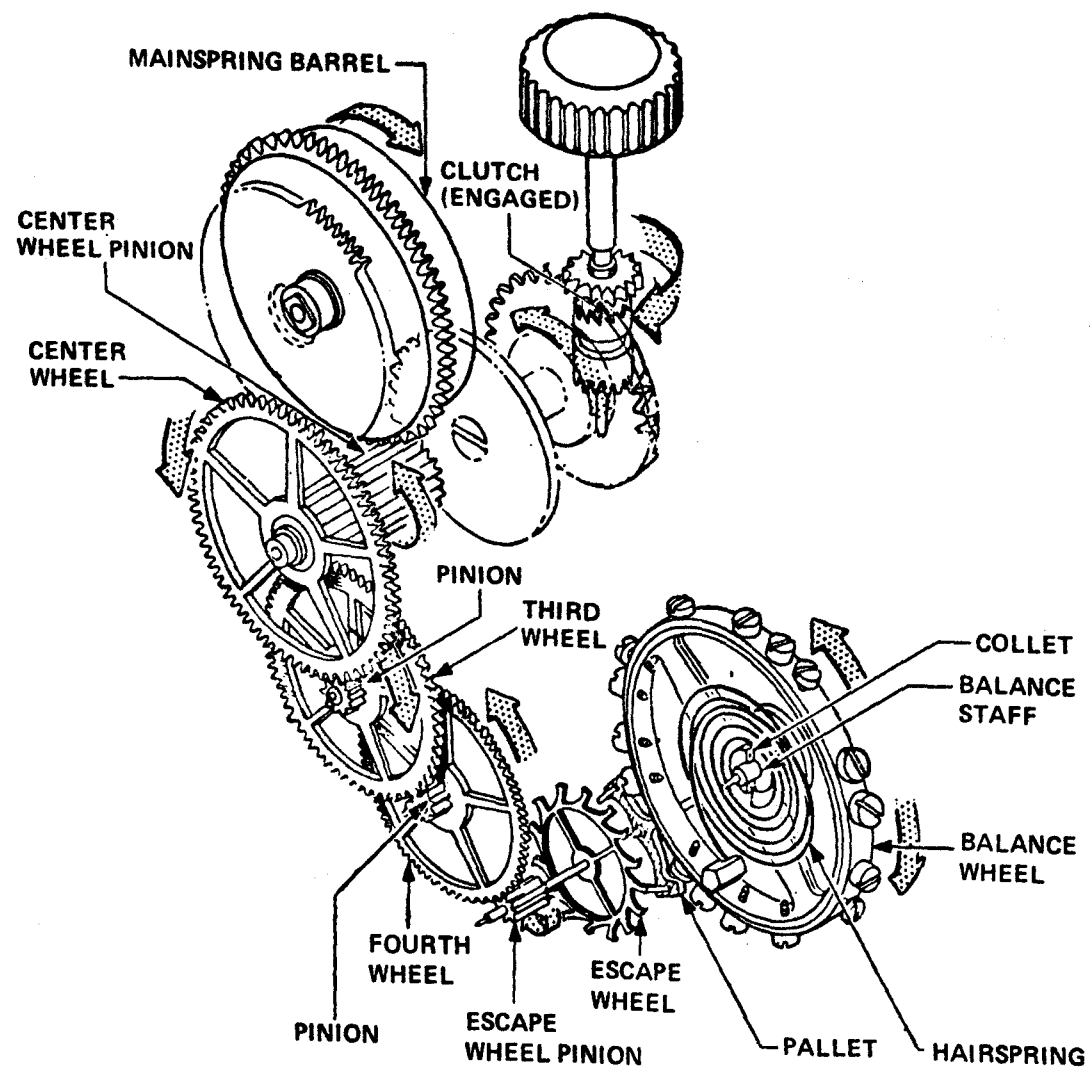


SAFE/ARM TIMER

FIGURE 1.3.1



BATTERY TIMER
FIGURE 1.3.2



POWER TRAIN - TYPICAL MECHANICAL ESCAPEMENT MOVEMENT

FIGURE 1.4.1



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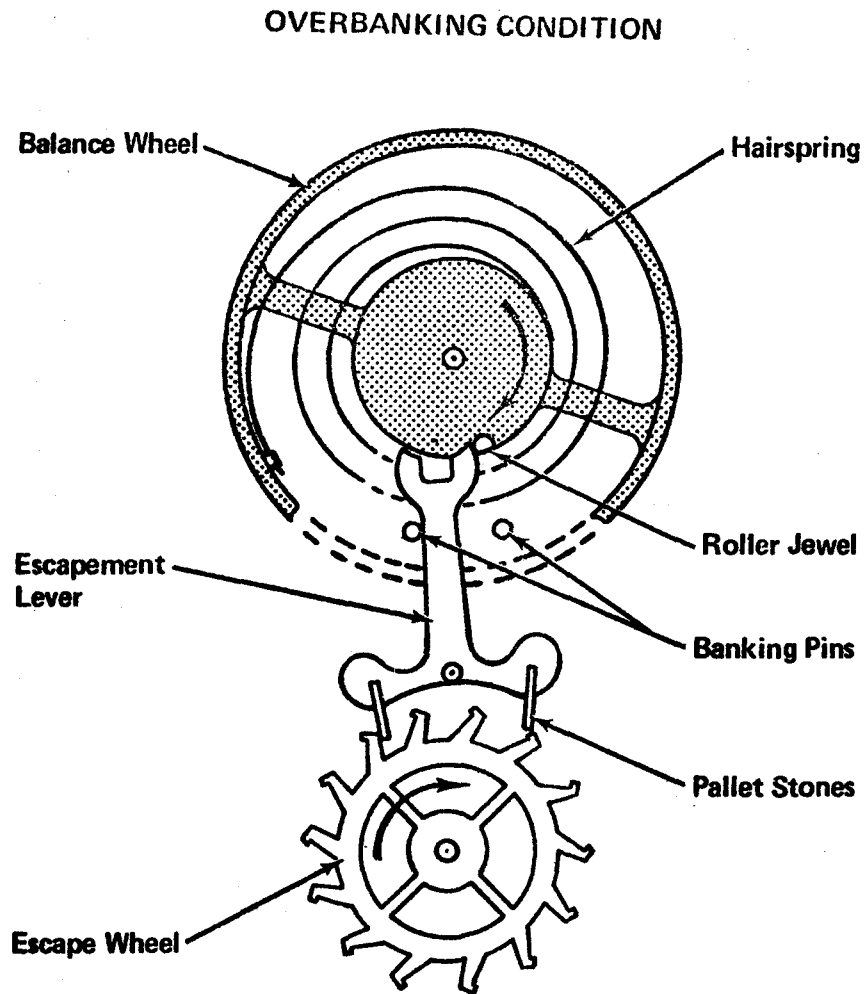
maximum amplitude must be less than that which would cause the balance to come around full swing and contact the escapement from the opposite direction. If this were to occur, the harmonic motion of the balance would be disturbed by the rebound off the escapement and the beat rate would increase, causing the movement to run faster than normal. This condition which is known as "overbanking," is illustrated in Figure 1.4.2. Typically, the maximum possible amplitude of a fully-wound watch is to the order of $1\frac{3}{4}$ turns. The operating amplitude of a watch in good condition is to the order of $1\frac{1}{2}$ to $1\frac{5}{8}$ turns with the balance wheel axis vertical (watch lying flat), and $1\frac{1}{4}$ to $1\frac{3}{8}$ turns with the balance wheel axis horizontal (watch on edge) due to increased balance staff pivot friction in this position.

The relationship between the beat rate and the amplitude of a balance wheel and hairspring assembly is termed "isochronism." The LSP watch movements are carefully hand adjusted to minimize the isochronal error so as to have essentially zero error through a large range of amplitude. In operation, this range can be exceeded downward and upward in amplitude with acceptable degradation of timing accuracy but with less assurance of reliable operation. The watch is apt to stop before it gets down to $1/8$ turn and is in danger of overbanking when it exceeds $1\frac{3}{4}$ turn. Practical limits within which reliable operation is assured are approximately one half turn minimum, with relatively poor timing accuracy as the amplitude decreases beyond $3/4$ turn; and $1\frac{5}{8}$ turns maximum to avoid overbanking.

In most instrument applications of watch movements, the primary concern is in the rate of the watch; whether it runs fast or slow, and how much. The amplitude of the balance wheel is selected by the watch designer to fall within a rather wide band of amplitude and has only a secondary effect on the rate.

In the LSP Timer, safety and reliability are of the utmost importance and highly precise timing is a second-order requirement. Balance wheel amplitude, rather than rate, is an extremely important factor due to the unusually wide range of environmental factors under which the watch is required to perform, and by the fact that there are upper and lower limits to usable watch amplitude.

A major problem, therefore, is to select an amplitude for factory setting which allow proper operation throughout all earth testing and lunar operating conditions. Initial estimates indicated that an amplitude of one turn at the point of manufacture would be satisfactory and engineering models have incorporated this value, as have all specimen watches used during the course of this investigation.



Overbanking is illustrated. Roller jewel is shown contacting escapement lever on "wrong" side while lever is restrained by banking pins. Rebound of jewel off lever is overbanking condition.

FIGURE 1.4.2



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2.0 CAUSES OF AMPLITUDE VARIATIONS

2.1 Mainspring Torque Variations

Mainsprings provide higher torque when fully wound up, and less as they run down. A characteristic torque curve is shown in Figure 2.1.1. The erratic torque variations at the high end of the curve are eliminated by the use of a recoil click in the winding ratchet mechanism which releases a few ratchet teeth before it locks the mainspring ratchet after winding. The low torque of the low end is eliminated by providing a longer mainspring run than is required for the mission involved. The resulting torque variations are thereby reduced to account for an amplitude variation of approximately one quarter of a turn.

Figure 2.1.2 presents the results of tests conducted to establish torque as a function of mainspring wind as expressed in number of turns of the mainspring barrel. These data, acquired mainly for use in correcting other test data to eliminate torque variation due to mainspring position, particularly during the vacuum tests which ran for many hours without opportunity to rewind the watches, are not representative of the production timer mainspring. The mainspring assembly has been modified to an auxiliary spring to increase the runout time in order to assure acceptable torque characteristics during the 90+ hour runout on the moon.

Additional amplitude variations, which may as noted among a lot of production watches, result from manufacturing tolerances, primarily in the thickness of the mainspring. Advantage may be taken of this variable, by selecting springs of higher or lower torque from a group, to provide the desired amplitude for a particular watch.

2.2 Watch Position

The amplitude of a watch balance wheel results from the impulse applied to the wheel by the escapement, and is attenuated by the various damping actions of several internal systems, one of which is the pivot friction. Variations in pivot friction due to the position of the watch are large enough to cause easily observable and reproducible variations in amplitude. They are caused, for example by changing the watch from a position in which the balance wheel rests on the end of one pivot of nearly zero friction radius, to a position in which the wheel rests in its bearings on the sides of two pivots, at a friction radius equal to the pivot radius. This variation in amplitude is held to less than one quarter turn by making the pivots of very small diameter. It should also be noted that, since the force exerted to cause friction is a function of the weight of the balance wheel, a gravitational factor is involved.

