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YAWSONDE DATA FOR M687-TYPE PROJECTILES WITH APPLICATION TO RAPID SPIN DECAY AND STEWARTSON-TYPE SPIN-UP INSTABILITIES

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June 1980

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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Specially prepared M687 projectiles were tested at Wallops Island, Virginia, on 28 September 1977 and 3 May 1978. Yawsonde data were obtained for all flights. The payload canisters were one piece cylinders of M687-type except that several of the canisters had heights that were non-standard. In an attempt to reproduce previously observed anomalous despin effects for M687 shell at shot exit, several types of liquids with fill ratios of 90 or 100% were tested at yaw levels up to ten degrees. The raw data from the projectiles tested did not indicate anomalous effects at shot exit, and these effects have only been observed when

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20. simulant-loaded binary canisters with burst discs were employed. It is most probable that the burst discs precipitate the anomalous spin behavior. Yawsonde data were also obtained for a 100% filled canister whose height was selected to produce a Stewartson-type instability during liquid spin-up. The flight data from one unstable round was consistent with computations of spin-up eigenfrequencies from recently developed methods.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

I. INTRODUCTION

The 155mm M687 binary projectile is shown in Figure 1. This projectile carries a liquid payload in two cylindrical canisters that are partially filled (approximately 90% of the available volume) and are separated by a pair of burst discs (as shown in Figure 1). During a flight stability investigation centered about the parent projectile, the M483A1, anomalous spin histories were noted for the M687[1]. In some instances rapid decreases in spin were observed at shot exit. For unstable flights, substantial losses in spin accompanied large angular motion. Analytical methods treating the stability of liquid-filled shell and liquid spin-up strictly apply to a single canister without burst discs. To provide for a comparison of theory and flight data, special M687 canisters are used. This report provides flight data for single canisters with fill ratios of 90 and 100%. A qualitative examination of the data show only smooth spin decays at shot exit, although the oscillatory nature of the spin records make such an examination difficult. Since non-smooth or anomalous histories were only observed when burst discs were employed, it is most likely that the burst discs produced the rapid despin effects observed at shot exit. A quantitive evaluation of the spin histories would be required, however, for final evaluation. Heretofore, yawsonde data for Stewartson-like spin-up instabilities were not available. For a fill ratio of 100%, a canister aspect ratio was selected by heuristic methods to produce an unstable flight. Three projectiles were tested and one unstable flight occurred. The yawsonde data were compared with results from a recently developed spin-up eigenfrequency code. The computer predictions and the flight data were consistent for this single case. The effects of large angular motion and rapidly decreasing spin during the terminal portions of the trajectory of liquid-filled shell are not addressed in this report.

II. BACKGROUND

The yawsonde allows an excellent method for tracing the flight of a projectile.[2] The angular and spin motion of a projectile is recorded. The projectile motion is presented in terms of Sigma N and Phi Dot versus time. Sigma N is the complement of the angle between a vector drawn to the sun and a vector aligned with spin axis of the projectile, while Phi Dot is the derivative of the projectile's Eulerian roll angle with respect to the sun plane, i.e., the plane containing the missile's axis

1. *W.P. D'Amico, V. Oskay, W.H. Clay, "Flight Tests of the 155mm XM687 Binary Projectile and Associated Design Modifications Prior to the Nicolet Winter Test 1974-1975," Ballistic Research Laboratory Memorandum Report No. 2748, May 1977. AD B0199690.*

2. *W. Mermagen and W. Clay, "The Design of a Second Generation Yawsonde," Ballistic Research Laboratories Memorandum Report No. 2368, April 1974. AD 780064.*

and the sun. For cases of large angular motion, the oscillatory nature of Phi Dot does not allow an easy interpretation of spin[3]. A proper reduction for Phi Dot is outlined in Reference 3, but the data within this report do not incorporate the methods of Reference 3. Hence the spin data are labeled Phi Dot (Raw).

Figures 2 and 3 are extracted from Reference 1 and show the yaw and spin histories of an XM687 (1/2 caliber boattail) that was launched with induced yaw. Figure 3 clearly shows a rapid decay in spin at shot exit and that is the only type of spin decay that will be considered within this report. A decay of 3 rps was evidenced in a little more than 1 second. One would expect a spin decay during the initial stages of flight as the projectile spins up the liquid. A substantial amount of work on the spin decay of liquid-filled projectiles has been accomplished by Kitchens and Gerber.[4] Figure 2 shows a rapid growth in yaw. This is produced by the large induced motion and is not solely produced by the liquid payload. Only a limited amount of yawsonde data have previously been recorded for bulk-filled liquid instabilities.[5] Also, these data are for fill ratios of 80 to 90% and do not provide a good comparison with recently developed theories for spin-up in completely filled cylinders.

A short review of the circumstances for non-smooth spin histories follows. First, non-smooth spin behavior is not peculiar to the M687. Flight data from the 8-inch XM736 binary projectile have also exhibited such behavior. Figures 5 and 6, Round 1184, show yawsonde data indicating a non-smooth spin decay, while Figures 7 and 8, Round 1183, show data for a smooth case. Note that the FMA* value for Round 1184 was greater than that of Round 1183. Hence, projectile yaw must be considered in an explanation of rapid spin decay. Second, there is a possibility that the double-walled cylinder of the M687 could slip. The M687 has an inner plastic canister that is supported by an outer metal canister. The canisters are not pinned to each other, but the metal

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3. *C.H. Murphy, "Effect of Large High-Frequency Angular Motion of a Shell on the Analysis of Its Yawsonde Records," Ballistic Research Laboratories Memorandum Report No. 2591, February 1976. AD B009421L.*

4. *C.W. Kitchens, Jr. and N. Gerber, "Prediction of Spin-Decay of Liquid-Filled Projectiles," Ballistic Research Laboratory Report No. 1996, July 1977. AD A043275.*

5. *A. Mark and W.H. Mermagen, "Measurement of Spin Decay and Instability of Liquid-Filled Shell via Telemetry," Ballistic Research Laboratories Memorandum Report No. 2333, October 1973. AD 771919.*

**The first maximum amplitude (FMA) is half the largest excursion in Sigma N first recorded, is a measure of the launch disturbance received by a projectile, and is used as an estimate to the first maximum angle of yaw.*

canister is keyed to the projectile body. The XM736, on the other hand, does not utilize an inner canister. From a spin history, the reduction in spin can be translated into an angular momentum decrement. Appendix I examines the observed decrements in spin and compares the associated angular momentum loss to computed values of angular momentum decrements for liquid spin-up and/or canister slippage. Good agreement is obtained if it is assumed that the spin decrement is produced by the liquid, while poor agreement is found if one assumes that the plastic liner and the liquid or the entire canister and the liquid slip. Hence, it seems most likely that anomalous spin effects are a result of an angular momentum exchange between the rigid parts of the projectile and the liquid payload. Slippage of canisters produces angular momentum decrements that are too large for the observed spin losses.

III. TEST FIRINGS

A. Instrumentation

Test firings were conducted at Wallops Island, Virginia, on 28 September 1977 and 3 May 1978. Figure 9 is a sketch of the launch area, which was located at PAD 2. A time-position radar and a break wire time zero system were operated by Wallops Island personnel. A muzzle chronograph and a ground receiving station were set-up and manned by ARRADCOM personnel. Main base telemetry from Wallops Station (approximately ten miles from the launch site) also monitored the yawsondes, but only the data from the mobile site were reduced. A fixed position sleigh was mounted with an M185 155mm tube, and yaw induction was produced by the use of a modified muzzle brake described in Reference 1. Yaw levels of 10 degrees or more were expected.

B. Hardware Description

Standard metal parts from M687 projectiles were used for this test, but special single piece canisters without burst discs were fabricated by the Chemical Systems Laboratory (CSL).* The canister materials were identical to those used in the production of standard M687 binary canisters. Three canister lengths were used, however. Short, regular, and long canister heights were employed, and these shell will be termed M687/S, M687/R, and M687/L, respectively. The M687/S and M687/R shell employed 1/4 caliber boattails, while the M687/L shell used 1/2 caliber boattails. Since the M687/L canister length was selected for unstable liquid payload behavior, half-caliber boattails were used so that aerodynamic damping would not overcome any yaw growth. In order to

The authors are indebted to Mr. W. Dee and Mr. N. Surratt for these specially modified M687 projectiles.

accurately determine the interior dimensions of the plastic canisters, measurements of interior length and mass were made prior to filling. The canisters were then filled and weighed, and an average interior diameter was computed. Three projectiles with solid payloads were also fired to determine aerodynamic spin damping. Two M687 projectiles were fitted with lexan slugs to simulate the fluid when it is in a state of rigid body rotation. These projectiles (M687-SLUG) and an M483 projectile were fired on 28 September 1977. A round-by-round summary and projectile physical measurements are provided in Tables 1 and 2, respectively. Table 3 lists the various liquids and fill ratios for the canisters and FMA values. Table 4 contains the interior dimensions of all canister types.

C. Yawsonde Data For 28 September 1977

Table 3 lists the M687/R projectiles in order of firing. The first projectile, E1-9188, was launched with yaw induction. This water-filled projectile was fired near the opening of the firing window and part of the large initial motion was beyond the view of the attitude sensors. An FMA greater than 10 degrees was achieved as seen in Figure 10. The associated spin history is shown in Figure 11. A time base error due to a faulty tape recorder drive is evidenced in Figure 11. Although the effects of the large amplitude motion on the spin are evident, no rapid spin decay at shot exit was measured. The spin history was typical for an M687. E1-9189, filled with silicon oil, was fired with an FMA of greater than 10 degrees and was also close to the edge of the firing window, as seen in Figure 12. Data for the initial motion was lost between 1 and 4 seconds when the sun was obscured by a cloud. The spin data in Figure 13 were also of a smooth nature. E1-9190 was loaded with silicon oil and was launched with yaw induction. The data (Figures 14 and 15) were of good quality, and behavior similar to E1-9189 was observed. An FMA of 13 degrees was achieved. Subsequent M687/R shell were launched with the standard muzzle brake removed to produce lower than normal launch yaws. E1-9191 was filled with water and had an FMA of 3 degrees (Figure 16). The spin data in Figure 17 exhibited a smooth decay for the entire trajectory. Figures 18 and 19 provide the solar angle data and spin history for E1-9192 which was also filled with water. The data for E1-9191 and E1-9192 are essentially the same. E1-9193 was filled with Freon E2. A launch yaw of 3 degrees resulted, and a slight growth in the fast mode yaw component occurred at 5 seconds. This behavior damped by 15 seconds, and by 20 seconds the anticipated limit cycle behavior returned with no further unusual behavior noted. The cause of this fast mode growth is unknown, but it could be caused by the liquid payload or by a Mach number dependent, nonlinear, small yaw effect. The spin history of E1-9193 is shown in Figure 21 and was smooth. E1-9194 was also filled with Freon E2, but no unusual angular motion was observed. Solar angle and spin data (Figures 22 and 23) were quite typical for an M687.

The last three rounds of this portion of the program were fired to obtain supersonic spin damping data and did not contain liquid payloads. A standard muzzle brake was employed for all three projectiles. Due to very low level clouds in the vicinity of the launch area, an M483 projectile was fired to determine the quality of data that would be obtained. An examination of the M483 data at the mobile telemetry van indicated that the clouds did not affect the quality of the data and the firing sequence was continued. E1-9195, an M483 (1/2 caliber boattail), was launched at Charge 7 and exhibited only a very small FMA level (Figure 24). Good data were received for 65 seconds of flight with Figure 25 providing the final seconds of the solar angle history. The spin data are shown in Figures 26 and 27. The last two rounds were the M687-SLUG projectiles, E1-9196 and E1-9197. E1-9196 was launched with an FMA value of 3 degrees, and the solar angle data are shown in Figures 28 and 29. Spin data are shown in Figures 30 and 31. E1-9197 was launched with very little initial motion and provided good clean data for more than 60 seconds (Figure 32 and 33). The associated spin histories are shown in Figures 34 and 35.

D. Yawsonde Data For 3 May 1978

Three M687/S projectiles were loaded with water and launched with a standard muzzle brake. Two of these shell had canisters that were filled to 100%, E1-9383 and E1-9384. Data are shown in Figures 36-39. The projectile motion was characterized by a slow mode limit cycle and a smooth spin history. E1-9385 was filled to 90%, but the yawsonde data (Figures 40-41) show qualitatively the same behavior as the two 100% filled rounds. Next, three M687/L projectiles were tested. The launch Mach numbers of these three shell were selected for lowest gyroscopic stability so that adverse liquid payload effects would not be overshadowed by aeroballistic damping. E1-9386 showed no unusual behavior in either yaw or spin (Figures 42 and 43). The next projectile, E1-9387, was unstable. The quality of the yawsonde data was excellent in that the optical sensors of the yawsonde were always in view of the sun and the motion of the projectile was traced to a peak-to-peak envelope of 120 degrees (Figure 44). The FMA was less than one degree with a precessional limit cycle dominating the motion for the first 7 seconds. At 7 seconds the fast mode became unstable and by 10 seconds the peak-to-peak motion was 13 degrees. The fast mode motion continued to grow and by 11 seconds dominated the motion. At 15 seconds the yawing motion broke into a new behavior which was characterized by very large amplitude double mode motion. The spin history, shown in Figure 45, was smooth until 12 seconds where an unexpected and unexplained increase in spin occurred. Behavior such as this was also observed for XM687 projectiles during the Nicolet winter test of 1974-1975.*

**Private communication, William H. Mermagen.*

At 15 seconds a strong coupling between the spin and yaw was observed. The next M687/L projectile, E1-9388, had only one operable optical sensor, hence only spin data are available (Figure 46). No unusual effects were noted. The final two projectiles were M687/R shell and were filled with water to 90%. Both shell were launched with yaw induction. E1-9389 had an FMA of 12.5 degrees, while E1-9390 had a value of 12.0 degrees. The yawing histories for these projectiles were quite different, however. E1-9389 had essentially a constant amplitude of yawing motion for the entire trajectory. By 5 seconds, the slow mode was damped and the fast mode had a peak-to-peak amplitude of 16 degrees. This type of motion persisted with a slight growth in amplitude to 18 degrees by 20 seconds. Towards the latter half of the flight the telemetry quality was poor and data were lost. On the other hand, Figure 49 shows the solar angle history for E1-9390. These data are dominated by a slow mode limit cycle (M483-like behavior). The spin histories for both of these rounds (Figures 48 and 50) showed no rapid spin down. The slight decrease in spin exhibited in Figure 48 at 17 seconds is probably the same type of phenomenon that occurred in Figure 45 (E1-9387). The spin histories for E1-9387 and E1-9389 have been re-reduced and no operational errors were found.

IV. DISCUSSION

All of the spin histories from projectiles fired during the 28 September 1977 and 3 May 1978 programs were of the smooth type, even under the conditions of large initial motion. All of the canisters were single cylinders and filled to either 90 or 100%. An examination of all M687-type shell indicated that non-smooth spin histories were associated only with projectiles that carried partially filled, tandem canisters separated by burst discs.[6,7] The burst discs and the debris produced by rupture could create conditions that are not suitable for laminar spin-up of the liquid. Kitchens and Sedney have conjectured that the rapid despin at shot exit is produced by a transition to a cellular flow similar to the type commonly found between counter rotating cylinders. This type of flow generates a larger shearing stress at the vertical wall of the cylinder than is normally found during laminar spin-up, hence a rapid spin down of the projectile would occur. This conjecture does not incorporate free surface effects nor does it provide for the presence of burst discs and any resulting debris. However, a qualitative examination of the flight data can not positively determine whether a spin history was smooth or non-smooth. Methods

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6. *C.W. Kitchens, Jr. and R. Sedney, "Conjecture for Anomalous Spin Decay of the 155mm Binary Shell (XM687)," Ballistic Research Laboratories Report 2026, October 1977. AD A050311.*

7. *W.P. D'Amico, "An Investigation of the Flight Vibration Environment of the 155mm M687-IVA Projectile," Ballistic Research Laboratories Memorandum Report 2755, June 1977. AD B019792L.*

such as those employed by Mark where the angular momentum history of the liquid is calculated from the yawsonde, trajectory, and meteorological data could be used to objectively characterize the spin histories.[8] Such a procedure is long and involved and will not be accomplished within this data report. However, an examination of all data sources strongly suggests that the presence of burst discs are required for rapid spin decay of M687 shell at very small Ekman numbers.* A correlation developed by Kitchens and Sedney for smooth versus non-smooth spin histories is not consistent with data presented within this report. For larger Ekman numbers, however, the conjecture of Kitchens and Sedney or similar types of fluid dynamical models could be applicable. During the testing of very large viscosity liquids a rapid despin at shot exit may have occurred. The amplitude modulation of the spin data and the quality of the telemetry transmission do not allow for a clear determination of the character of the spin history, however.[9] This particular projectile was a 155mm shell and carried a single piece steel canister completely filled with glycerol. An FMA of 12 degrees was achieved and the Ekman number was 4.45×10^{-4}, which is within the range of the Ekman numbers discussed within this report.

Much of the recent flight experience with liquid-filled shell has been with binary-type payloads. These payloads have rupture discs and fill ratios of less than 100% and can not readily compare with theories for 100% filled, clear cylinders. To provide yawsonde data that can be compared with new analyses for flight instabilities during spin-up, a non-standard M687 canister length was selected. Table 4 lists the various types of canister geometries and aspect ratios that have been tested. Figure 51 shows a summary of M687 early flight experience and indicates that unstable conditions for this configuration are most probable at a fill ratio of 80%. The rationale for selection of the unstable canister height follows. The mechanism by which the liquid payload destabilized the projectile motion is rather simple in concept. If a natural frequency of oscillation of the liquid (an eigenfrequency) is approximately equal to the nutational frequency of the projectile,

8. A Mark, "Measurements of Angular Momentum Transfer in Liquid-Filled Projectiles," Technical Report ARBRL-TR-2029, November 1977. AD A051056.

9. W.P. D'Amico, W.H. Clay, and A Mark, "Diagnostic Tests for Wick-Type Payloads and High Viscosity Liquids," Ballistic Research Laboratory Memorandum Report ARBRL-MR-02913, April 1979. AD A072812.

* Reference 8 uses a Reynolds number ($Re = \Gamma a^2/\nu$). An Ekman number (E) is commonly used for rotating flows. For the case where both Re and E use an identical characteristic length, then $E = 1/(Re)$.

a resonant condition is established; and a wave motion occurs within the liquid. The resulting pressures from this wave motion (not a sloshing motion since the rotational forces are much larger than body forces) produce a destabilizing couple on the projectile. The non-dimensional nutational frequency, τ_{NU}, of the projectile can be determined directly from the yawsonde data by dividing the faster yawing frequency of motion (from the SIGMA N data) by the local spin frequency (from the PHI DOT data). The Stewartson[10] solution for the non-dimensional eigenfrequencies considers an inviscid fluid that is in rigid body rotation. The analysis of the wave motion indicates a three dimensional structure r, θ, z with mode numbers n, m, j. For the case of a projectile instability m=1, and the notation is collapsed to only n and j with m=1 being understood. It is necessary to determine which combination of n and j, i.e., which mode, produces the poor flight behavior of E1-9387.

Experience with liquid-filled gyroscopes has indicated that the disturbances produced by higher mode numbers are substantially damped by viscosity. Hence, for practical purposes only combinations of n=1 and j=0, 1, 2, 3 are important. Table 5 provides a portion of the Stewartson tables for n=1 and lists the relationship between the eigenfrequencies, τ_{1j}, and the aspect ratio, (c/a)/(2j+1). The j=0 and j=1 modes will not produce resonant conditions since they are associated with eigenfrequencies that are much larger than the non-dimensional nutational frequency, τ_{NU}, of the projectile (approximately 0.08). The j=2 modes for these projectiles, however, are quite close to τ_{NU}. Figure 51 and Table 5 indicate that a longer cylinder (higher aspect ratio since the diameter of the canister is fixed) should have a higher probability of instability at 100% than the XM687. The M687/L represents the longest canister that could be obtained for an M687-type projectile. On the other hand, the M687/S was not selected to produce unstable behavior. The M687/S was only intended to be a shorter canister height than the standard M687 (or the M687/R).

Three M687/L projectiles were fired with one unstable flight resulting. We would like to determine whether the flight instability occurred prior to spin-up. Analysis of the roll equation for this projectile would produce an angular momentum history of the liquid from which the state of liquid spin-up can be inferred, but this will not be accomplished within this report. Instead, we can use calculations for

10. *Stewartson, K., "On the Stability of a Spinning Top Containing Liquid," Journal of Fluid Mechanics 5, Part 4, 1959.*

M687/R projectiles that have been previously made by Kitchens and Gerber. They have calculated the spin decay and the time to liquid spin-up for M687/R projectiles and found good agreement with yawsonde data when the spin histories were smooth. For an M687/R filled with water and fired under similar conditions to E1-9387, the time required for liquid spin-up was 19 seconds. Figure 52 shows growth of the fast mode component of yaw as early as 8 seconds, hence E1-9387 suffered a spin-up instability.

Recently, numerical procedures have been established for the calculation of spin-up eigenfrequencies for a completely filled cylinder. The codes have been checked against experimental data only for the case of rigid body rotation[11], m=1, and axisymmetric oscillations, m=0, during spin up[12]. These comparisons indicated reasonable agreement. The codes were used to predict a time dependent eigenfrequency history for E1-9387 for the n=1 and j=2 mode. As a first approximation, the spin history of the projectile was assumed to be a simple impulsive start to the first measured yawsonde spin. Also, no spin decay during flight was assumed. The in-bore spin of the projectile could be computed from an interior ballistics model and the yawsonde determined spin could be fitted for future calculations. Several computed eigenfrequency histories are provided in Figure 53. The solid line represents the history for the aspect ratio of E1-9387, while the dashed lines are for aspect ratios that are slightly different. Note that the aspect ratio of the M687 projectile would represent a 13% decrease from the aspect ratios of E1-9387. The Stewartson eigenfrequency, Table 5, is approximately equal to zero. This inviscid eigenfrequency should be a good approximation to the actual eigenfrequency when the Ekman number is very small. The steady state eigenfrequency prediction from the code also approaches a zero value. From Figure 52, the fast precessional mode began to grow at approximately 7 seconds, while from Figure 53 an eigenfrequency of 0.08 was predicted at that time. Recall, the yawsonde data indicated $\tau_{NU} = 0.08$. Hence, the spin-up eigenfrequency prediction matches the measured value of the coning frequency of the projectile, and a resonant condition should exist. Since a flight instability did result, it was probably caused by an n=1 and j=2 spin-up mode. This is the first comparison between the spin-up eigenfrequency code and projectile data, and the predictions and the flight data are consistent for this case. It is not known why only one of the three M687/L projectiles was unstable, however.

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11. *C.W. Kitchens, Jr., N. Gerber, and R. Sedney, "Oscillations of a Liquid in a Rotating Cylinder: Part I. Solid-Body Rotation," Ballistic Research Laboratory Technical Report ARBRL-TR-02081, June 1978. AD A057759.*

12. *Y.M.Lynn, "Free Oscillations of a Liquid During Spin-Up", BRL Report No. 1663, Aberdeen Proving Ground, Maryland, August 1973. AD 769710.*

V. CONCLUSIONS

Specially prepared single canister M687-type projectiles were fired under the conditions of large and small yaw in an attempt to reproduce previously observed anomalous rapid despin of the projectile at shot exit. A variety of liquids were used to produce data over a substantial range of Ekman numbers with launch yaw levels as high as 10 degrees. All spin histories were qualitatively examined and determined to be smooth. It is conjectured that non-smooth spin histories are produced by binary canisters that contain rupture discs. This conjecture is supported by an examination of previous yawsonde data where non-smooth spin histories have only occurred for binary payloads with burst discs. Yawsonde data for a 100% filled cylinder that suffered a Stewartson-like spin-up instability was also presented, and a comparison with a recently developed eigenvalue code gave consistent results with the one unstable flight that was observed.

VI. ACKNOWLEDGEMENTS

The authors are indebted to Dr. R. Whiting who modified available schemes for spin-up velocity profile and eigenfrequency prediction into a single source code. The eigenfrequency predictions within this report were obtained by Dr. Whiting.