MAINSRING TORQUE CURVE

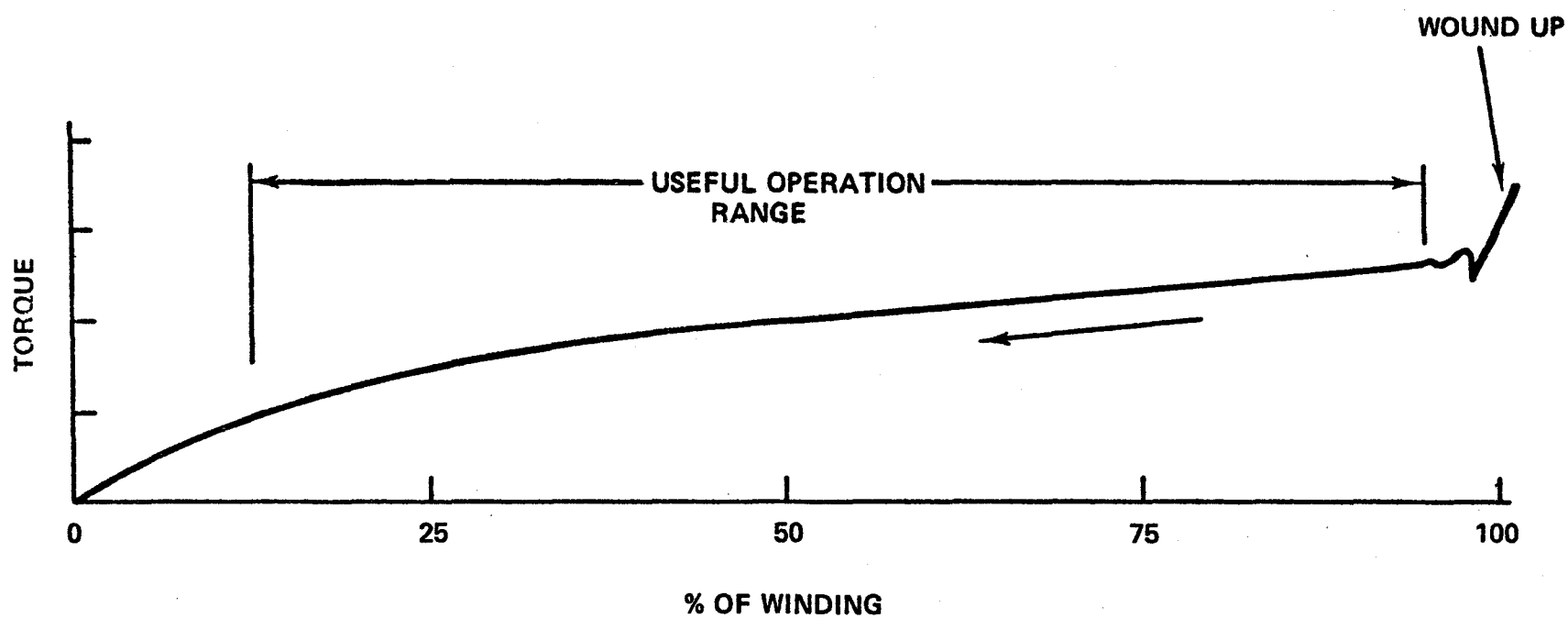
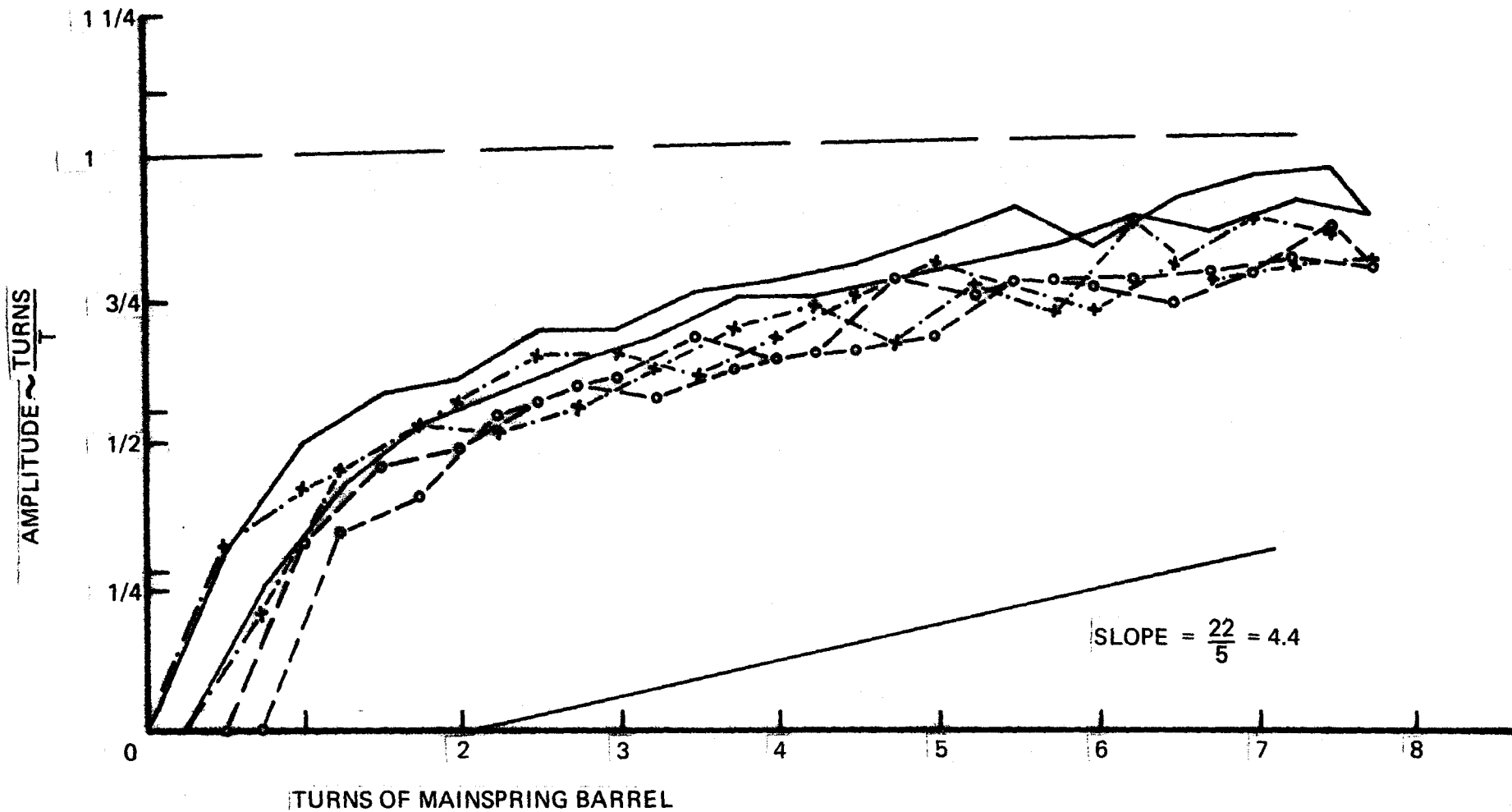


FIGURE 2.1.1



AMPLITUDE VS MAINSPRING WIND DOWN

Figure 2.1.2



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The attitude of the watch movements within the LSP timers are constrained to a stem 'up' edge position by the requirement to locate the pull pins on top of the explosive packages. Thus the flat position amplitude is of interest only in the unlikely and otherwise unacceptable situation in which the timer falls over onto its side after deployment.

It is also of interest to note that, since the two watch movements in each LSP explosive package are aligned in planes at right angles to each other, only one of the two timers will change position if the package falls over on any side. Thus, only one timer can overbank as a result of position change of the explosive package, tending to create a failsafe condition which would cause a dud rather than a premature explosion since the timers must both runout within their respective time windows to create the conditions required to detonate the package.

The results of tests conducted to precisely measure the difference in balance wheel amplitude of three hack watch movements on edge and in a flat position at various positions along the mainspring torque curve are presented in Figure 2.2.1. It may be seen that two of the test watches never exceed a difference of $1/4$ turn while the third watch was slightly in excess of $3/8$ turn.

2.3 Gear Train Variations

The amplitude of the watch balance wheel is a direct function of the torque delivered to the escapement which drives the balance wheel. This torque is produced by the mainspring and is reduced by the gear ratio and the efficiency of the gear train between the spring and the escapement. Although the gear ratio is nominally fixed by the number of teeth in the gears and pinions, in actuality there are variations in the curvature shapes of the individual gear teeth. In addition, variations in quality of polish, hardness, and actual material composition of gear teeth, pivots, and bearings, as well as the lubricant, combine to create variations in the friction and, thereby, the efficiency of the gear train. These changes in ratio and in efficiency result in measurable variations in torque delivered to the escapement, and cause accompanying variations in balance wheel amplitude.

The effect of these variations may be observed throughout the test data acquired during this investigation. However, the maximum variation due to gear variations would not be expected to exceed $1/8$ turn in a quality watch movement which indicates that other factors are in operation to cause variations in observed data greater than that. It may also be noted

THE EFFECT OF POSITION ON BALANCE WHEEL AMPLITUDE

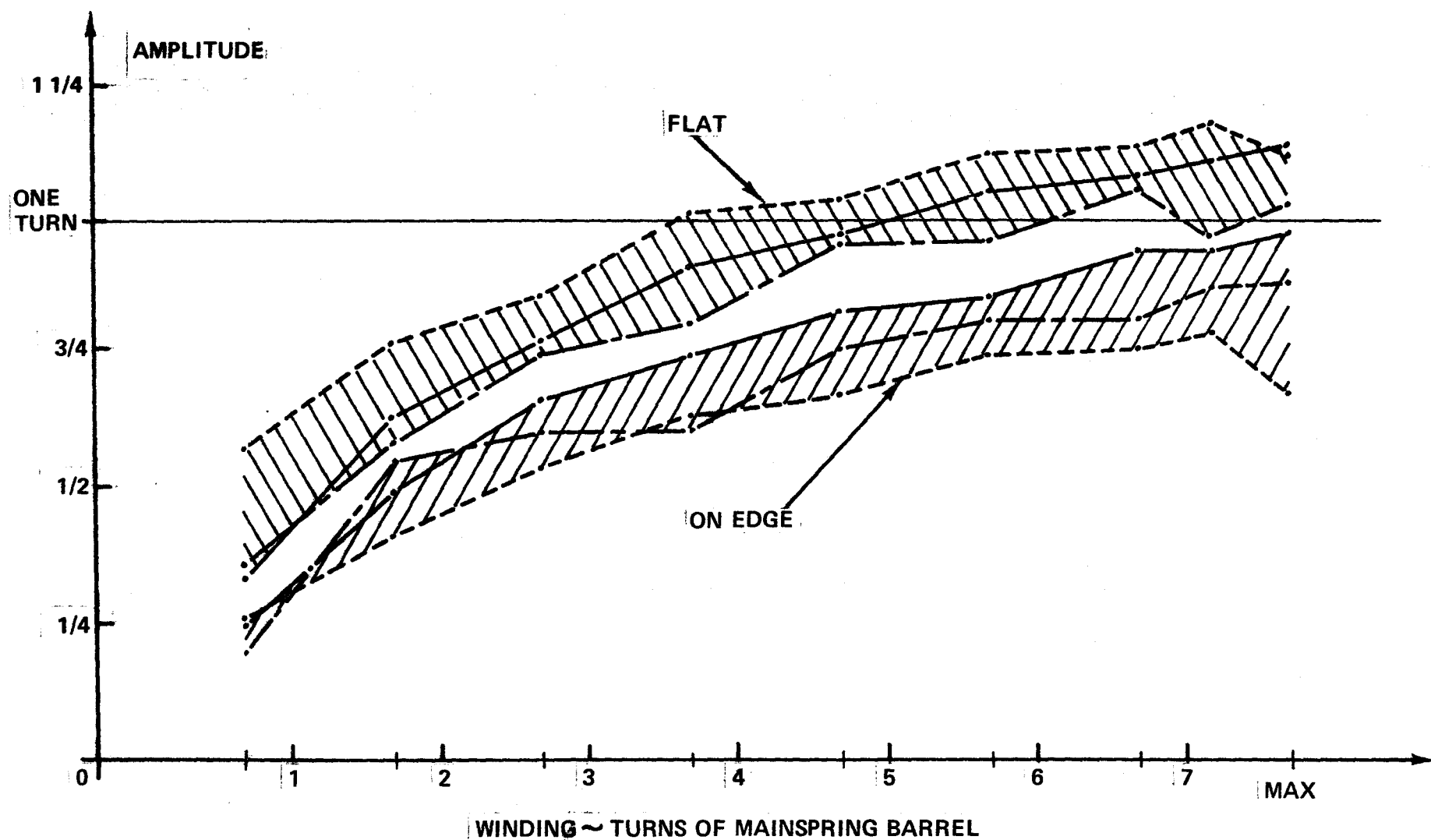


Figure 2.2.1



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that the specimen watches were operated for several weeks uncased and exposed to contamination as well as to the extreme test environments.

Gear train variation is not considered as a separate item in establishing worst case conditions as the effect is included within the values selected as worst case for the other conditions which affect balance wheel amplitude. However, it must be considered in establishing mainspring design requirements to attain the desired nominal factory amplitude.

2.4 Lubrication

For a watch mechanism to function properly, it must have very low internal friction within the gear train and escapement. In addition, this friction must be of a constant value if the amplitude of the balance wheel is to remain constant. Solutions worked out and perfected over centuries have evolved into a basic design utilizing hardened and polished tool steel gear pinions and pivots running jewelled bearings to provide the required low friction gear train. Friction force is reduced to a minimum by making use of very hard materials to allow the pivot diameters to be very small. Thus the friction torque, working at nearly zero radius, becomes nearly zero. These tiny pivots, heavily loaded by a powerful mainspring, and the balance wheel pivots, loaded by the weight of a heavy balance wheel, operate at pressures near the yield point of hardened steel. A lubricant which will keep these from wearing out must therefore have extreme pressure lubrication properties.

A watch oil, however, must be quite fluid to eliminate fluid friction difficulties, particularly at low temperatures. It must be kept in place between the pivot and the jewel by means of ingenious shapes and non-spreading oil properties which hold the oil in the reservoir by surface tension and non-wetting action. Mineral oils spread so easily that they are not useful as watch oils; and vegetable oils such as castor oil, while having the required film strength, turn to gum too rapidly to be practical. Animal oils, neatsfoot oil and certain fish oils, were commonly used until the fairly recent development of synthetic oils which display good non-spreading qualities, acceptable film strength, and excellent non-gumming properties. This last item has proven to be a great improvement over the animal oils and has resulted in their adoption in watch applications. Without it, the three year storage capability of the LSP Timers would not be possible.

The Bulova Watch Company, in their U.S. and Swiss factories, as well as much of the Swiss watch industry, had used the neatsfoot based oils



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of Moebius, the largest Swiss producer of watch lubricants. Their synthetic lubricant, Moebius "Syntalube," was quickly adopted by the industry after its introduction and has been used by Bulova with excellent results for over 15 years. A slightly heavier viscosity version, Synta-viscolube, has been used in the Accutron tuning fork watch for several years with equal success.

Because the temperature for the LSP lunar mission ranges from +40°F to +168°F, concern over the reduced viscosity and increased spreading to be experienced, compared to lower temperature operation normally experienced in consumer watches on earth, suggested the use of Synta-Viscolube. Lack of a low temperature operation requirement accentuated the choice since Viscolube lubricated watches stop at the relatively high temperature of approximately -30°F. The possibility of operating in a high vacuum under certain conditions also suggested a preference for Viscolube.

Having made a tentative choice of Moebous Synta-Viscolube for the lubricant at the beginning of the program, experiments were devised to prove its ability to provide satisfactory operation in the environment of the LSP mission. The first and largest problem seemed to be the effect of high vacuum. Presuming at first that the oil would evaporate in high vacuum, the initial experiments consisted of mounting watches and exposed oil samples in a glass bell jar and subjecting them to a 1×10^{-5} torr vacuum overnight. It was expected that the watches would stop and that the exposed samples would evaporate and disappear. This did not happen. The watches continued to run and the samples did not change. The samples, which were macroscopic droplets of oil placed on a polished steel screw head on a watch, showed no signs of vapor emission, streaks on the polished surface nearby, or decrease in size. This experiment demonstrated that the maintenance of pressure on the watch mechanism of the order of 10^{-5} torr would assure satisfactory lubrication under lunar conditions.

Extrapolation of subsequent tests requested by Bendix indicated that the oil would probably withstand 180°F at 10^{-13} torr conditions on the moon in the event of complete seal failure, and that any remaining vestige of sealing[^] would prove to be adequate for proper watch operation. On the basis of these tests, all watch movements used in the overbanking investigation were lubricated with Moebius Synta-Viscolube as will all watch movements subsequently prepared for the LSP Program.

2.5 Temperature

Extensive tests were conducted to evaluate the effect of temperature on balance wheel amplitude. Two series of tests were performed, at



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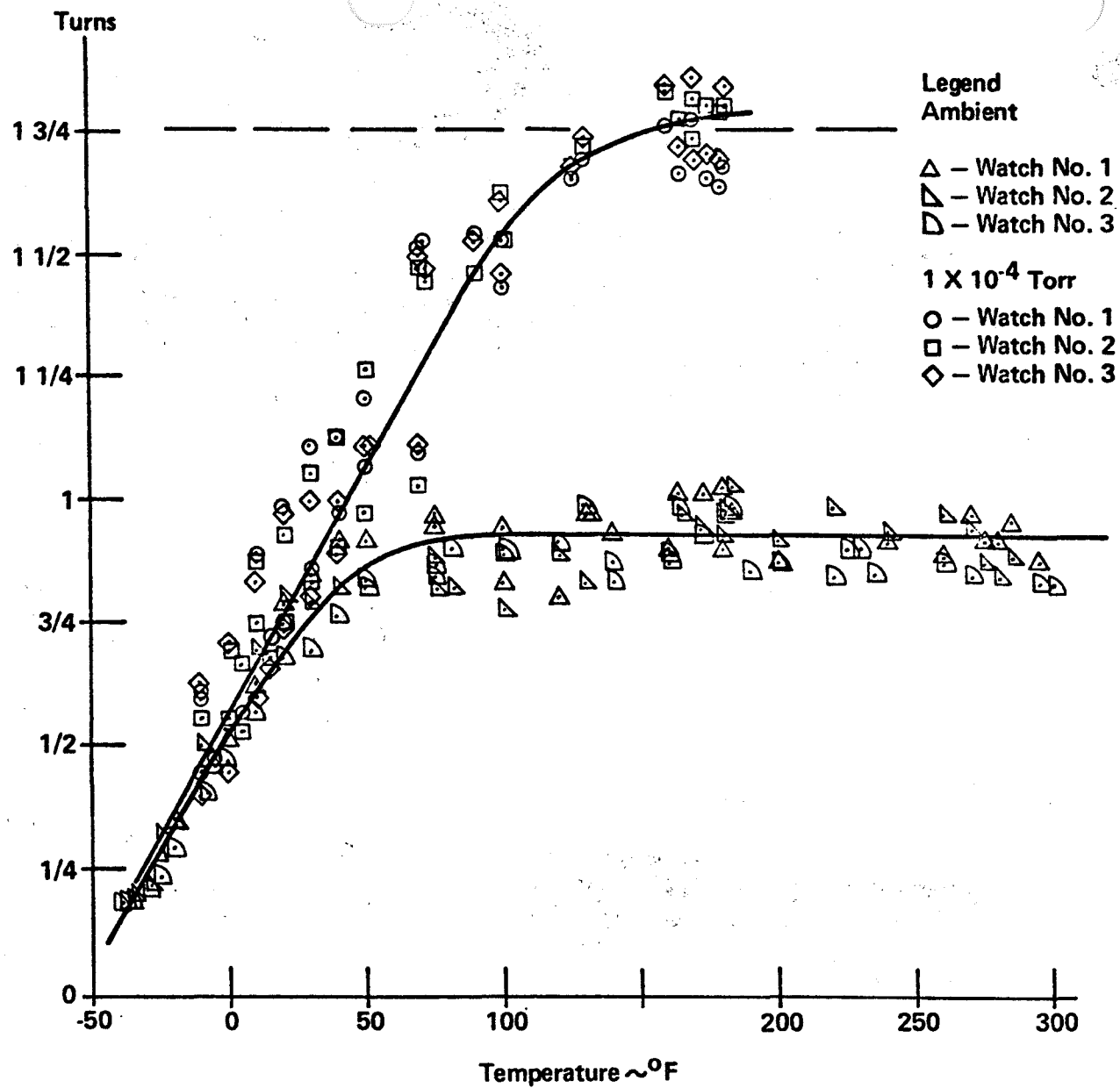
ambient pressure and in the range of 1×10^{-4} torr, to explore the inter-relationship between temperature and pressure. The summary results, corrected to eliminate torque variations due to mainspring wind down, are presented in Figure 2.5.1.

The effect of reduced pressure on the results of these tests are dramatic. Whereas a sharp point of inflection is displayed on the ambient curve in the 40 - 50°F range which renders amplitude essentially independent of temperature above this point, the vacuum curve rises steadily at a nearly constant rate and could cause a fully wound watch to overbank above 150°F. This is demonstrated by the points plotted above the 1 3/4 turn line, which is not physically possible for the balance wheel is constrained to approximately 1 3/4 turns. These points result from large torque corrections on measurements made after running the vacuum chamber (and the watches) overnight to get down to test pressure. It may be inferred that, had the measurements been made immediately after winding the watches, overbanking would have been observed in at least two of the test watches.

The close grouping of the data at the cold end of the curve suggests that pressure has little effect on amplitude at low temperatures but that there is almost a straight line relationship between temperature and amplitude in the range from stoppage at -35°F (-20°F in vacuum) to the point of inflection at 40 - 50°F.

Figure 2.5.2 presents the Bendix predicted worst case hot and cold temperature time histories for the explosive packages on the lunar surface. The worst case cold represents a package removed from the LRV at the beginning of the second EVA and at the minimum specified LSP deployment temperature of +40°F. The worst case hot condition represents a package moved from the LM into sunlight at the beginning of the second EVA oriented for maximum heat absorption and carried on LRV in the sun throughout the traverse and deployed at the end of the third EVA. The maximum temperature range over which the timers will be running are +40°F to +168°F.

Timer operation on earth requires operation in a simulated lunar terrain in high desert country, probably during winter months. Tests were run to evaluate the effect on watch amplitude of oil thickening at low temperatures.



Effect of Temperature on Balance Wheel Amplitude

FIGURE 2.5.1

LSP TIMER OPERATIONAL TEMPERATURE EXTREMES

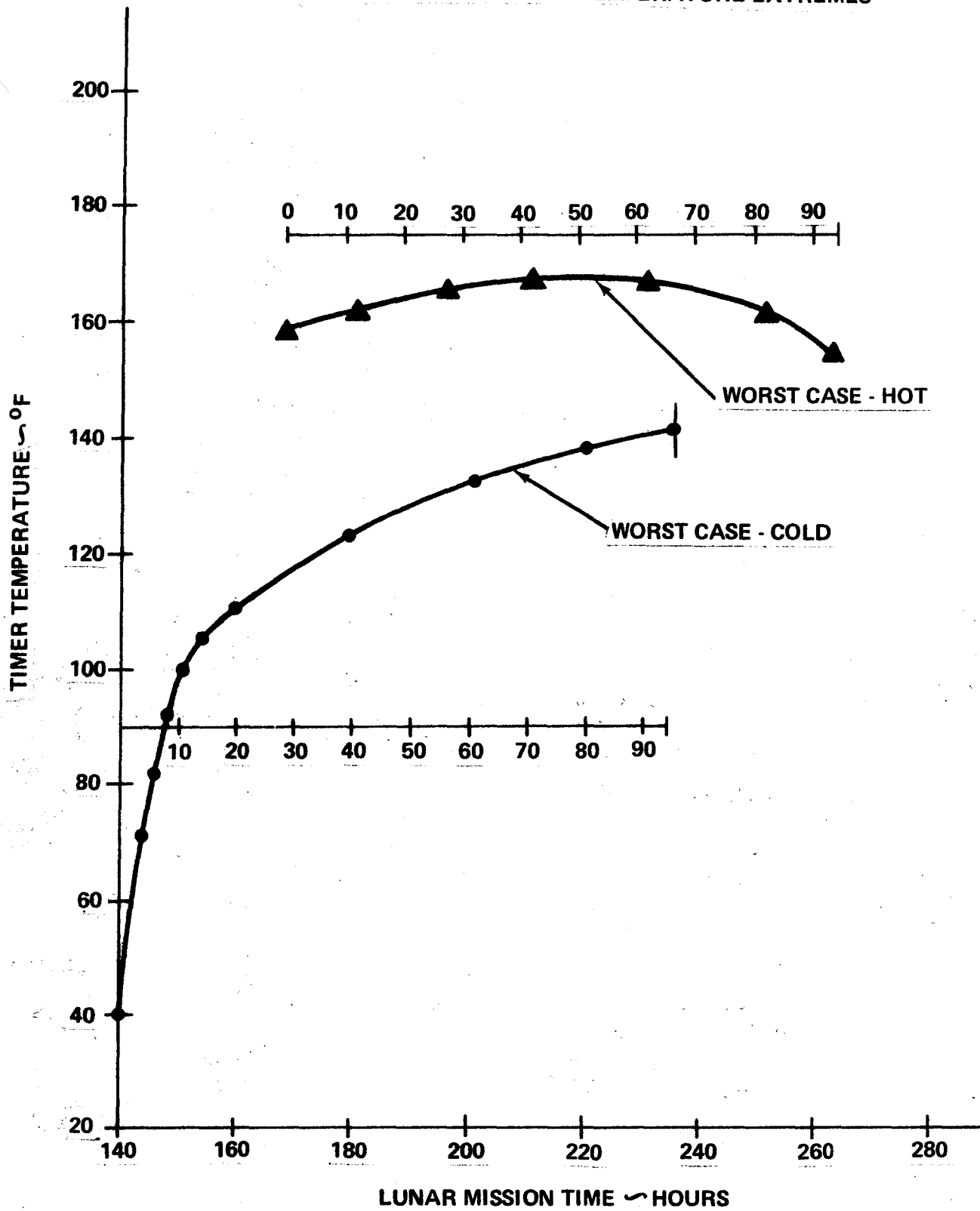


FIGURE 2.5.2



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The data presented in Figure 2.5.1 indicates that amplitude is maintained near $1/2$ turn, where it will continue to keep good time, at temperatures approaching zero °F, and that watches continue to function, albeit erratically, down to a temperature of about -35°F. Thus it appears that low temperature will not limit operation in earth testing, where explosive package temperatures will be maintained at the minimum predicted lunar temperature of +40°F by external heat sources. Watch movement functioning in the low temperature range requirements of the LSP is not degraded by the choice of a rather thick watch oil.