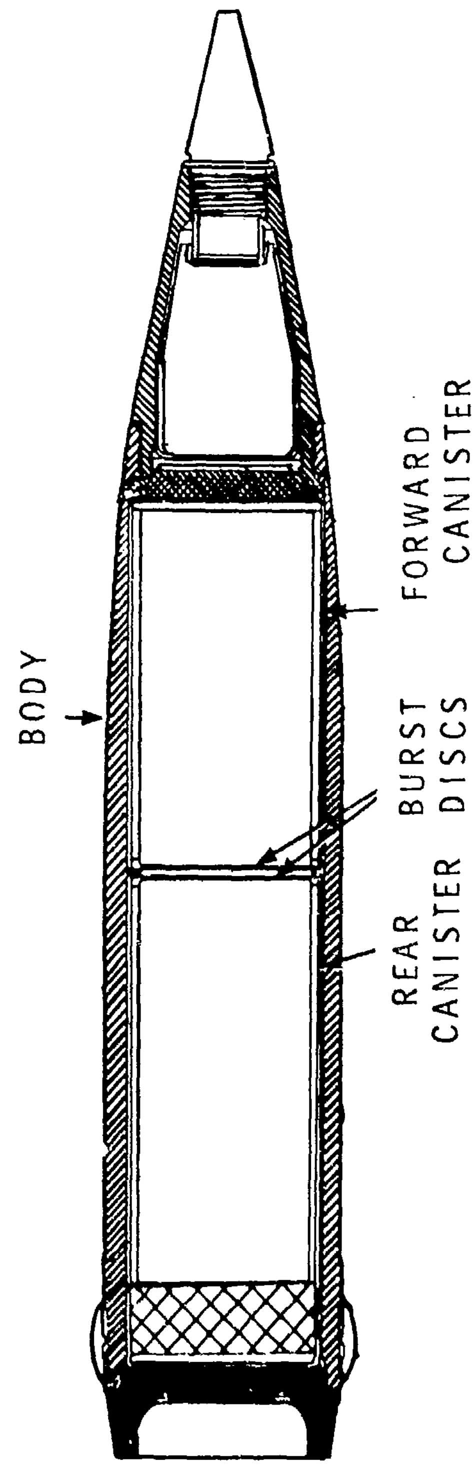


Figure 1. M687 Projectile

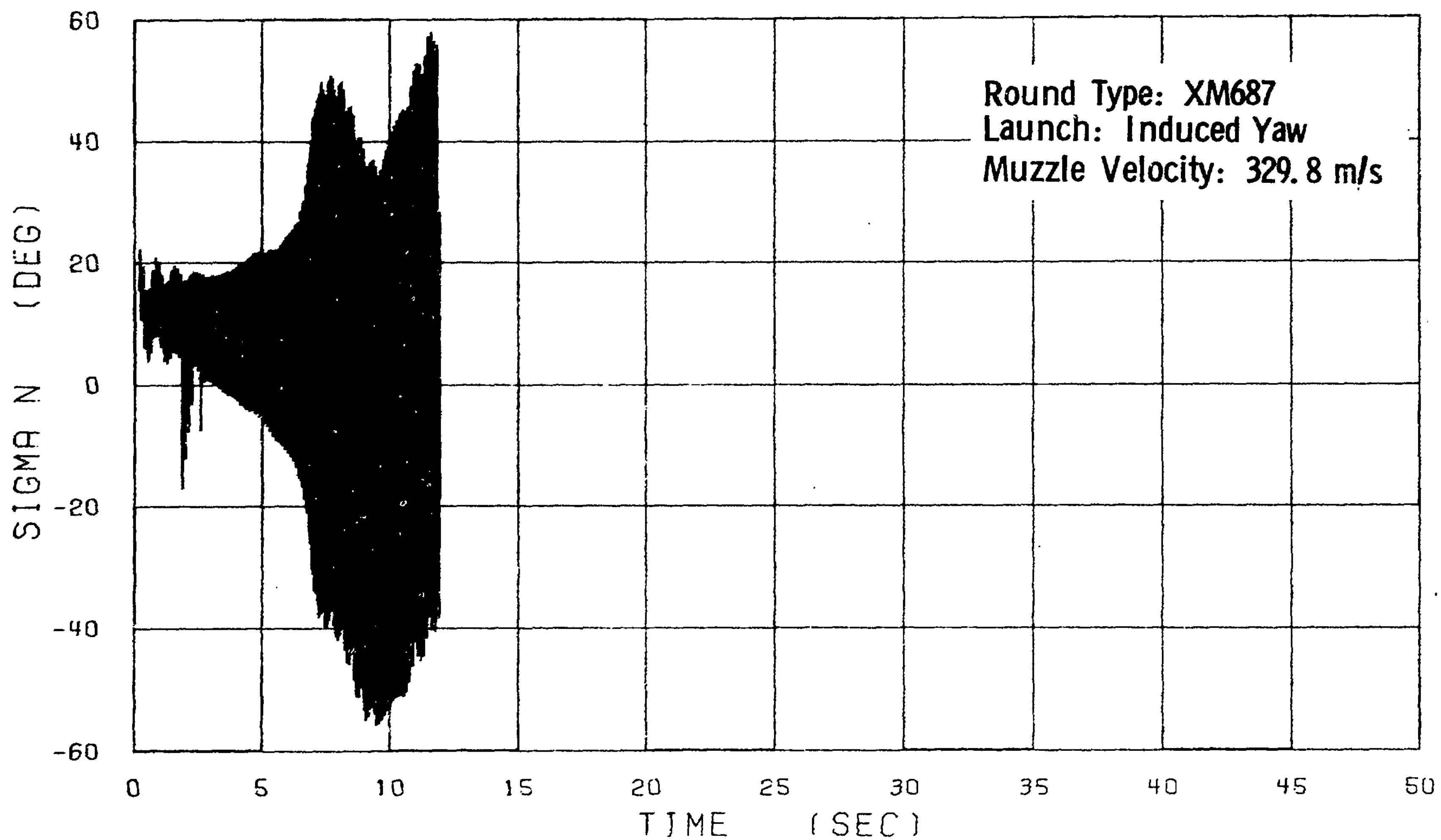


FIGURE 2. SIGMA N VS TIME ROUND 7254

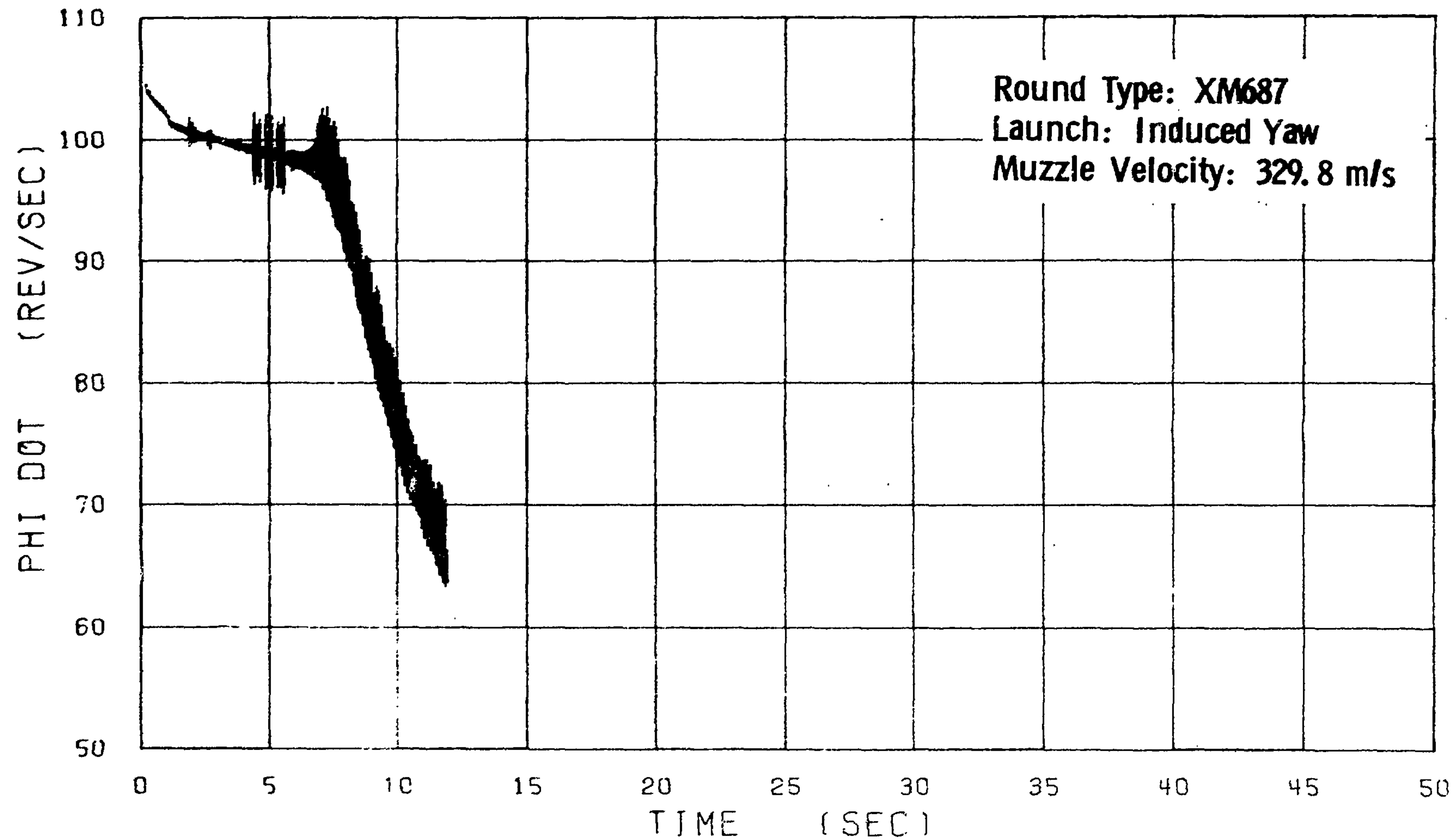


FIGURE 3. PHI DOT VS TIME ROUND 7254

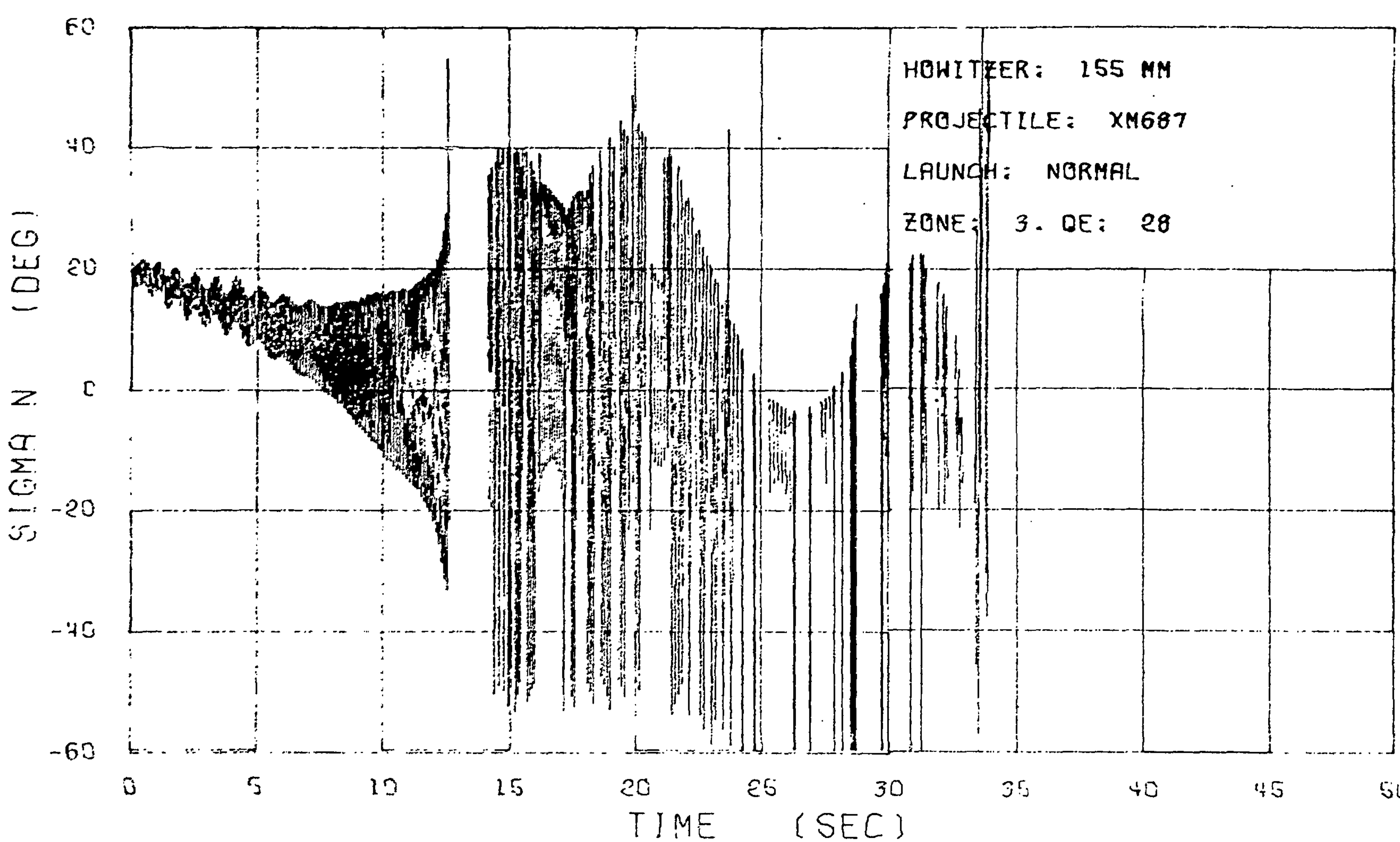
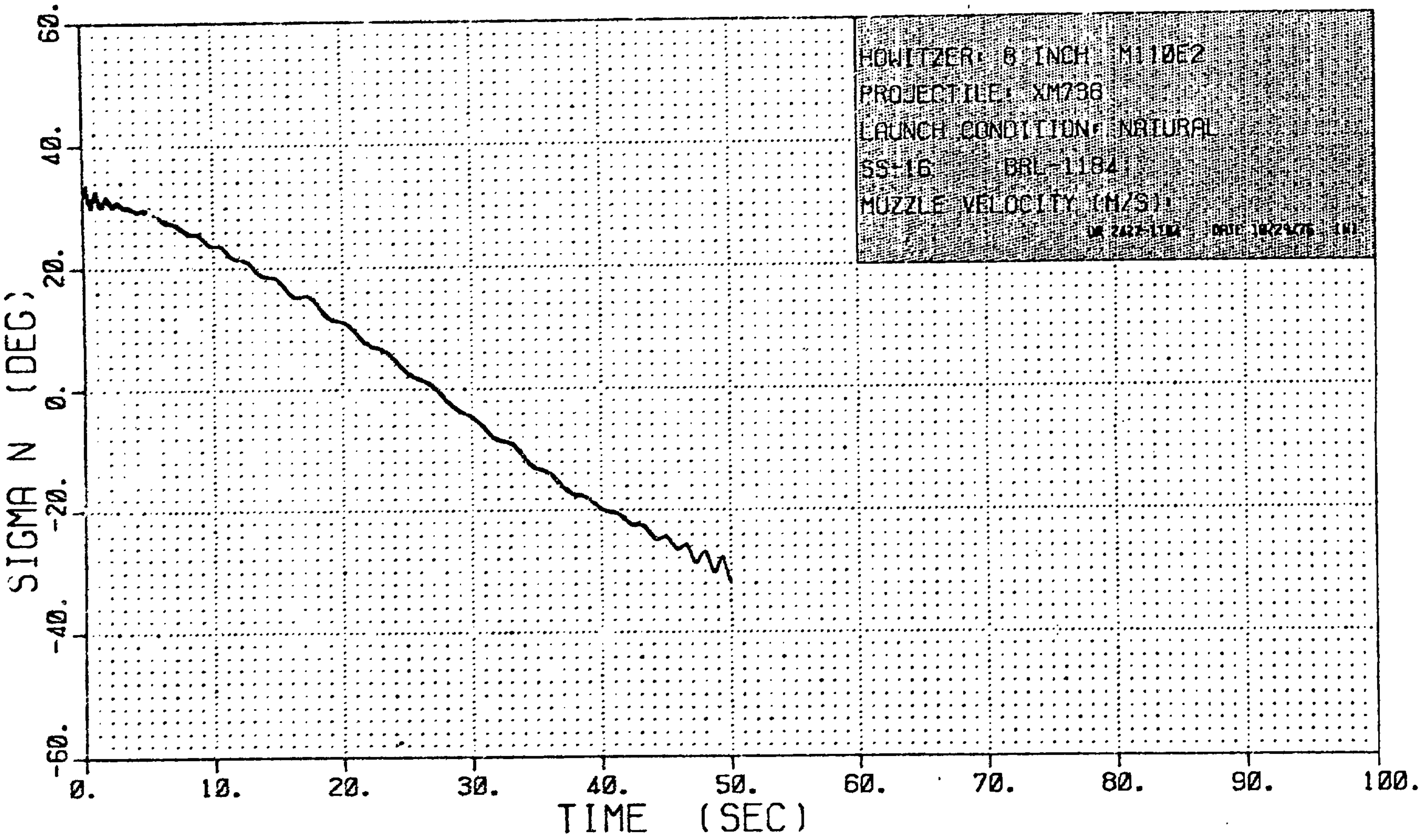


FIGURE 4. SIGMA N VS TIME ROUND E1-5975



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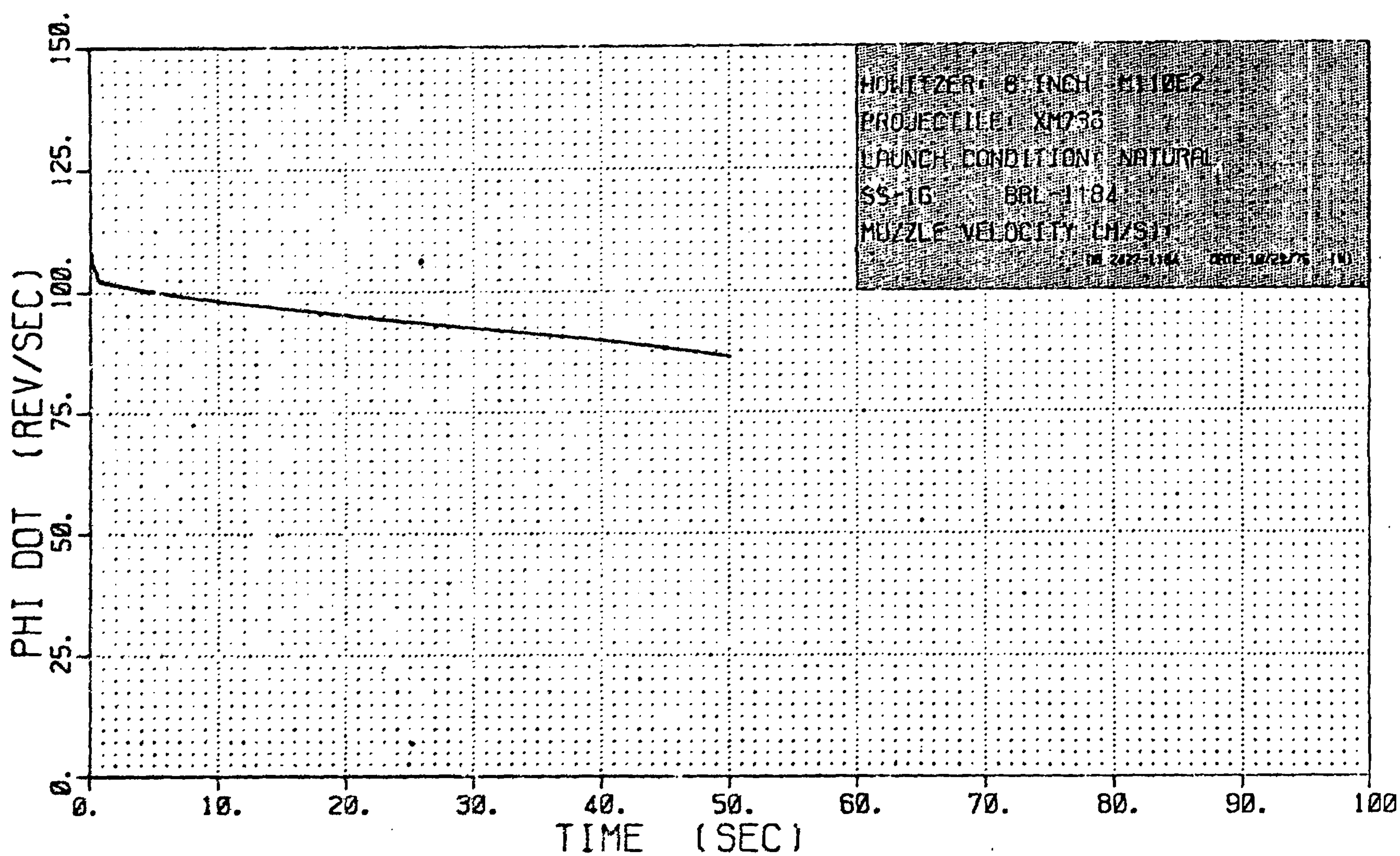