2.6 Pressure

The original interest in the parametric relationship between temperature and pressure as they affect balance wheel amplitude was aroused during a series of preliminary vacuum tests utilizing visual observation of the balance wheel to determine amplitude. It appeared that a significant "break point" existed in the 1 torr range which suggested that leakage down to that range would not significantly contribute to an overbanking condition. It also became apparent at this time that reliance on the visual measurements of amplitude made by skilled watch makers was an unacceptable method of acquiring test data of such potential significance. This provided the impetus to adapt the fiber-optic instrumentation system developed for the C-135A gravity tests to the environmental test set up in the Bulova Laboratory.

The results, as presented in Figure 2.6.1, substantiated the trend indicated in the initial tests, and a significant break point does exist in the 1 torr range. The maximum effect at 180°F, 1 torr, results in an increase in amplitude of approximately $1/4$ turn. At the ambient temperature (approximately 75°F) only one of the three test movements showed any appreciable change in amplitude ($1/8$ turn). However, beyond 1 torr the slopes increase sharply and in the hot case, extend into the overbanking region. These results correlate with the temperature test results previously discussed.

The significant conclusion to be drawn from these tests is that non-catastrophic leak rates which assure a minimum pressure of 1 torr during lunar operations have no great significance to the overbanking problem.

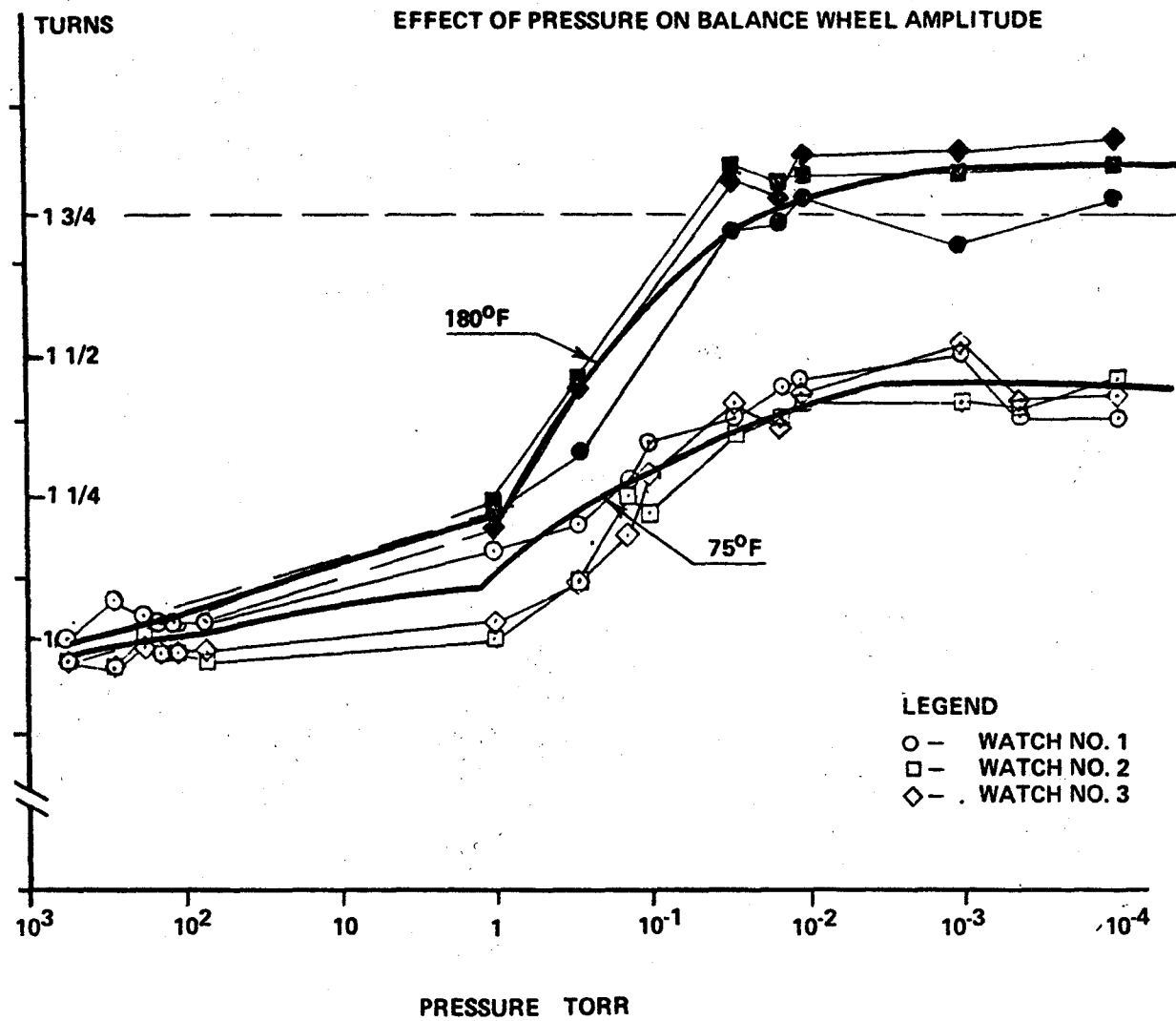


FIGURE 2.6.1



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2.7 Gravity

Experimental determination of the effects of temperature and pressure was a relatively routine matter involving the preparation of specimen watches and the setting up and calibration of a temperature controlled vacuum chamber. Evaluating the effect of gravity was another matter and proved to be the most difficult to measure accurately.

It was known that watch balance wheel amplitude changes about $1/4$ turn when the watch is changed from an edge position to a flat position only because of changes in bearing friction. From this it could be inferred that the effect of gravity is not negligible and that a substantial increase in balance wheel amplitude over the nominal earth value could be expected when the watch was operating on the lunar surface. A centrifuge test was devised to provide g vs. amplitude data in the approximate range of 1 to 10 g. It was then proposed to extrapolate this curve backward to the lunar $1/6g$ area. Not being completely convinced that this procedure would result in valid data, additional test methods were sought for cross-correlation.

As a result, two other methods were proposed; low or zero g flights in the C-135A aircraft operated by the United States Air Force as a zero g test and research facility and in the 500 foot free fall zero g research facility operated by the NASA Lewis Research Center. Tests were ultimately performed at both facilities under the sponsorship of the NASA Manned Spacecraft Center, the procuring agency for the LSP Experiment.

The first attempt to approximate the effect of lunar gravity was to extrapolate centrifuge data back through 1 g. Although not considered to be too reliable an approach at the time, the results as presented in Figure 2.7.1 proved to correlate well with the other approaches taken; i. e., an approximate increase of $1/4$ turn.

Free fall drops were conducted in the NASA Lewis Research Center 500 foot drop, test facility. The quality of the data acquired was outstanding, the results of the two tests being so repeatable that the second test was only spot checked to verify that the repeatability was consistent. Unfortunately, however, the duration of the drop was only five seconds, which was an insufficient period of time for the effect to develop completely and to stabilize. The results are presented in Figure 2.7.2.