Figure 6. Phi Dot versus Time - Round 1184

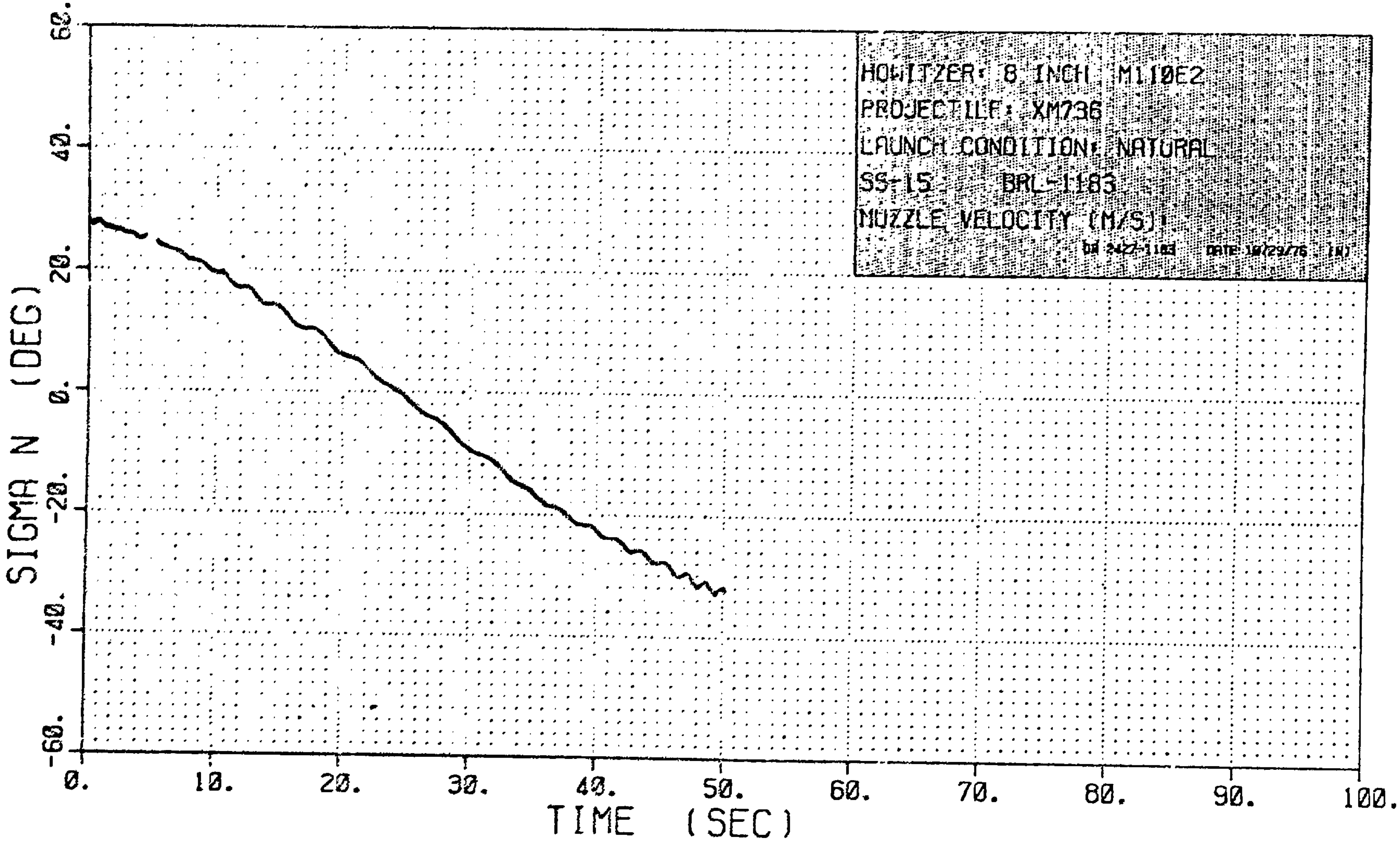

Figure 7. Sigma N versus Time - Round 1183

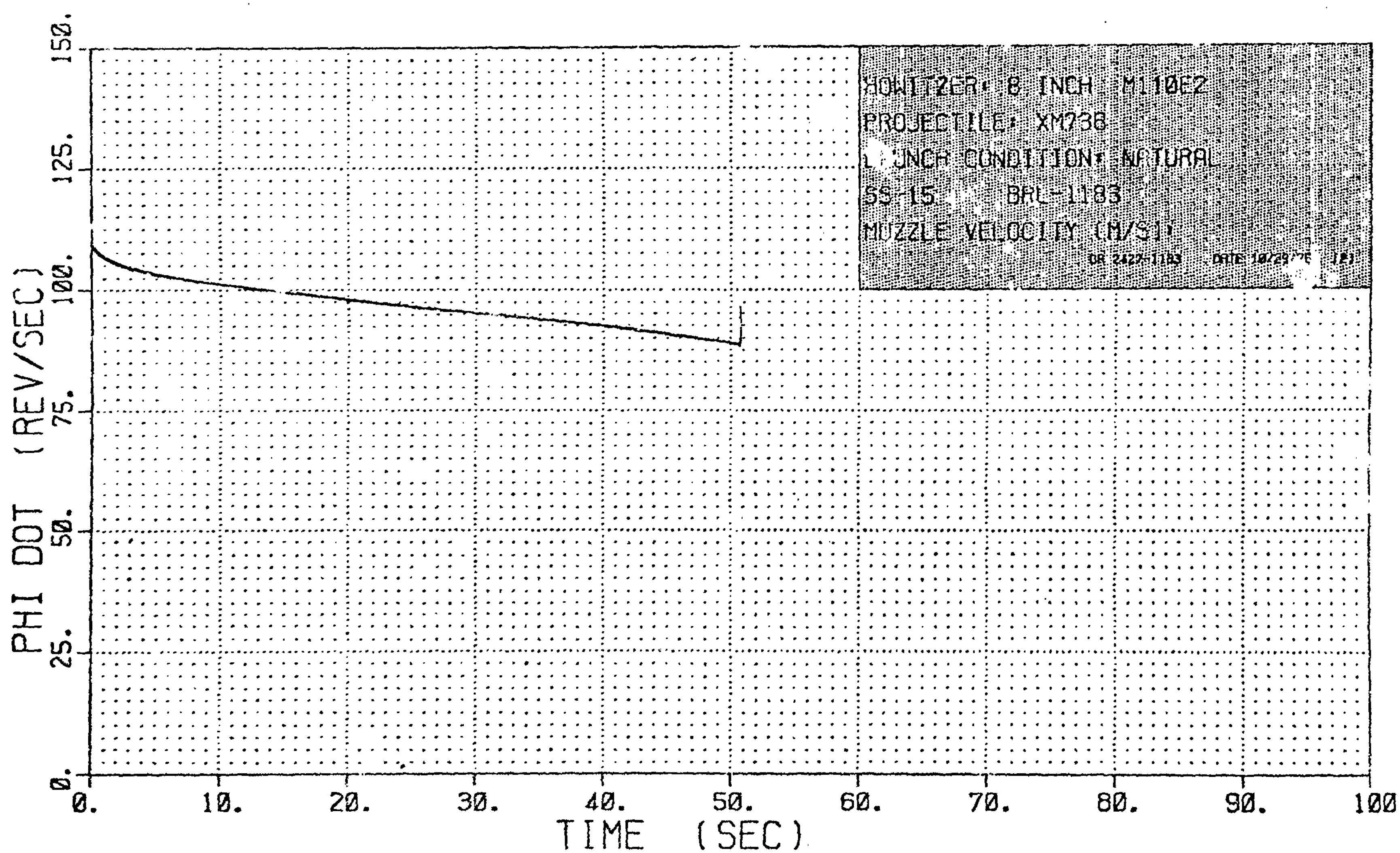

Figure 8. Phi Dot versus Time - Round 1183

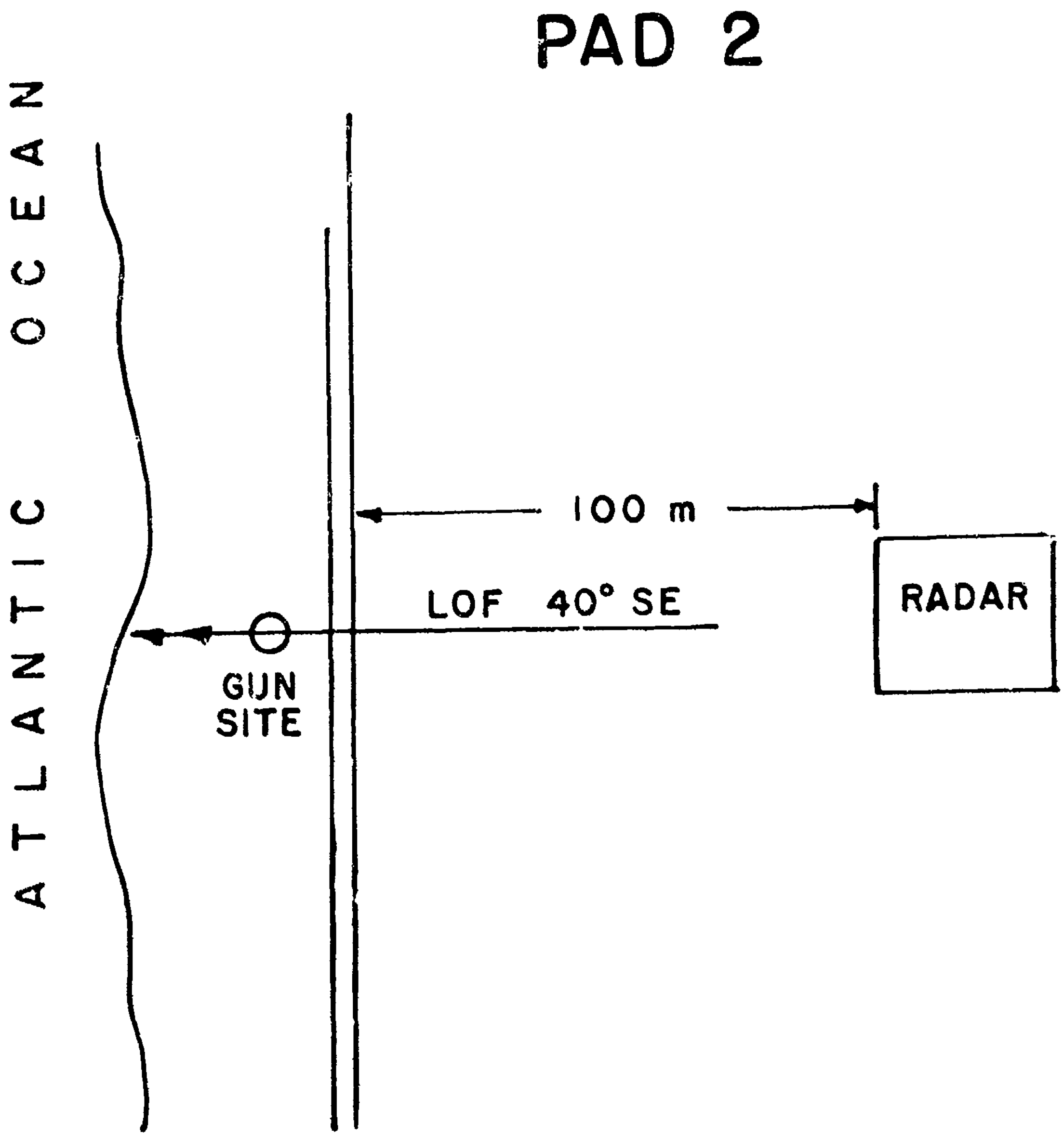

Figure 9. Wallops Island Launch Facility

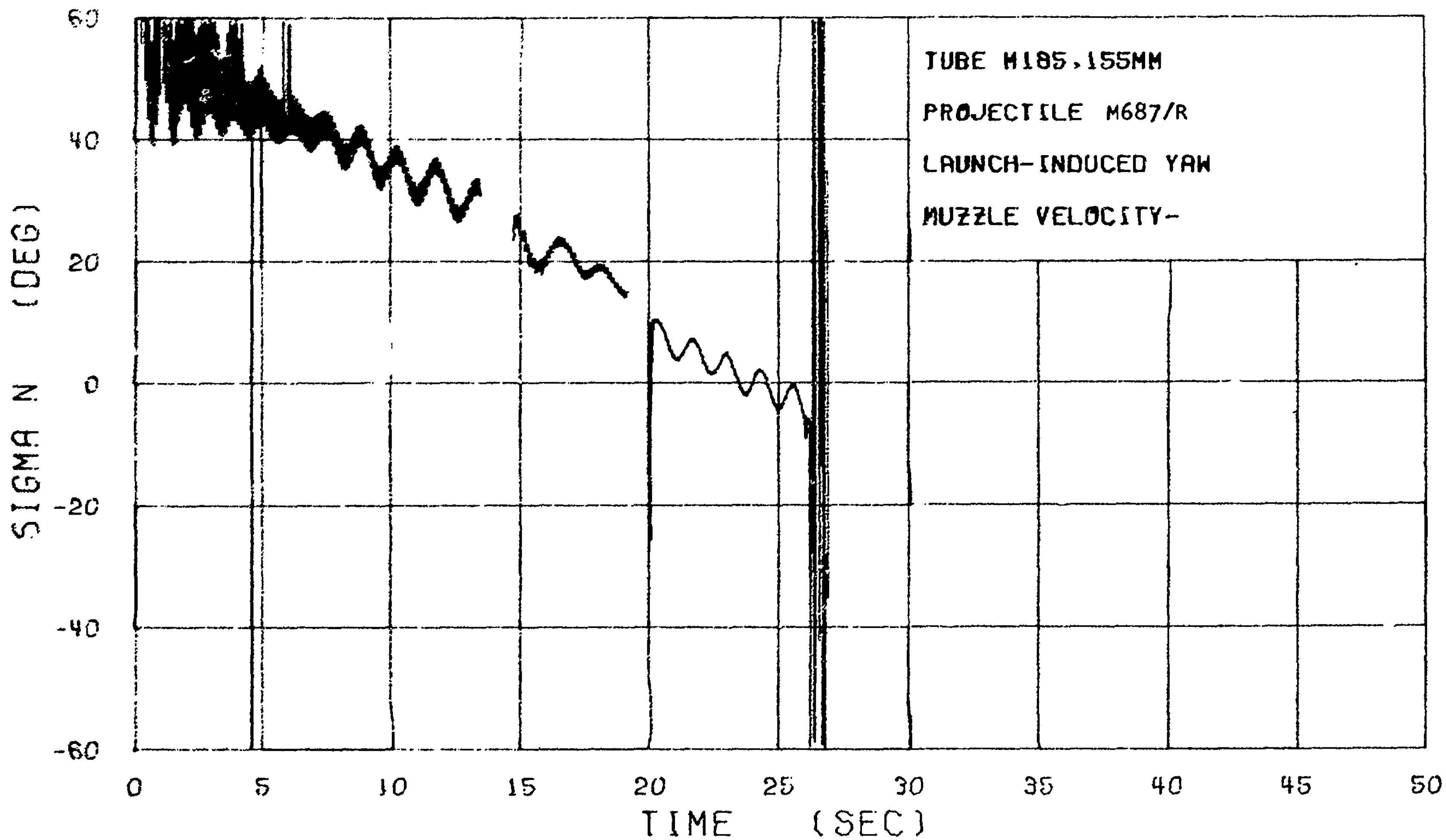

FIGURE 10. SIGMA N VS TIME RØUND E1-9188

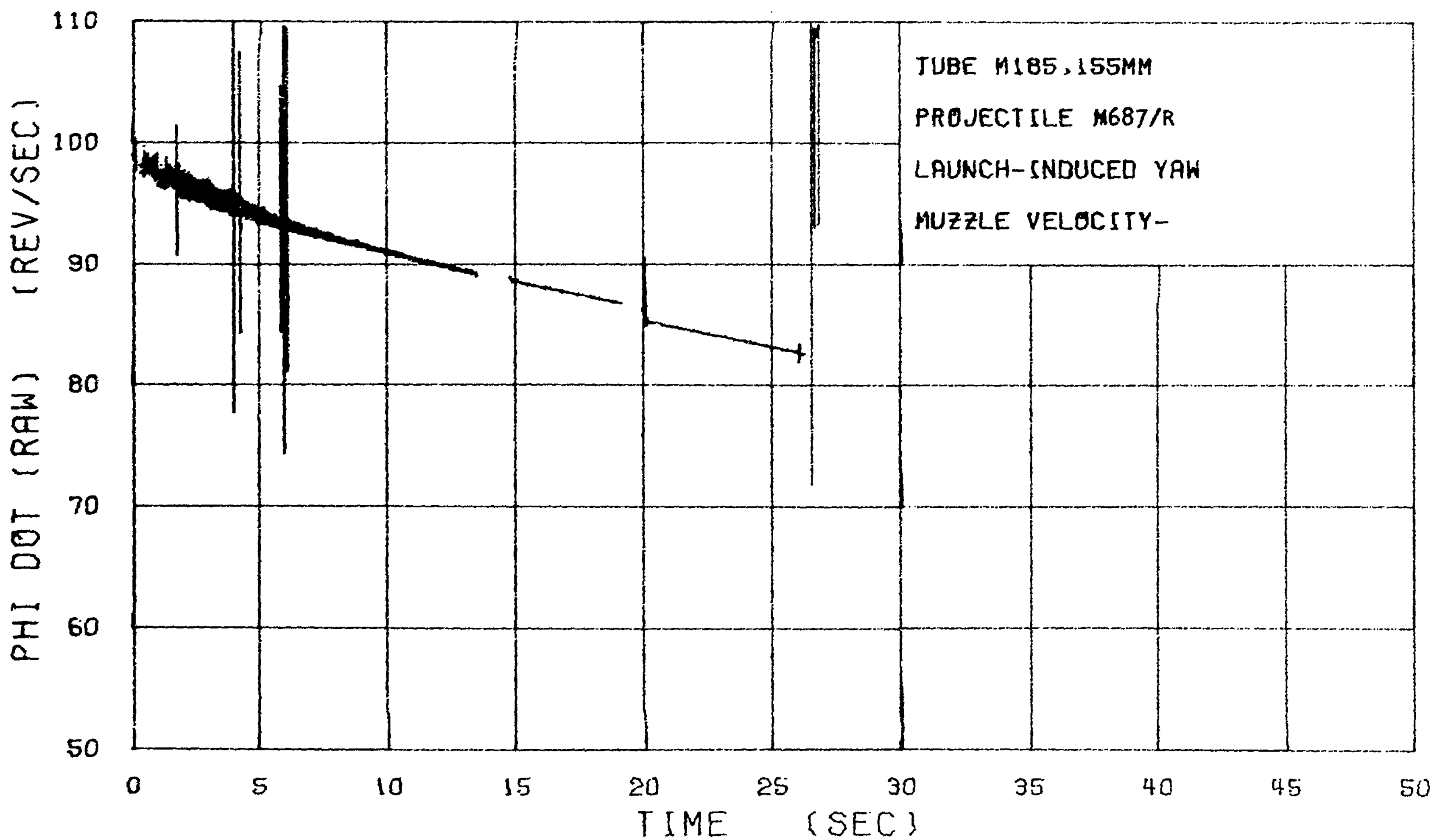

FIGURE 11. PHI DOT (RAW) VS TIME ROUND E1-9188

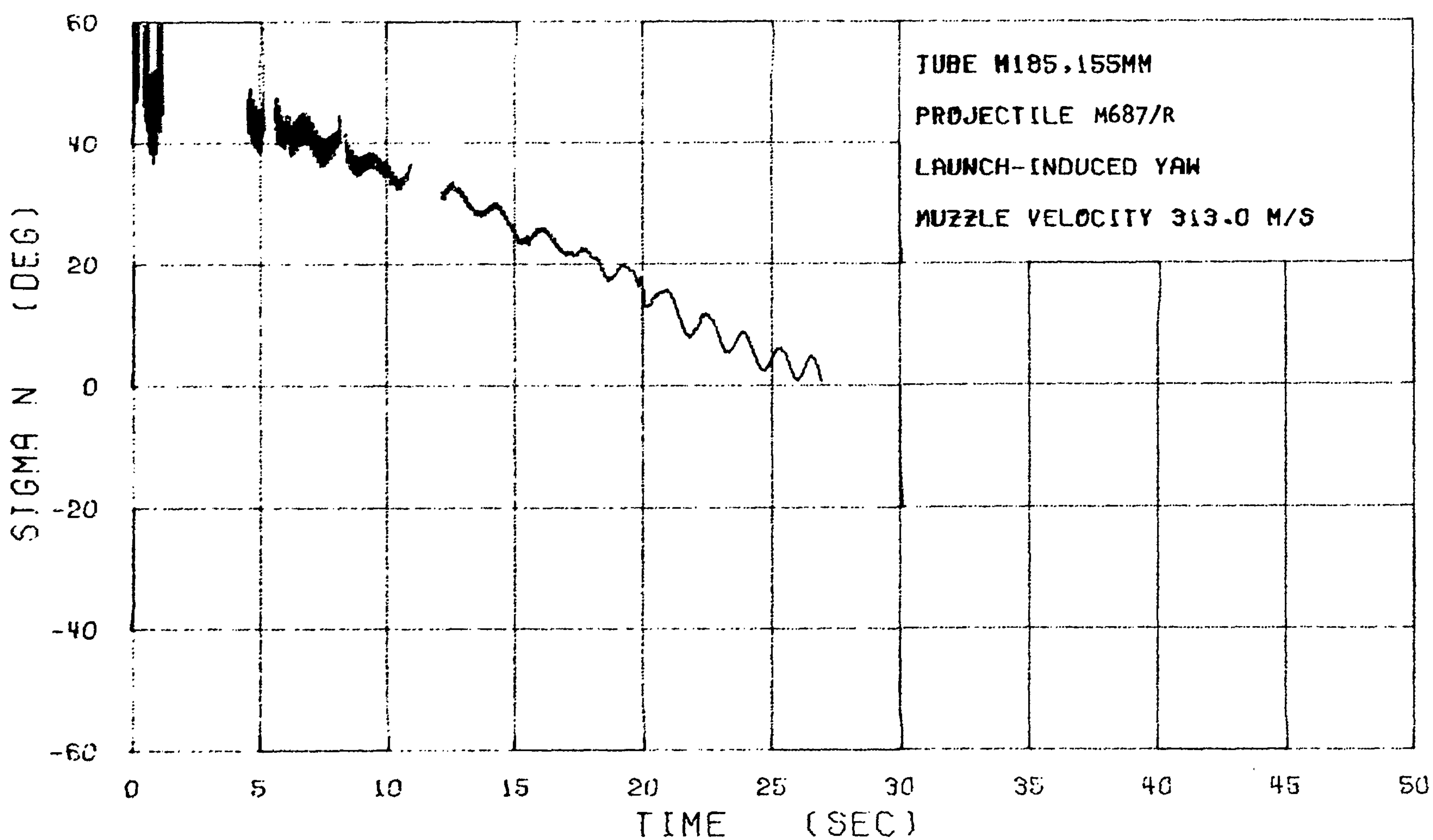

FIGURE 12 SIGMA N VS TIME ROUND E1-9189

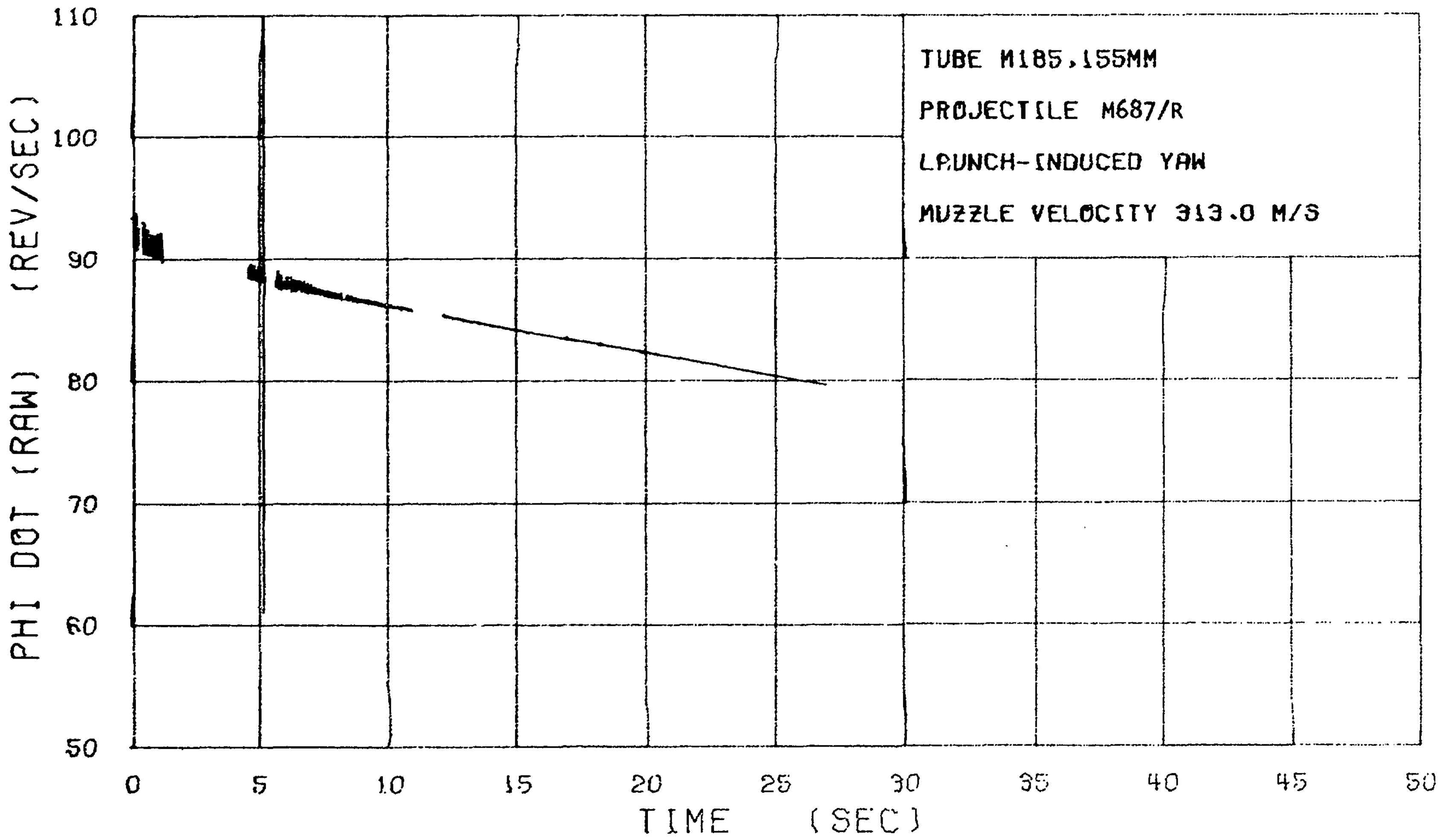

FIGURE 13. PHI DØT (RAW) VS TIME ROUND E1-9189

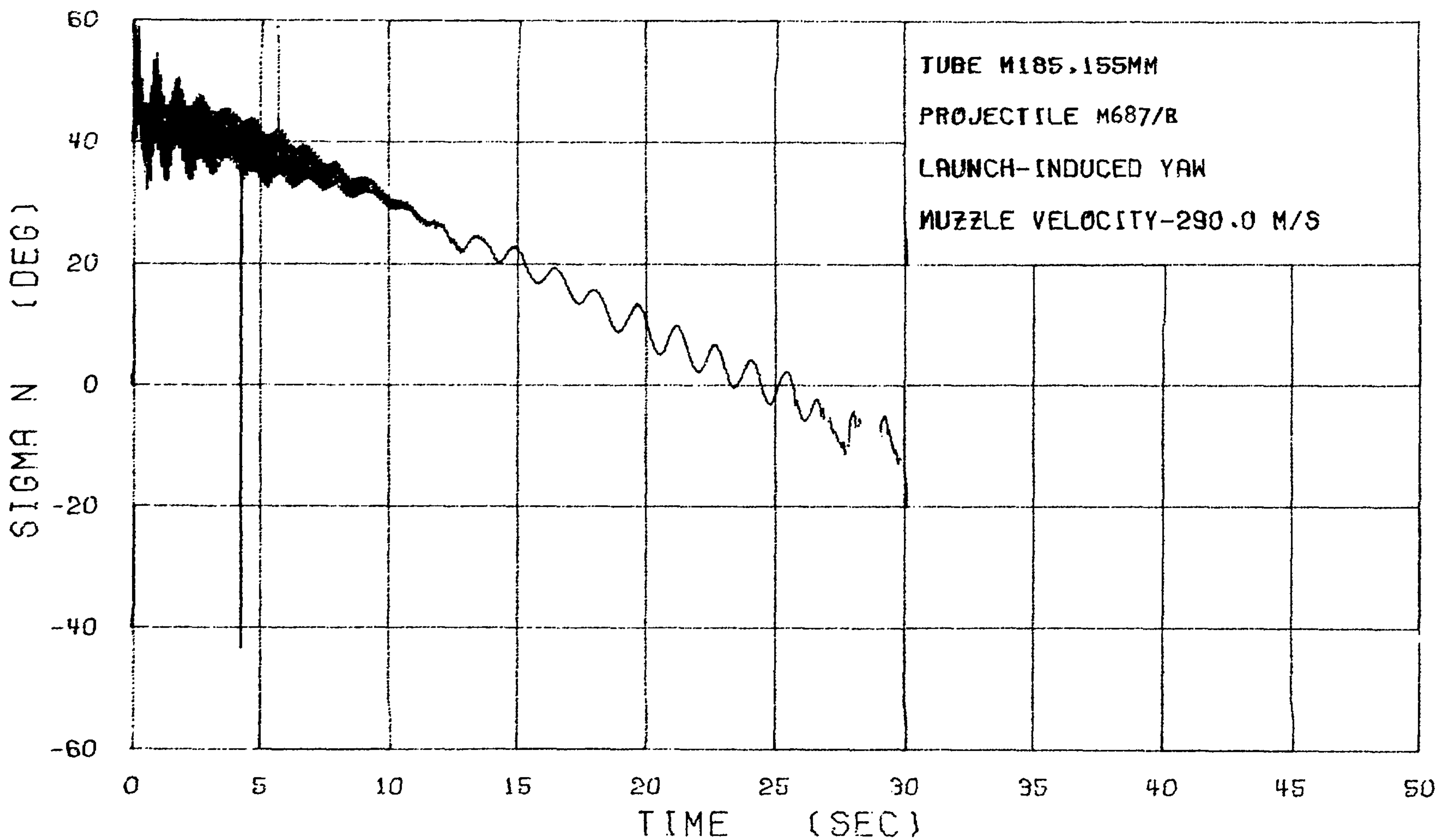

FIGURE 14. SIGMA N VS TIME ROUND E1-9190

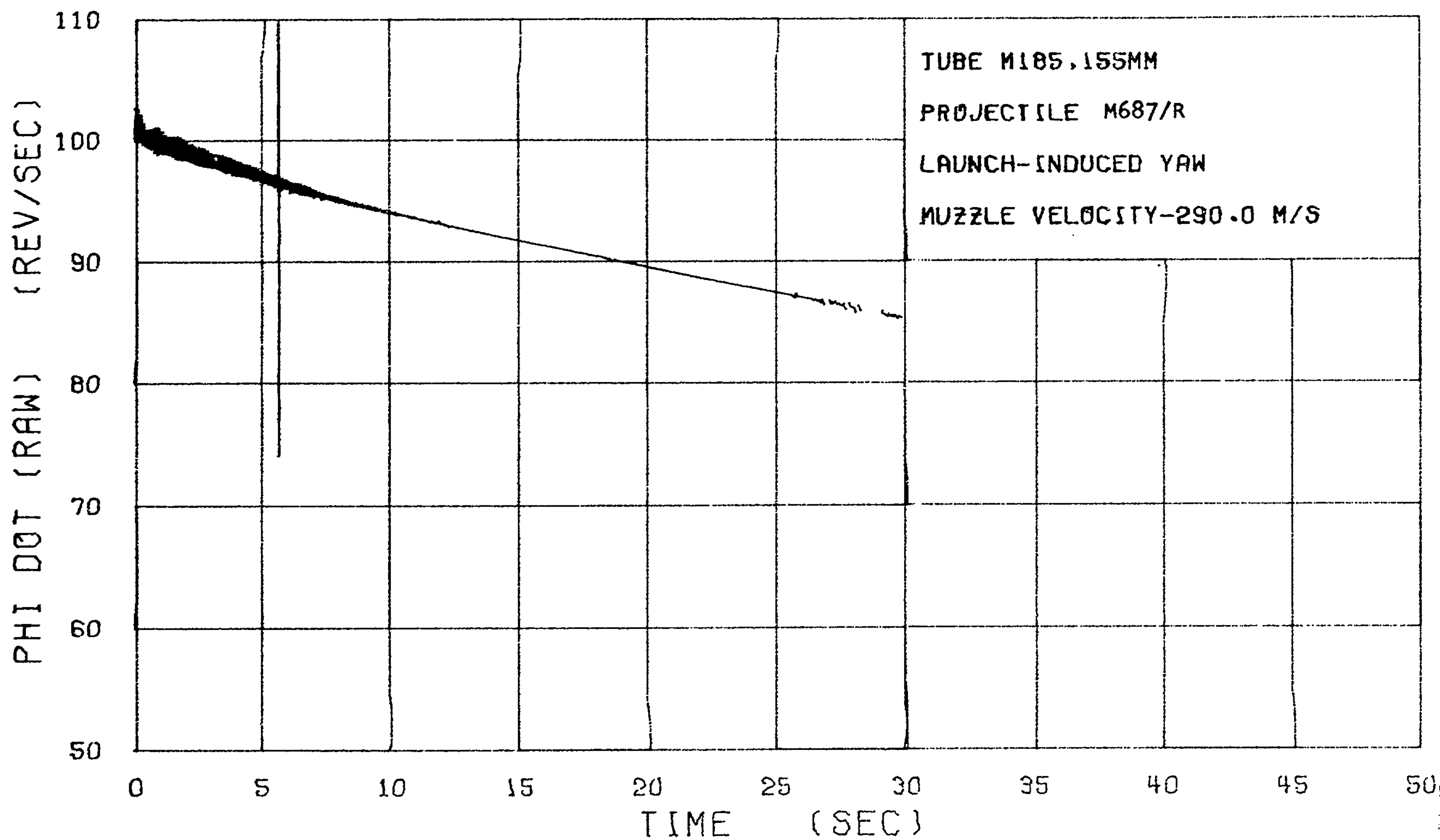

FIGURE 15. PHI DOT (RAW) VS TIME ROUND E1-9190