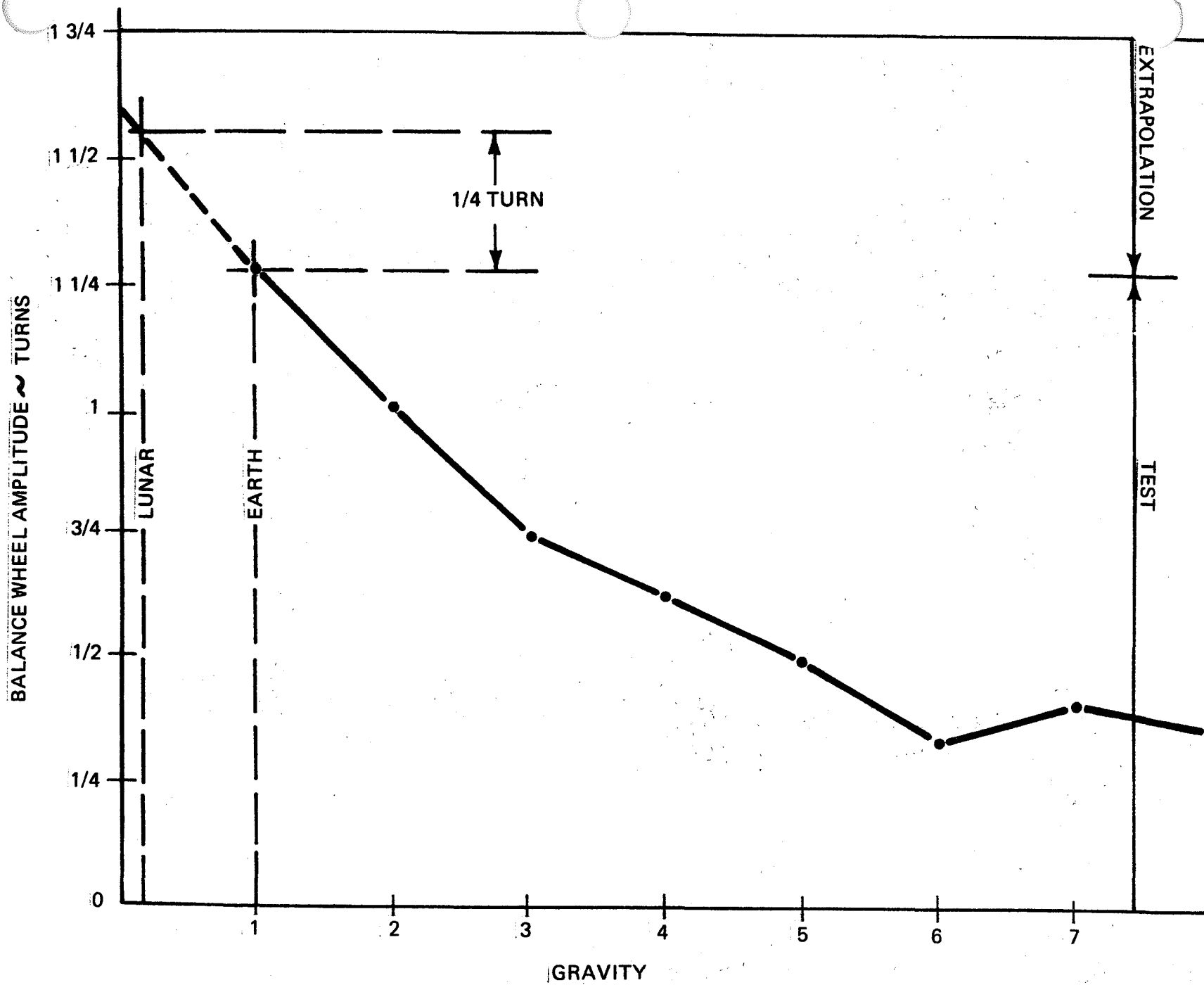


Figure 2.7.1

FREE FALL TEST RESULTS
LEWIS RESEARCH CENTER

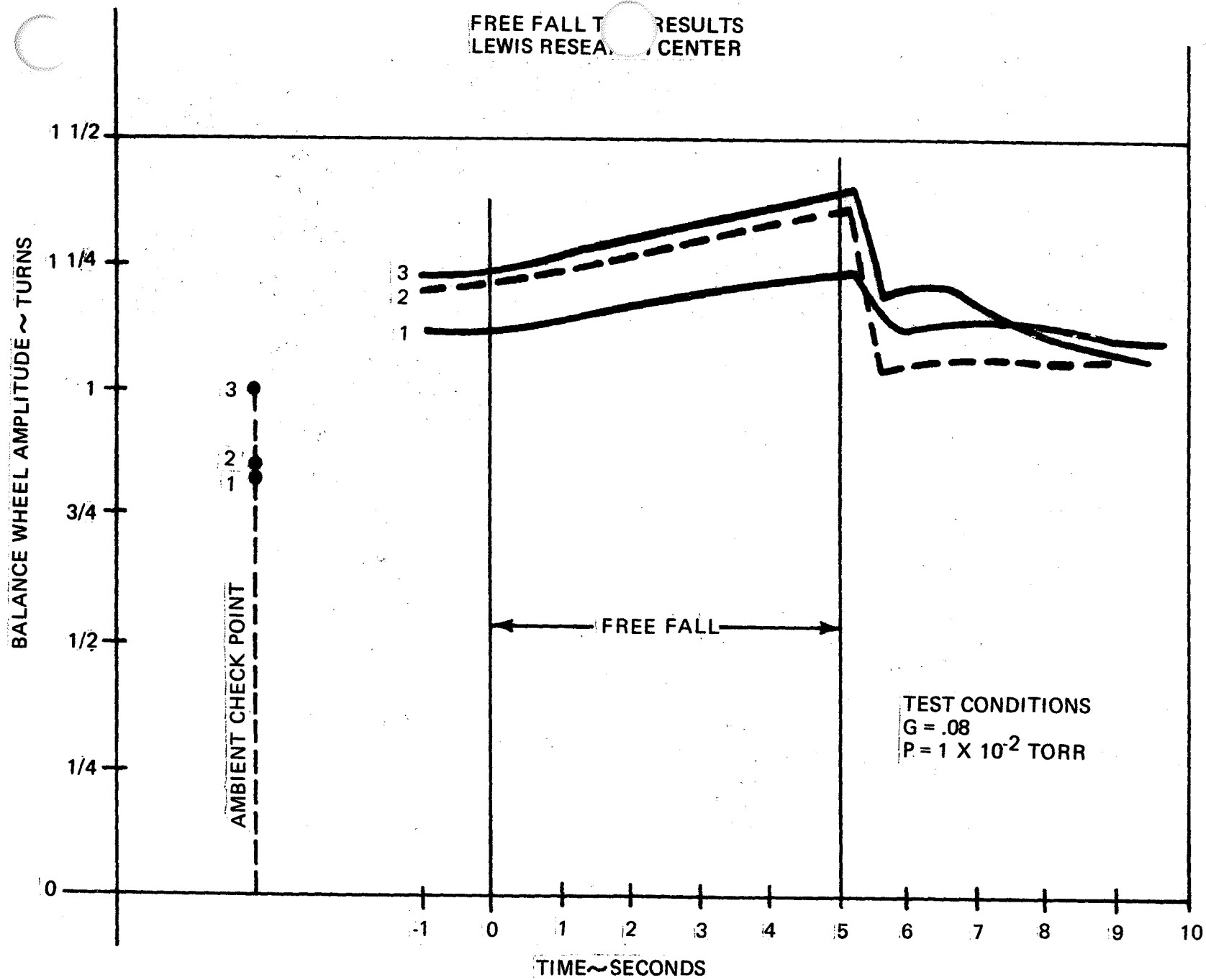


Figure 2.7.2



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Extrapolation to a steady state condition, utilizing a geometric progression which yielded a curve with the approximate characteristics of the C-135A test curves, also provided results of approximately 1/4 turn increase in amplitude as noted in Figure 2.7.3. The change in amplitude as a result of the difference in pressure between the laboratory (ambient) and the test chamber immediately prior to the drop (1×10^{-2} Torr) also correlates with the results presented in Figure 2.6.1.

The test data acquired in the C-135A flight tests suffers from the fact that these tests were run very early in the investigation and did not profit from the learning experience as did later tests. Specifically, the importance of knowing the position of wind down of the mainspring was not appreciated and the failure to keep track of this important variable made correlation of data from flight to flight impossible. In-flight conditions also affected the repeatability of the data; for example, the in-flight one g measurements were made in almost every case while the airplane was turning, climbing, or descending. Vibration also affected both the operation of the watches and the readability of the accelerometer trace. Nevertheless, a careful review of all the data recorded on six flights and more than 100 zero g and lunar g maneuvers, fails to disclose increases in balance wheel amplitude which grossly exceed 1/4 turn.

Typical time histories are presented in Figure 2.7.4 of complete C-135A test maneuvers. The watch movements respond to the gravitational changes from nominal 1 g to 2 g as the airplane pulls up into the maneuver, then the test g (zero or lunar) going over the top, 2 g again during the recovery, and finally 1 g steady state until the next maneuver is entered. What the time histories do not show is the change in vibration level in the airplane as power settings are reduced and airspeed bleeds off going over the top of the maneuver. As vibration apparently acts to dampen balance wheel amplitudes, an unknown increment of the total change in amplitude may be attributed to changes in vibration levels within the airplane.

Figure 2.7.5 presents all the balance wheel amplitude measurements made on a single test watch during one test flight. There were three watches in the test installation. Although their individual characteristics were different, the net resulting changes in amplitude of the three were essentially the same.