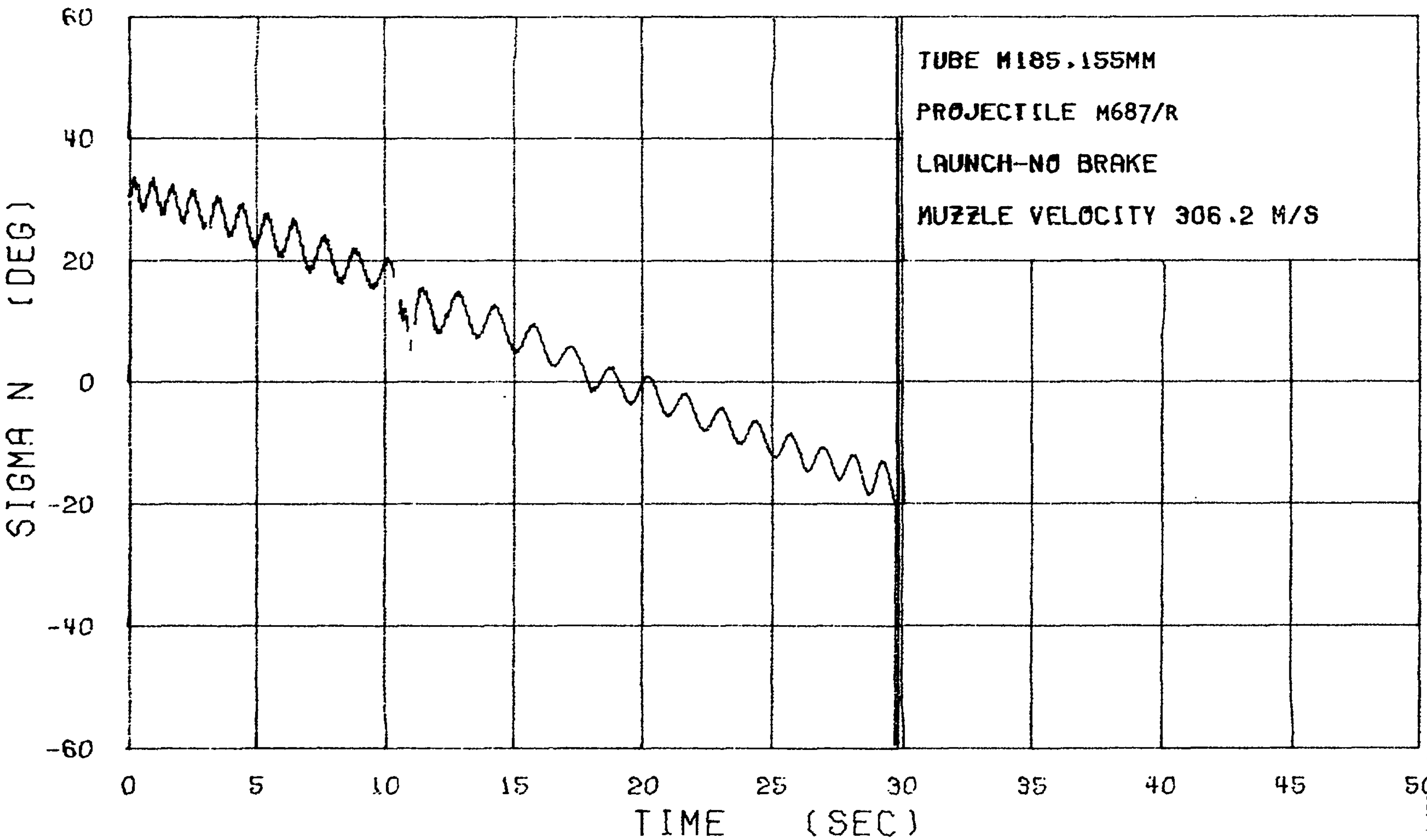

FIGURE 16. SIGMA N VS TIME ROUND E1-9191

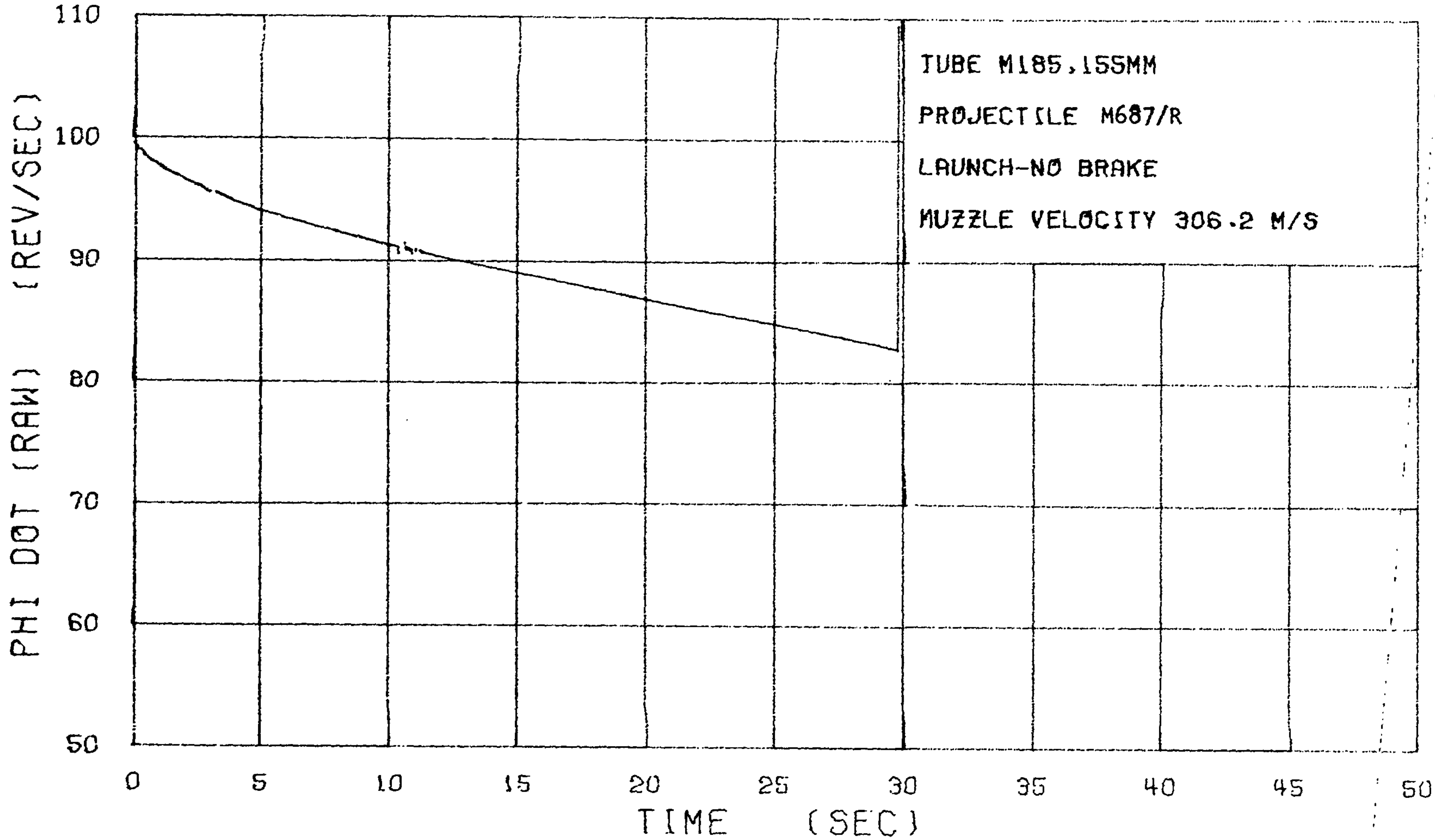

FIGURE 17. PHI DØT (RAW) VS TIME RØUND E1-9191

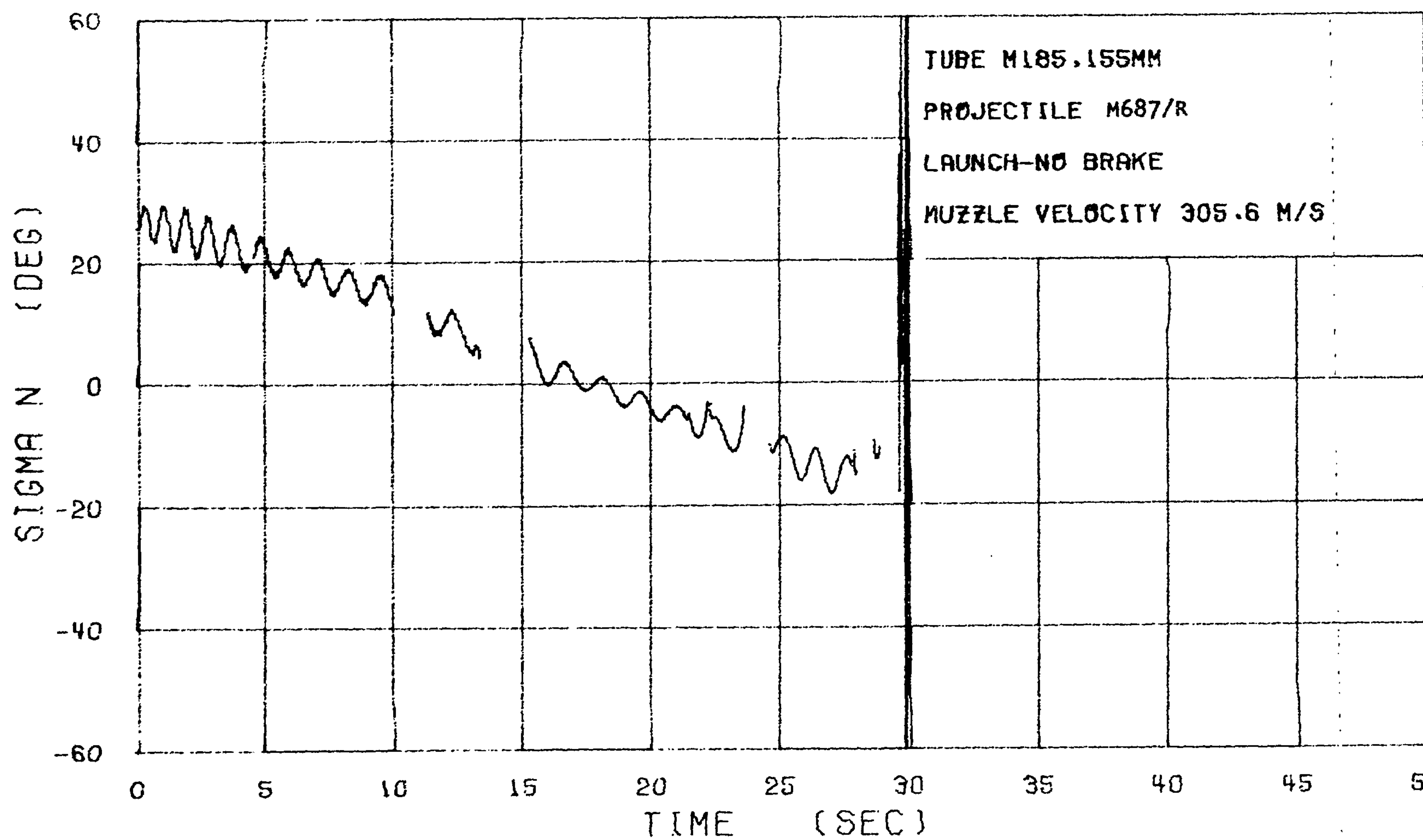

FIGURE **18.** SIGMA N VS TIME ROUND E1-9192

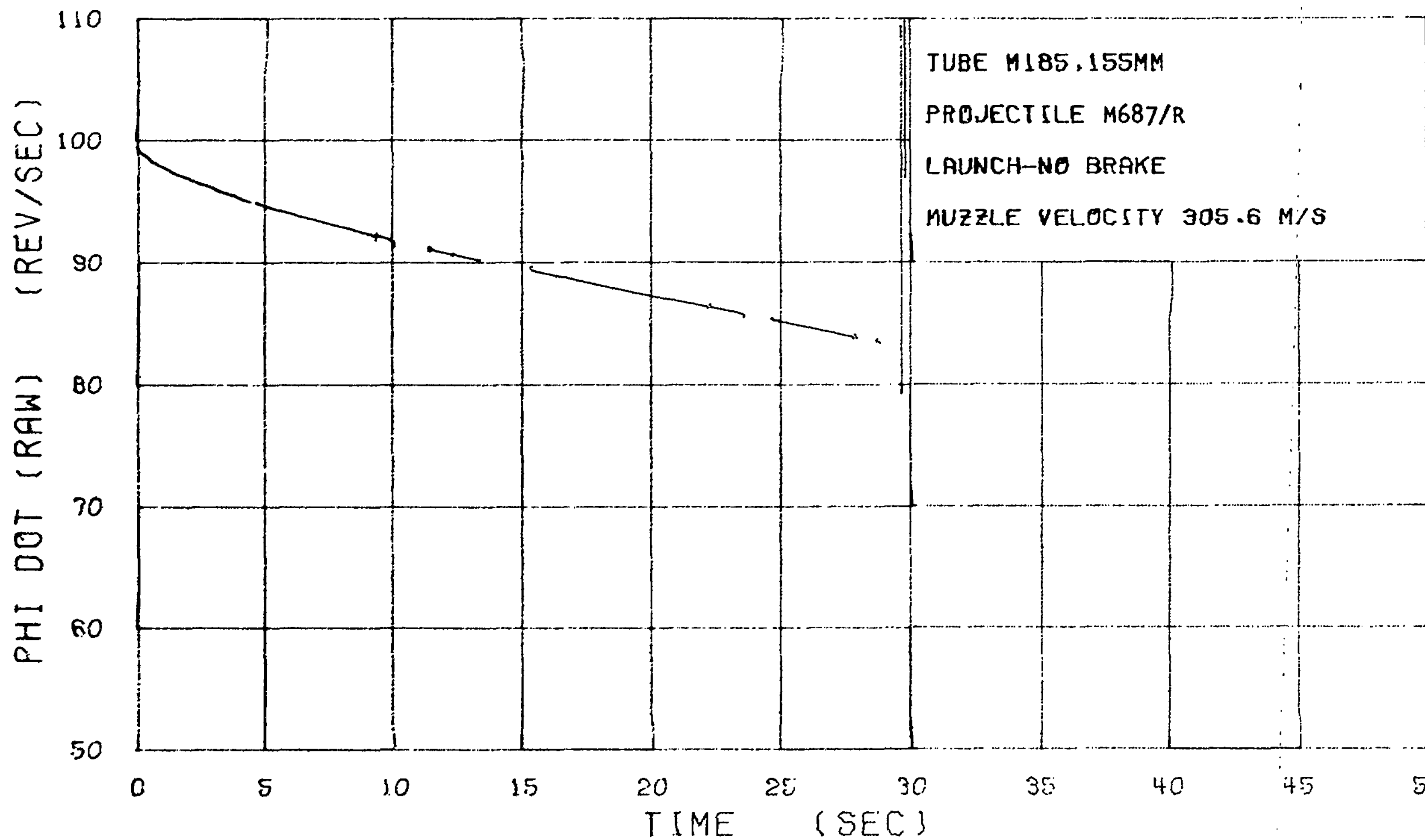

FIGURE 19. PHI DOT (RAW) VS TIME ROUND E1-9192

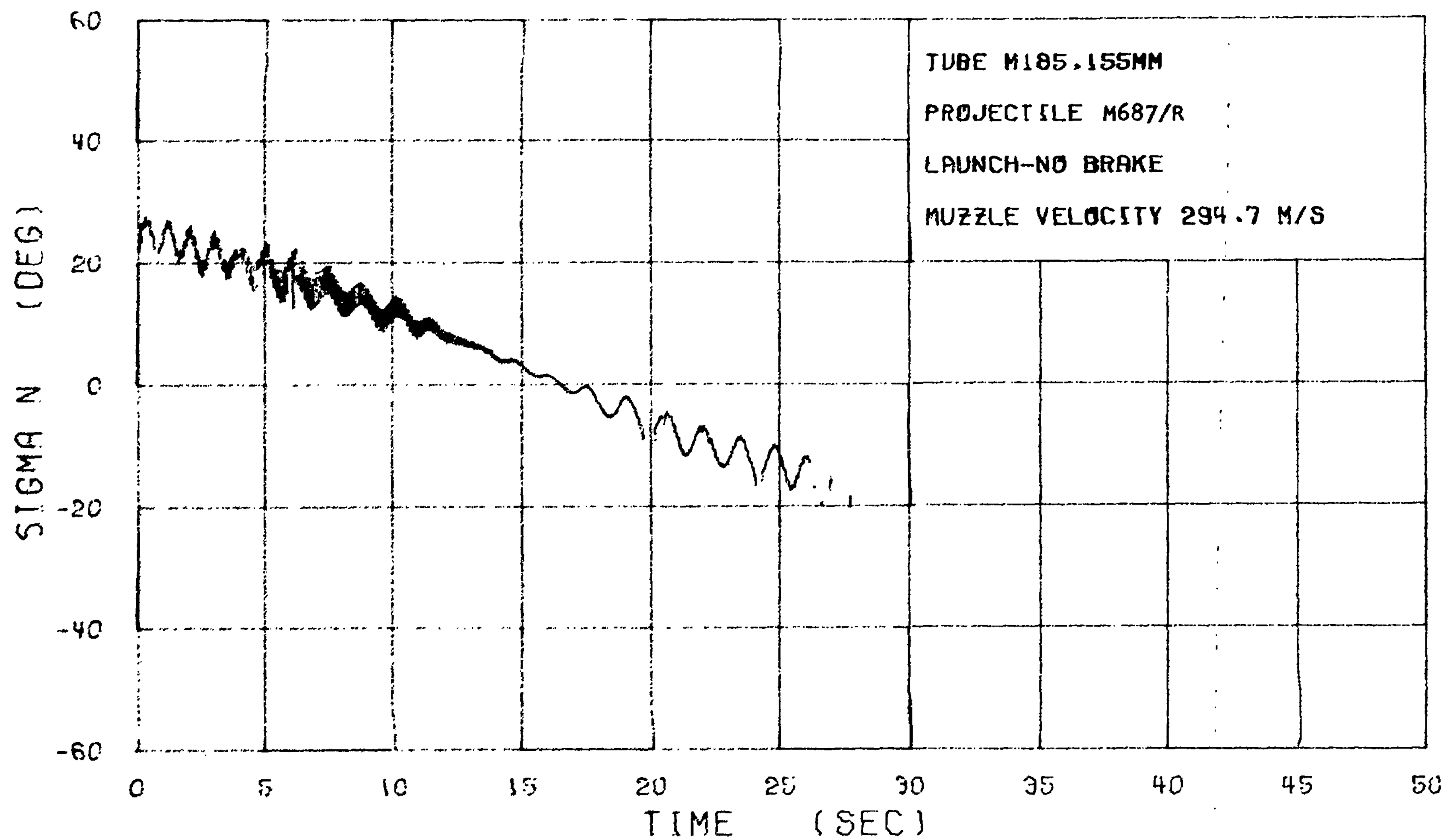