EXTRAPOLATION OF FREE FALL TEST RESULTS LEWIS RESEARCH CENTER

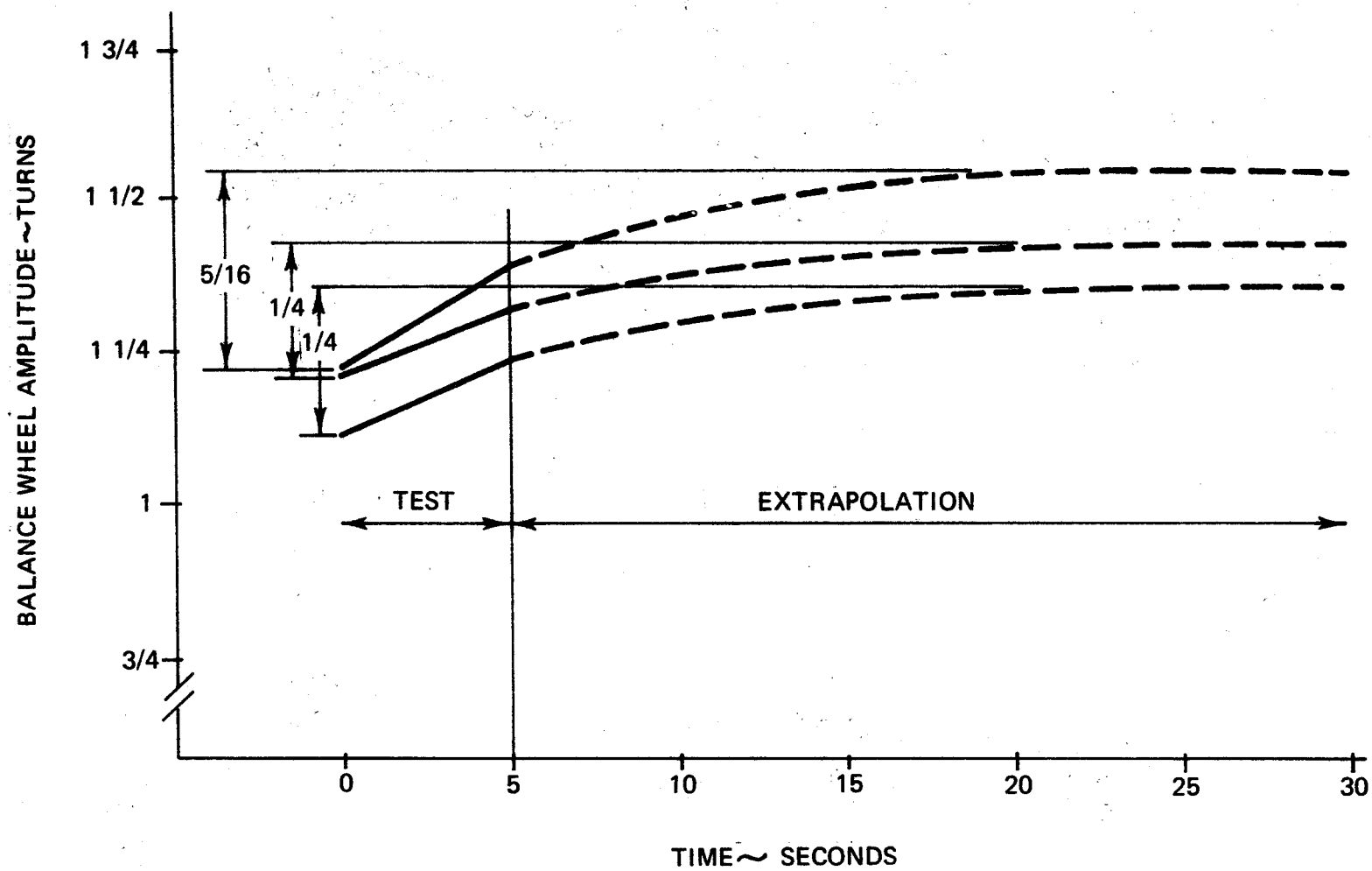


Figure 2.7.3

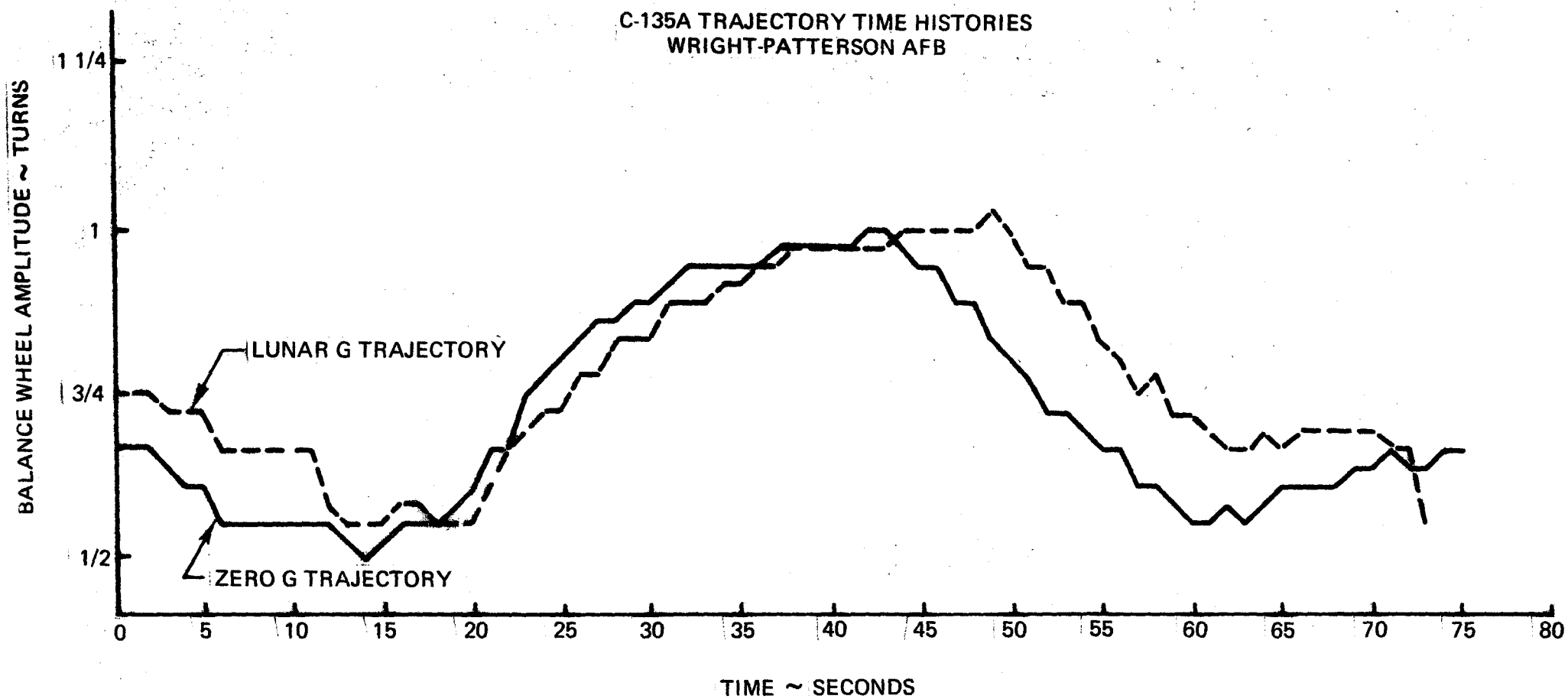


Figure 2.7.4

BALANCE WHEEL RESPONSE TO GRAVITATIONAL FORCES
C-135A FLIGHT TESTS AT WRIGHT-PATTERSON AFB

G LEGEND

- △ - 0
- ◇ - 1/6
- - 1
- - 2

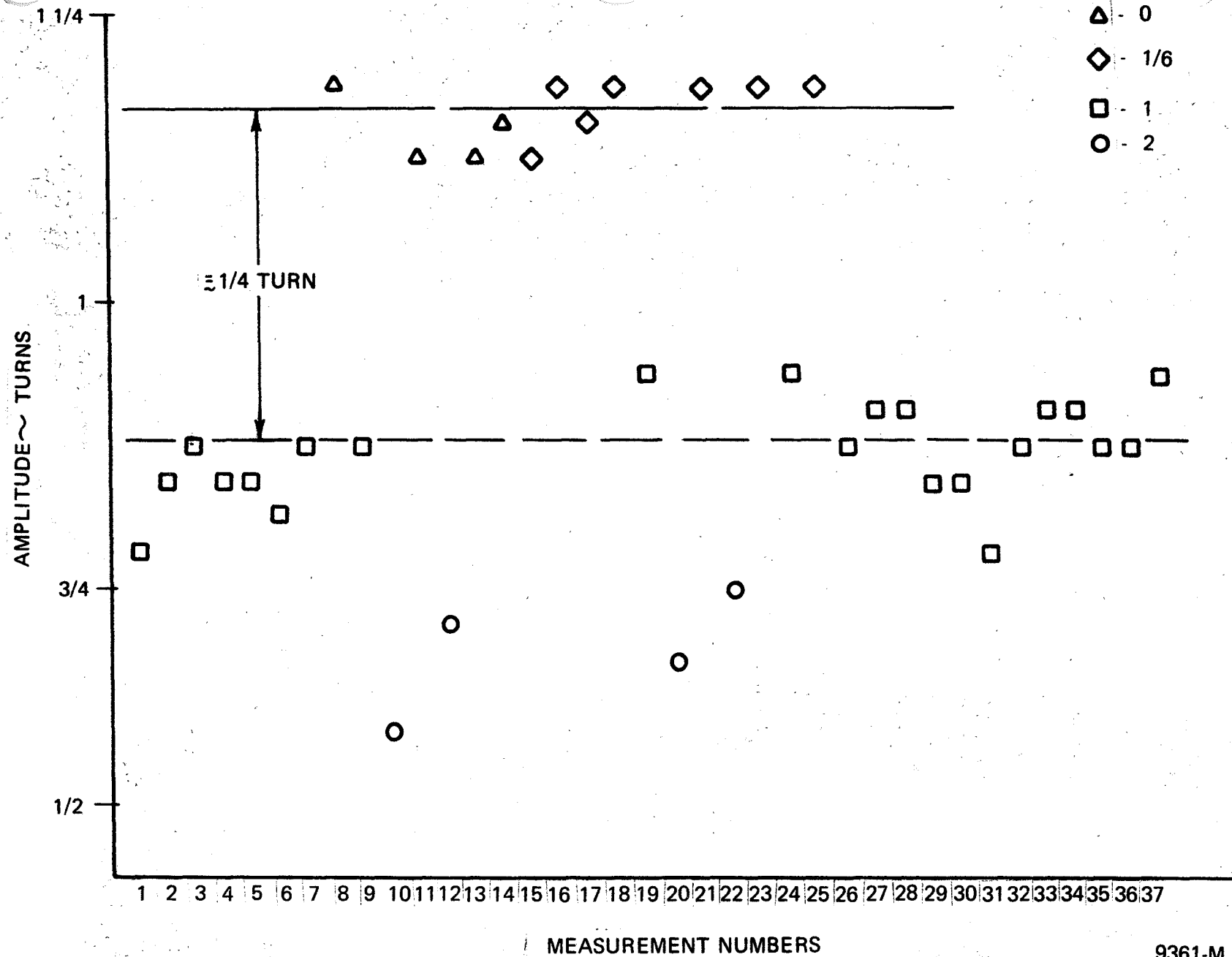


Figure 2.7.5



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The amplitude of the first few 1g measurements are much lower than later measurements as they were made prior to engine start in an airplane that had cold soaked overnight in subfreezing weather (the airplane was deiced with ethylene glycol prior to its morning takeoff). As the airplane interior warmed up the amplitude measurements followed the characteristic temperature curve of Figure 2.5.1. The scatter of the subsequent measurements is attributed to non-repeatability of test conditions due to the airplane environment as discussed above.

2.8 Summary

A study of the data presented in this section resulted in establishing the production watch movement mainspring torque specification as depicted in Figure 2.8.1. Each movement is tested during the timer acceptance test procedure to verify that balance wheel amplitude is one turn plus or minus $1/4$ turn at any point on the runout curve. A worst case summary of the environmental effects on balance wheel amplitude is presented in Figure 2.8.2. It should be noted that, although not expressed in the mainspring torque specification, there is a characteristic reduction in torque as the timer runs out. Therefore the worst case conditions as presented apply only to the period immediately following the start of the watch movements.

The conditions presented in Figure 2.8.2 demonstrate that a timer watch movement having the basic mainspring torque characteristics indicated will barely approach the overbank threshold under worst case hot conditions on the lunar surface and will perform satisfactorily under worst case cold conditions anticipated during earth testing. It is only when failure modes are introduced that overbanking can finally be induced.

The key design feature, which must be carefully incorporated into the production timers in order to avoid a failure mode which would result in overbanking on the moon is the maintenance of pressure within the control module cavity which houses the watch movement. An equivalent increase in amplitude of $3/8$ to $1/2$ turn beyond the overbanking threshold is avoided by maintaining pressure at as low a value as 1 torr.

The other failure mode to be considered is the tipping over of an explosive package on its side so as to cause the position of one watch movement to change from "on edge" to "flat". As previously discussed, the increase in amplitude as a result of this change in position is to the order of

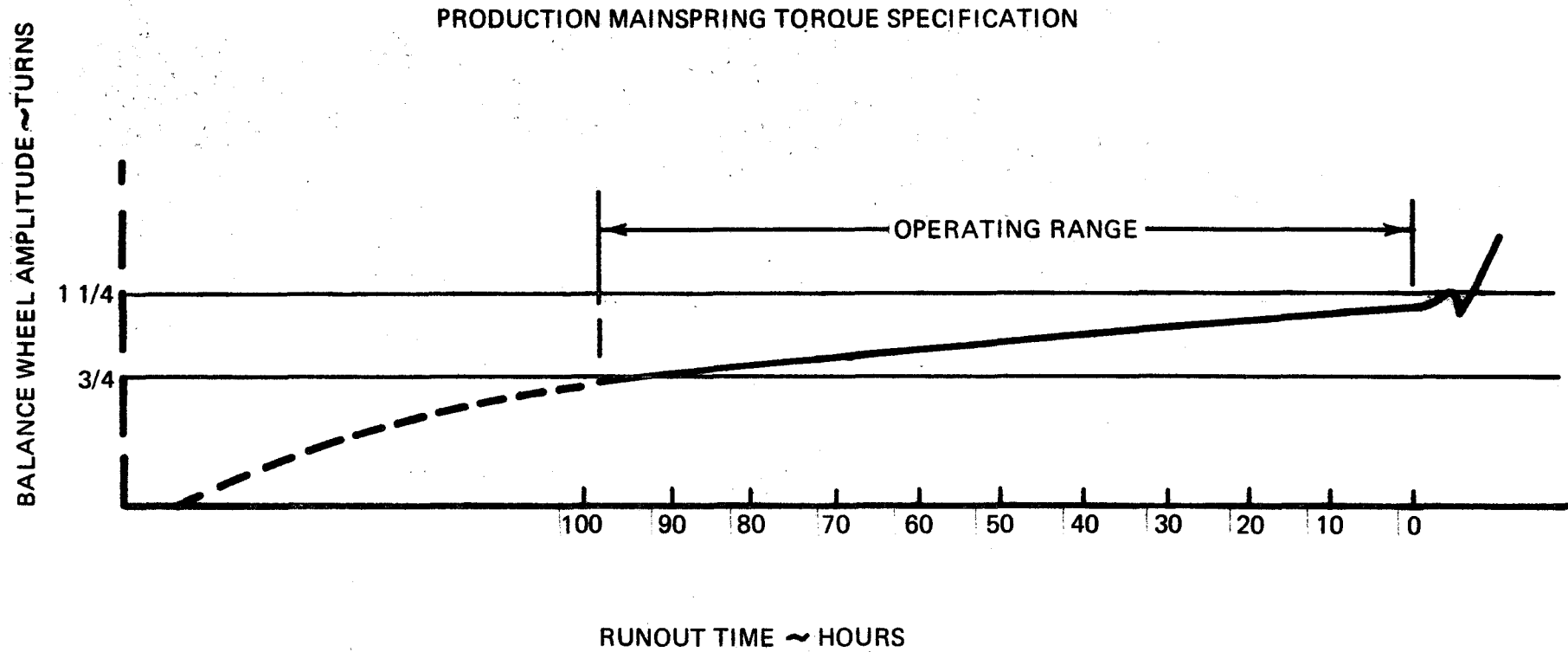


Figure 2.8.1

9361-M

SUMMARY — ENVIRONMENTAL EFFECTS ON BALANCE WHEEL AMPLITUDE

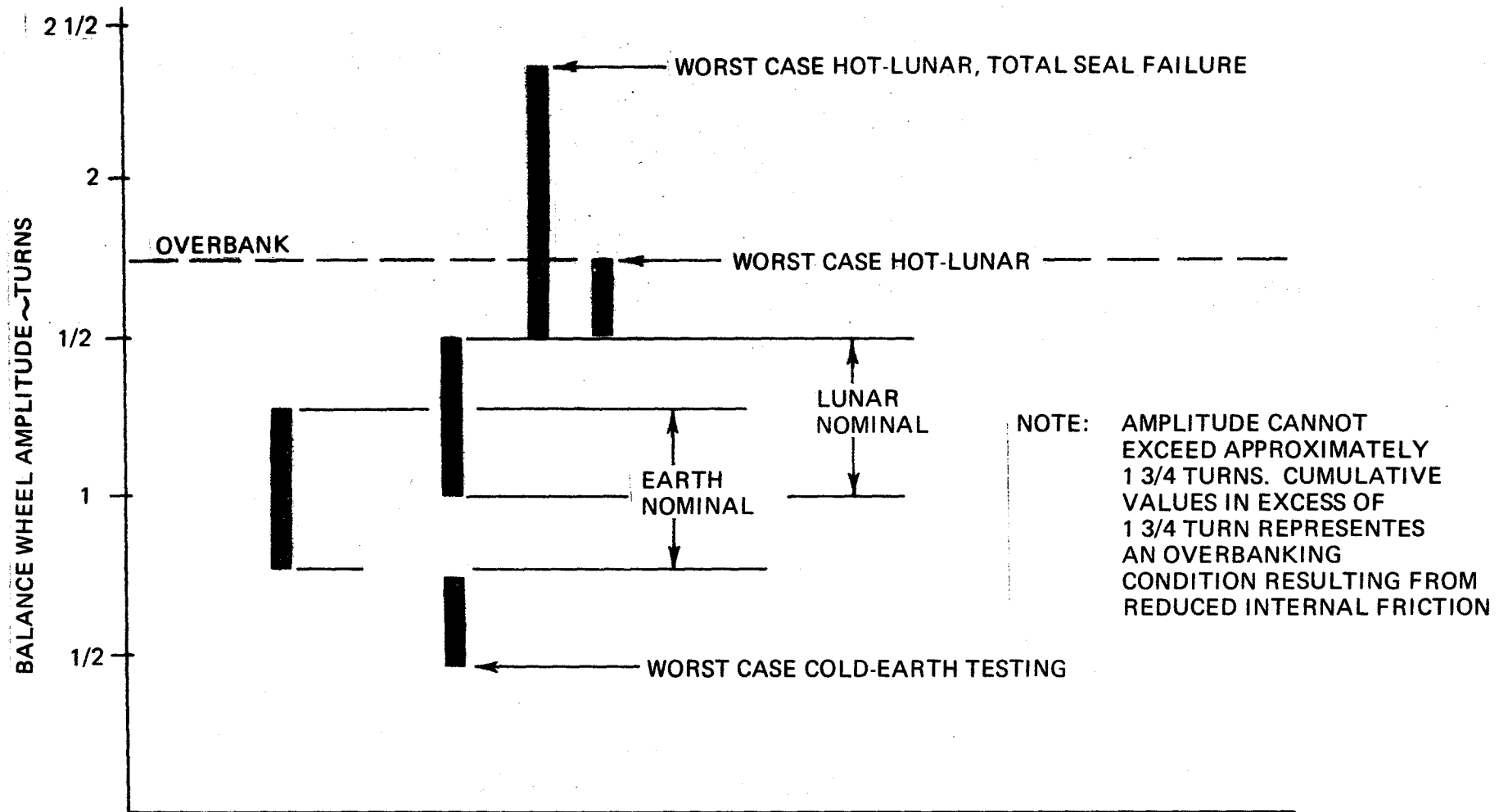


Figure 2.8.2



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+1/4 turn. However, it is debatable whether or not an increase of this magnitude would occur on the Moon in addition to the increase attributed to the lunar gravity field for the same basic mechanism is at work in response to either condition; a reduction in internal friction as a result of unloading the balance wheel pivot bearings.

With no data available to verify an alternate approach, it cannot be assumed that the gravity effect and position error are not cumulative. On the other hand, the relative positions of the two timers in the explosive packages on perpendicular planes assures that only one timer will overbank as a result of position change if both timers were at the overbank threshold before the package tipped over. With an error induced in only one timer as the result of overbanking, the error will either be large enough to cause a misalignment of the firing window; i. e., the battery timer will actuate at a point in time when the safe/arm slide is not in the arm position, or it will not and a normal firing sequence will occur. In neither case is there any affect on astronaut safety or on the performance of the remaining explosive packages.

In summary:

1. The LSP Timers are likely to overbank as they approach predicted worst case hot conditions on the lunar surface but only if a control module seal failure has caused the control module internal pressure to fall below the 1 torr range.
2. Tipping over an explosive package on the lunar surface may have no effect at all on balance wheel amplitude. At worst, the effect can be applied to only one of the two timers in each explosive package.
3. The maximum equivalent balance wheel amplitude which may be attained under cumulative worst case conditions simultaneously in both timers is to the order of $2 \frac{3}{8}$ turns.



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2.9 Instrumentation Notes

Traditionally, balance wheel amplitude is measured visually to an accuracy of $1/8$ turn. Production measuring instruments have become available in recent years which, although relying on a skilled watchmaker to perform the initial calibration, permit measurements to be made by relatively unskilled assemblers. As originally conceived, the tests described in this report were to utilize visual observation to determine balance wheel amplitude under the various conditions investigated.

As this method was patently impossible in the centrifuge tests, Bulova proposed to adopt a fiber optic instrumentation setup originally developed for a fuze-timing requirements. The technique utilized was to scribe equally spaced radial scribe marks on the balance wheel and to detect the passage of each scribe mark past a light beam as a change in the intensity of light reflected into a photo cell. The number of voltage "blips" generated on a strip chart recorder during each oscillation of the balance wheel could then be counted as the number of scribe lines that had passed a fixed point, from which the amplitude could be simply calculated.

This method was quite successful on the centrifuge tests even though the electronics portion of the system, optimized for the fuze-timing requirements, was not quite up to expectations. In searching for an instrumentation approach for the C-135A tests, it was decided to redesign the fiberoptics into a three-channel system to measure three watch movements simultaneously and to optimize the electronics for watch measurements. This was done in minimum time and the system performed in an outstanding manner from the first time it was powered up.

Again, when it turned out that visual measurements of balance wheel amplitude through several layers of glass in the thermal-vacuum chamber were completely unreliable, the fiber-optic system was adapted from the C-135A configuration, and all thermal-vacuum tests were repeated using this system with equal success. As a result, all balance wheel amplitude data presented in this report were recorded with fiber-optic instrumentation except for the Lewis Research Center drop tests, which were recorded on motion picture film.

The test installation in the C-135A is shown in Figure 2.9.1. A sequence of photographs taken during the free fall test are shown in Figure 2.9.2.

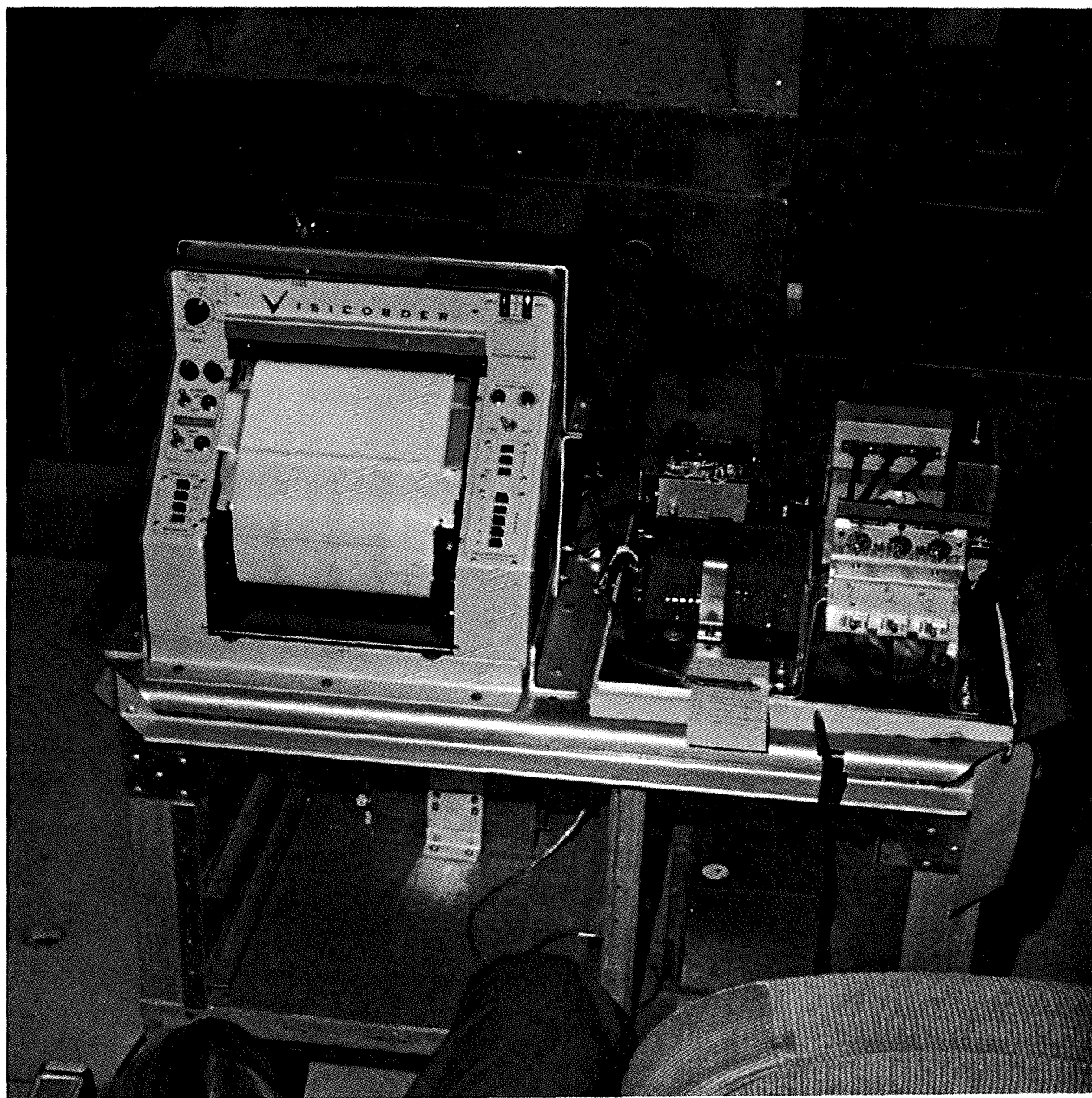
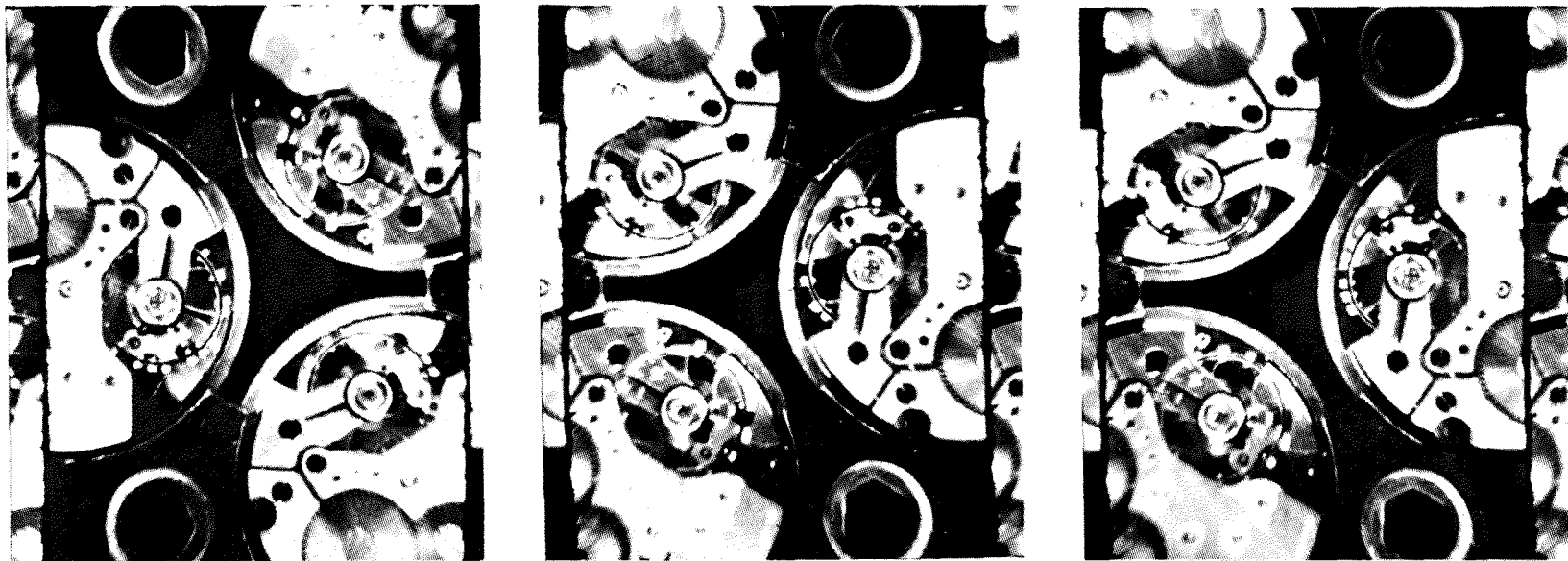


Figure 2.9.1 C-135A Test Setup

FILM SEQUENCE
LEWIS RESEARCH CENTER DROP TESTS



- FRAME RATE - 400/SEC
- APPROXIMATELY 2 SECONDS AFTER RELEASE

Figure 2.9.2



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The centrifuge test utilized a balance wheel with 72 scribe lines; i. e., every five degrees. In order to avoid the anticipated problem of having to change paper rolls in the strip chart recorder in flight, the C-135A tests were conducted with balance wheels with 32 scribe lines; i. e., every 11.5 degrees. This proved to be a poor choice as test technique developed during the tests minimized paper usage and made the loss of accuracy unnecessary. Balance wheels with 72 scribe lines were used again during the thermal vacuum tests and are considered to be the optimum value to be used under all conditions if tests of this nature are to be performed again in the future.

The motion picture camera used in the drop tests ran at 400 frames per second. Each frame was projected and measurements carefully made around the point of change of direction to establish the amplitude of each oscillation recorded. Although these measurements are extremely accurate, they are also, by far, the most laboriously acquired data in the investigation.



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3.0 PREDICTION OF WORST CASE ERROR

Having determined that overbanking may occur on the moon under certain worst case conditions, it becomes mandatory to determine the effect of the resulting timing error on the safety of the astronauts and on the probability of success of the experiment. The lack of reliable data or experience to predict the error rate as the result of overbanking resulted originally in the cautiously conservative position that the rate could be several times greater than normal, which raised the spectro of timers running out prior to the departure of the astronauts from the moon. This was the basis for categorizing the potential hazard as "Safety Catastrophic".

The following approach was taken to develop some understanding of the effect of overbanking on the accuracy of the timers and a method of relating this to the conditions which could presumably cause overbanking on the moon. If a watch could be overbanked under controlled conditions, the resulting change in rate could be measured. By varying the controlled condition a curve could be constructed of error as a function of overbank from which reliable predictions could be made.

This was accomplished by the use of an existing Bulova test fixture to apply a known torque to the mainspring barrel of a test watch movement and by measuring the resulting change in rate, or error, against a stop watch. The torque was varied by hanging a series of calibrated weights from a cable and pulley arrangement on the test fixture. By applying increasingly heavier weights, torques greatly in excess of that developed by the mainspring were applied to the mainspring barrel to cause overbanking over a range of values. The results of one test with the watch in two positions is presented in Figure 3.0.1.

On the left side of Figure 3.0.1, it may be seen that the application of a known torque to a fully wound down mainspring barrel resulted in the winding of the barrel to a point of equilibrium at which a certain balance wheel amplitude was attained. As the torque was increased incrementally, the barrel would up further and the amplitude increased in a predictable manner. When the barrel was fully wound the amplitude continued to increase as a function of applied torque until the maximum amplitude was attained and the balance wheel overbanked. Up to this point there was no timing error measurable with the stop watch.

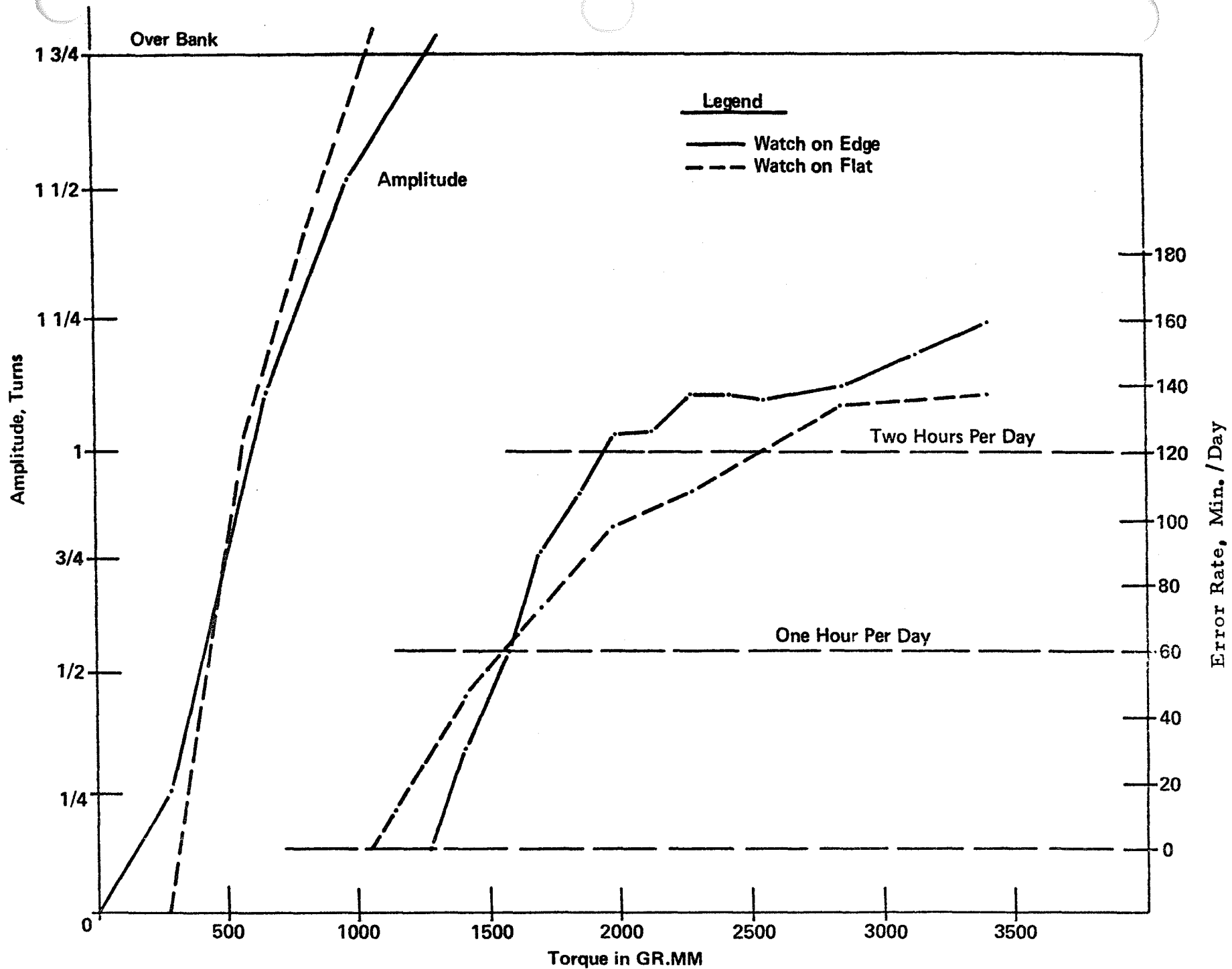


FIGURE 3.0.1

Amplitude and Error Rate vs Torque



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The curve continues on the right side of the figure but now, with the maximum amplitude attained and the watch running overbanked, the error rate becomes the dependent variable. Figure 3.0.2 repeats this portion of the curve and presents similar results for two other test specimens.

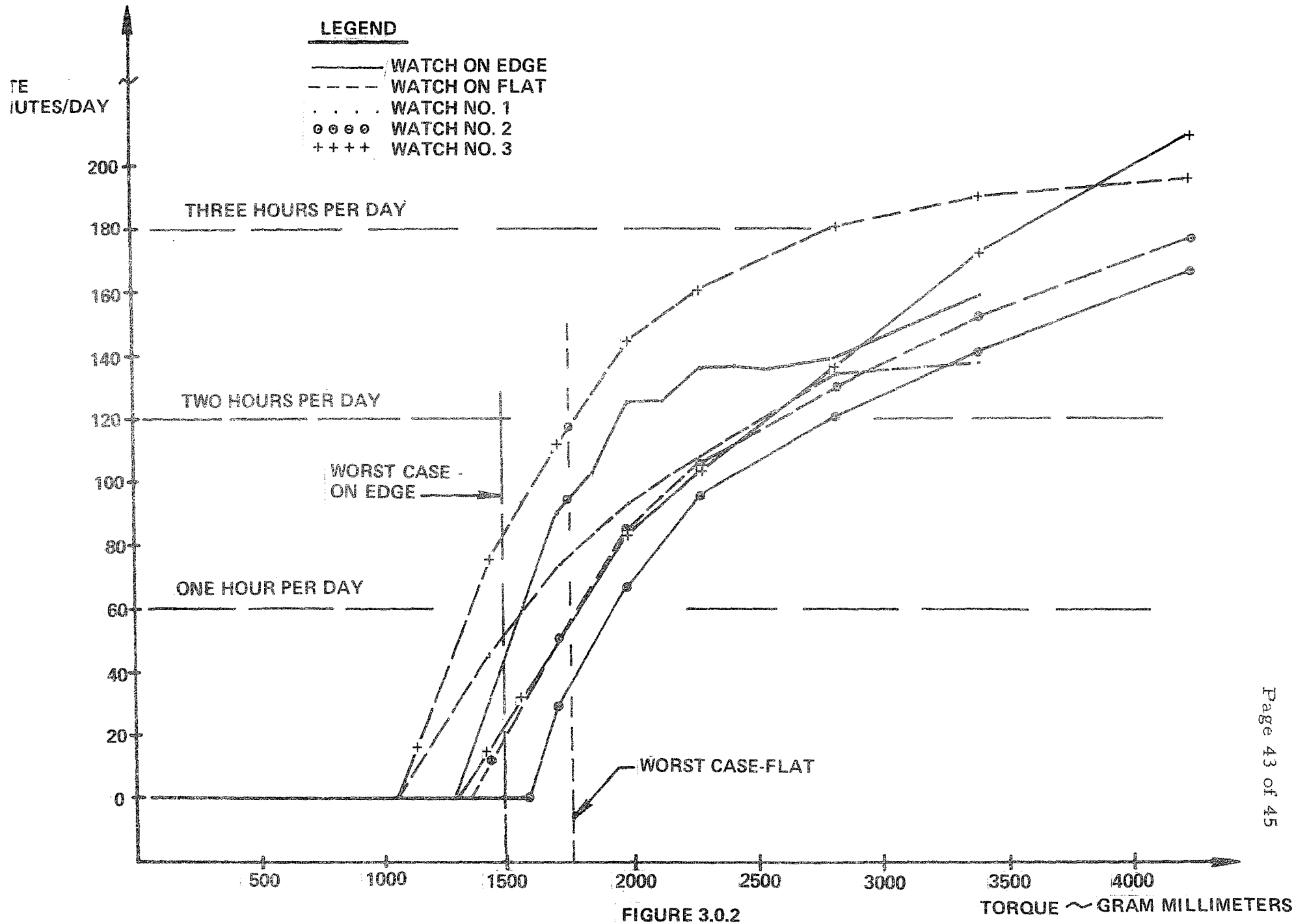
Although the timer vs. torque function is an approximate straight line, error vs. torque displays exponential characteristics. This indicates an absolute limit on the operating rate of the escapement which, once achieved, is independent of available torque.

The worst case error curve of Figure 3.0.2 was combined with a straight line approximation from Figure 3.0.1 to develop the general worst case curve presented in Figure 3.0.3. In order to maintain a continuity across the overbanking line which would relate the two portions of the curve in a manner useful to this investigation, a construction was performed as indicated. The linear slope (one turn per 600 grammillimeters of torque) was utilized to scale off values of equivalent amplitude equal to values of error rate. It now becomes a simple matter to equate error rates to equivalent amplitudes in the overbanking range by simply reading across the curve.

It may be demonstrated, as a matter of interest, that the general worst curve as finally established by interpretation of test data, closely approximates the exponential curve, $y = k - ke^{-kx}$. It should also be noted that the worst case establishing the curve is for a watch movement "on flat" rather than "on edge", which provides an additional reason for ignoring the effect of a tipped over explosive package on amplitude; i. e., the effect is factored in automatically by use of the worst case curve.

Referring back to Figure 2.8.2, it is predicted that the equivalent balance wheel amplitude under worst case hot temperature conditions and with a total seal failure which would create hard vacuum conditions within the control module housing is $2 \frac{3}{8}$ turns. Referring to Figure 3.0.3 and reading across from $2 \frac{3}{8}$ turns, it is indicated that the timer error rate under these conditions is 70 minutes per day or 4 hours and 40 minutes over a nominal 4 day mission. However, this assumes that the characteristic mainspring torque curve maintains a maximum value throughout the mission. This is contrary to the facts which have been demonstrated during this investigation (Figures 2.1.2 and 2.2.1) and during the acceptance tests which have been conducted on timers delivered to date.

ERROR RATE VS TORQUE



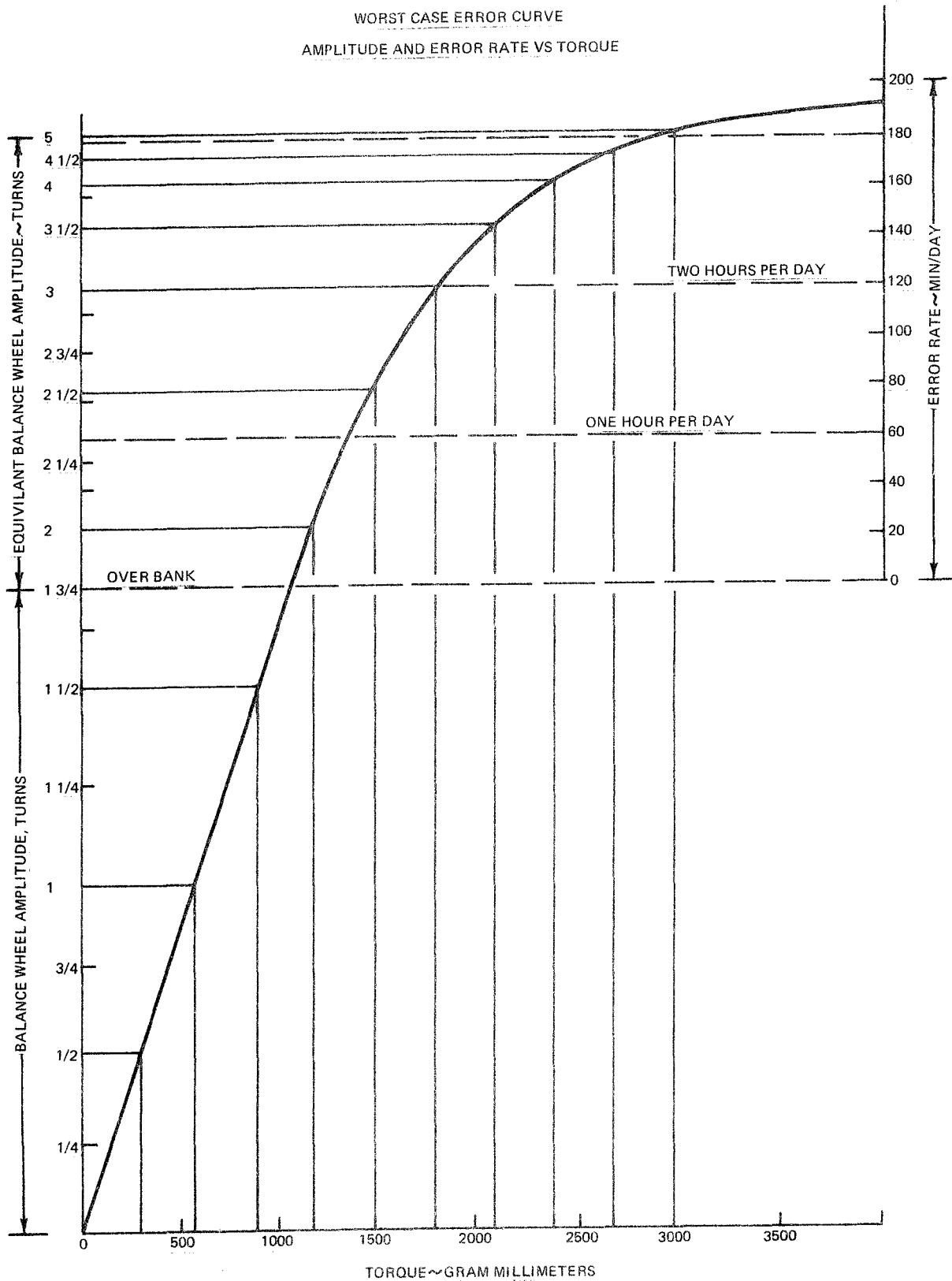


Figure 3.0.3



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It is more reasonable to assume that, if starting at a maximum value of $1 \frac{1}{4}$ turns, the torque curve will degrade linearly to one turn by the time the timer runs out. Therefore, the average worst case

equivalent amplitude would be $\frac{2 \frac{3}{8} + 2 \frac{1}{8}}{2} = 2 \frac{1}{4}$ turns, or a total

error of 3 hours and 20 minutes over a nominal 4 day mission. This is approximately 10% of the 30 hour safety margin added to the contingency launch time of the LM and is not significant from the safety viewpoint. On this basis the original "Safety Catastrophic" classification of the over-banking problem is reduced to "Safety Negligible".