FIGURE 20. SIGMA N VS TIME ROUND E1-9193

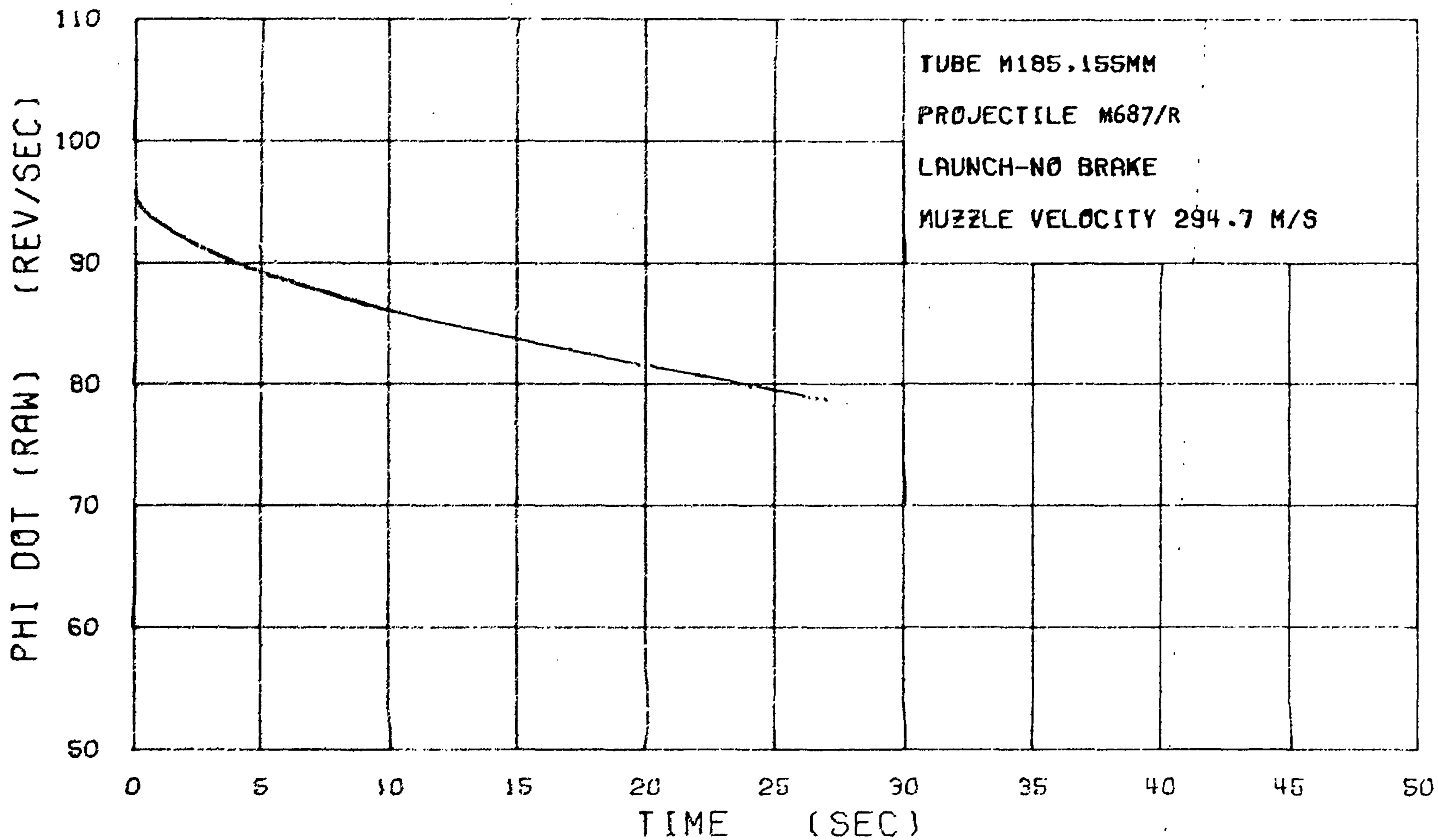

FIGURE 21 PHI DOT (RAW) VS TIME ROUND E1-9193

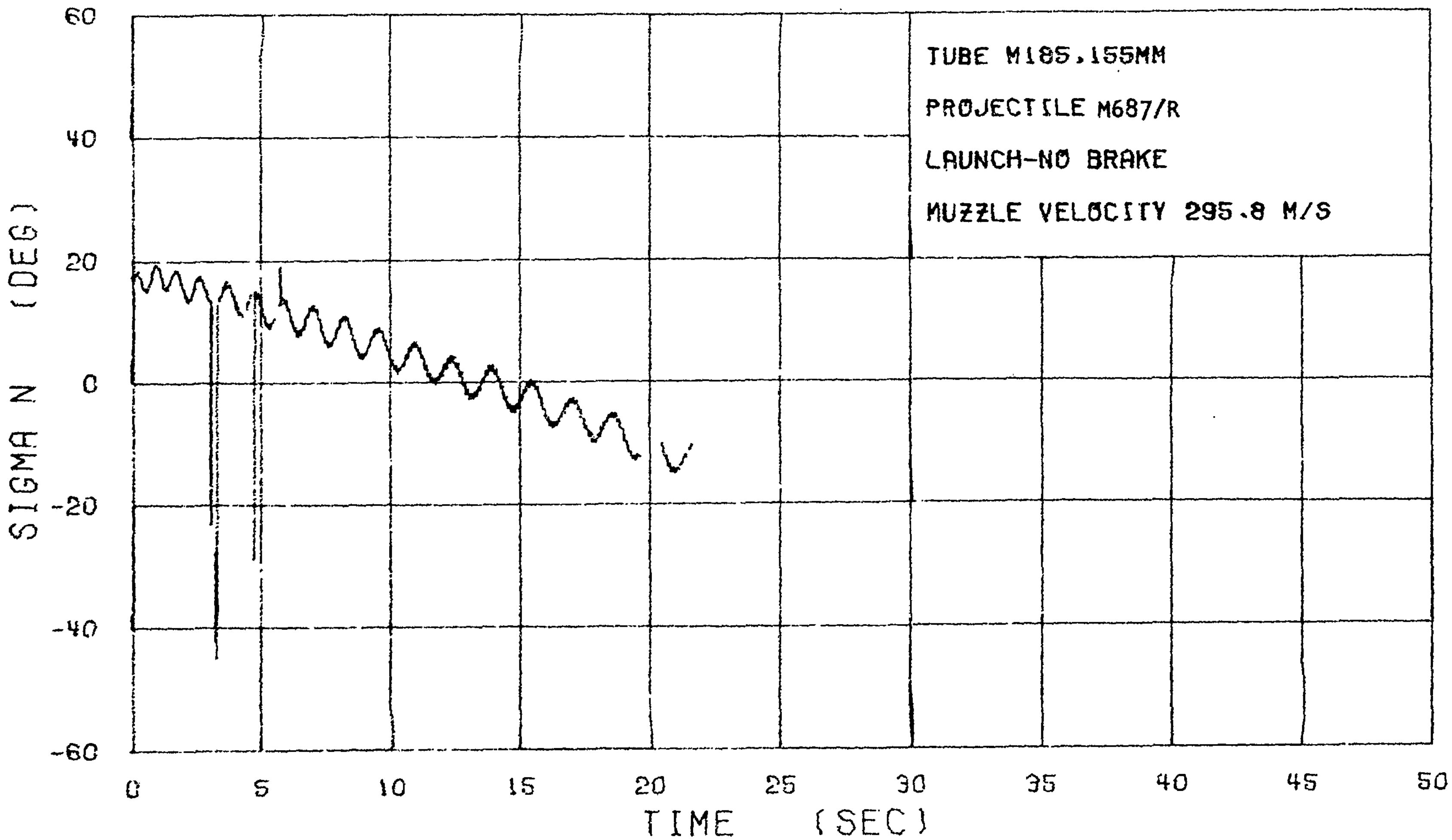

FIGURE 22. SIGMA N VS TIME ROUND E1-9194

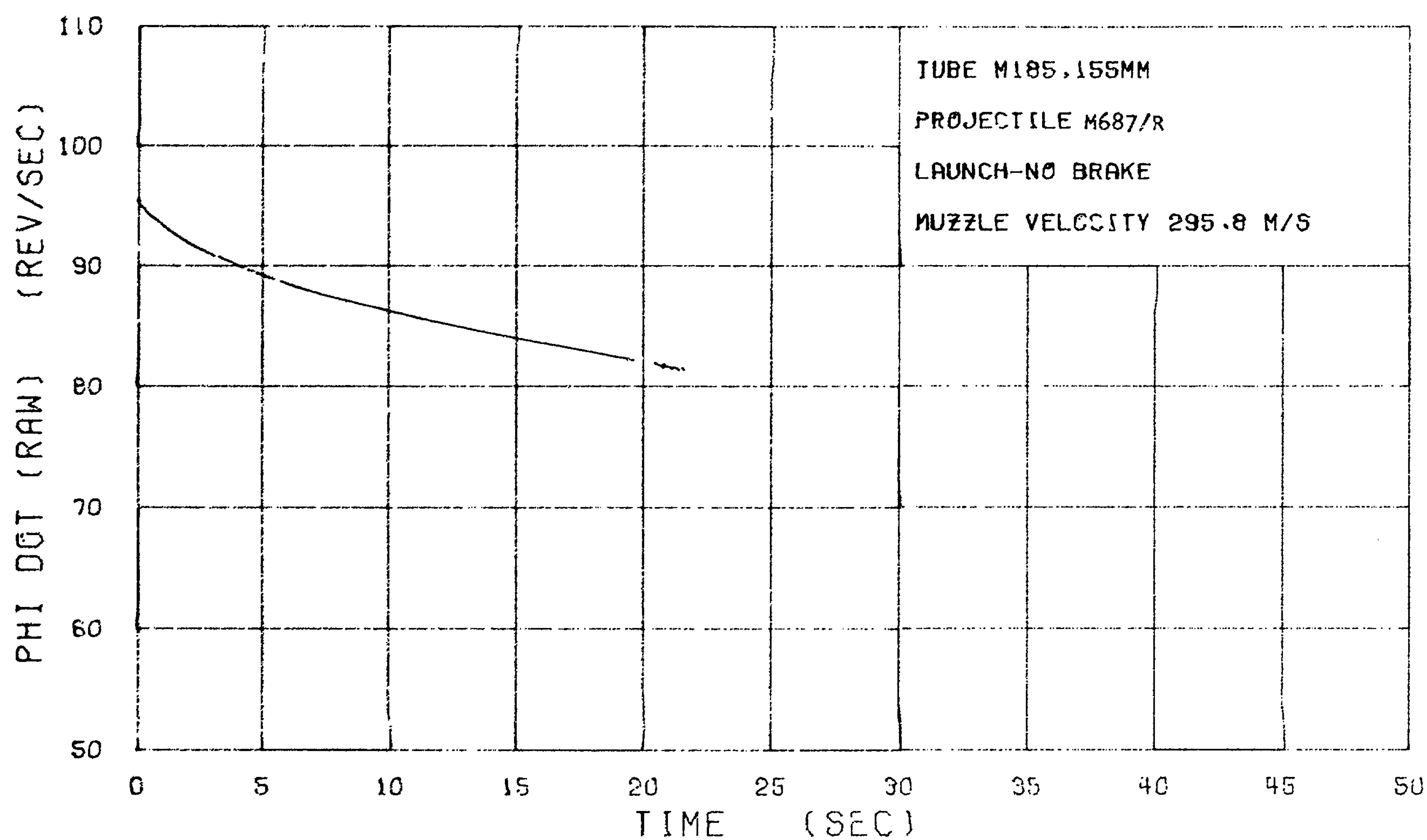

FIGURE 23. PHI DOT (RAW) VS TIME ROUND E1-9194

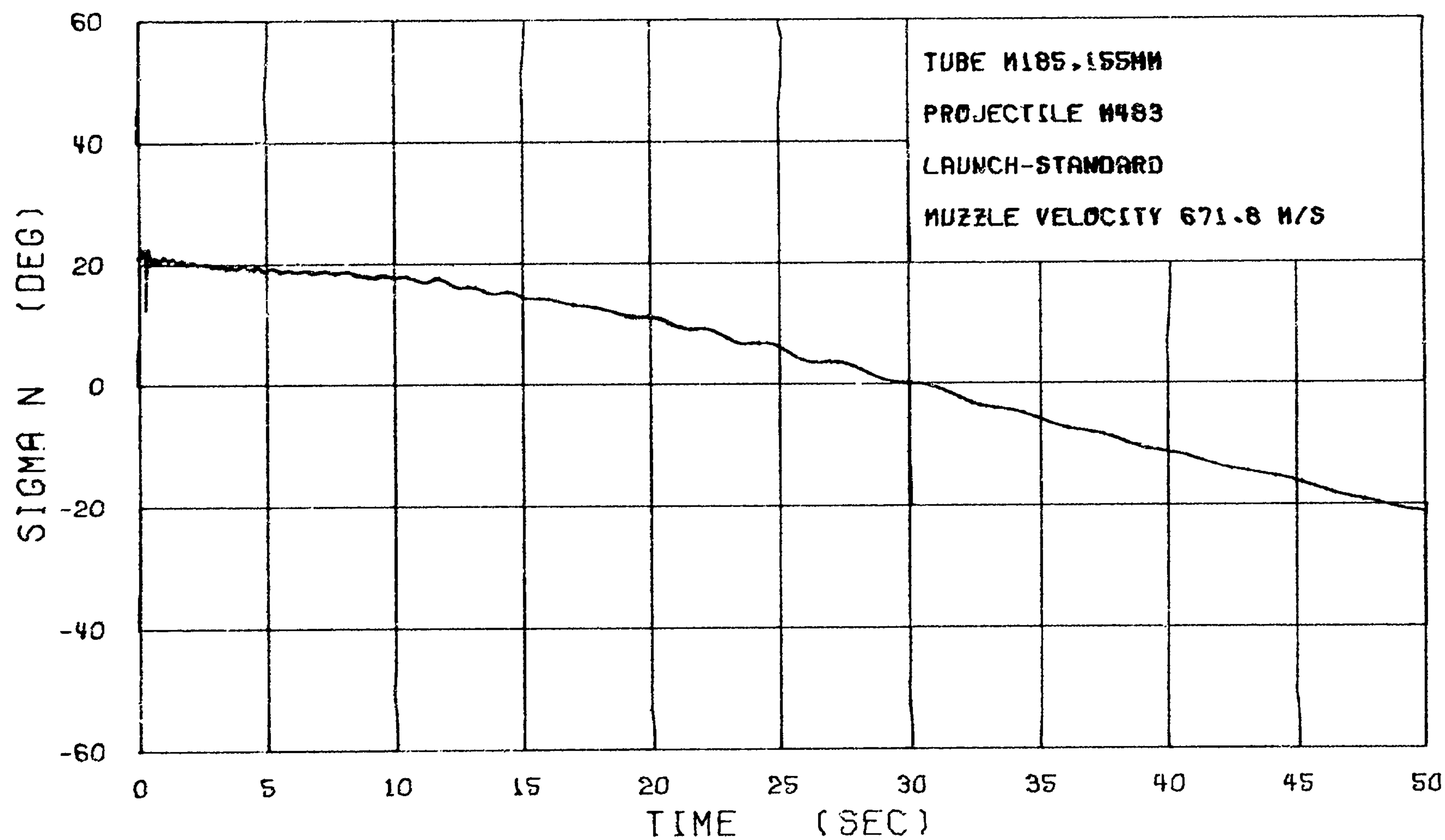

FIGURE 24. SIGMA N VS TIME ROUND E1-9195

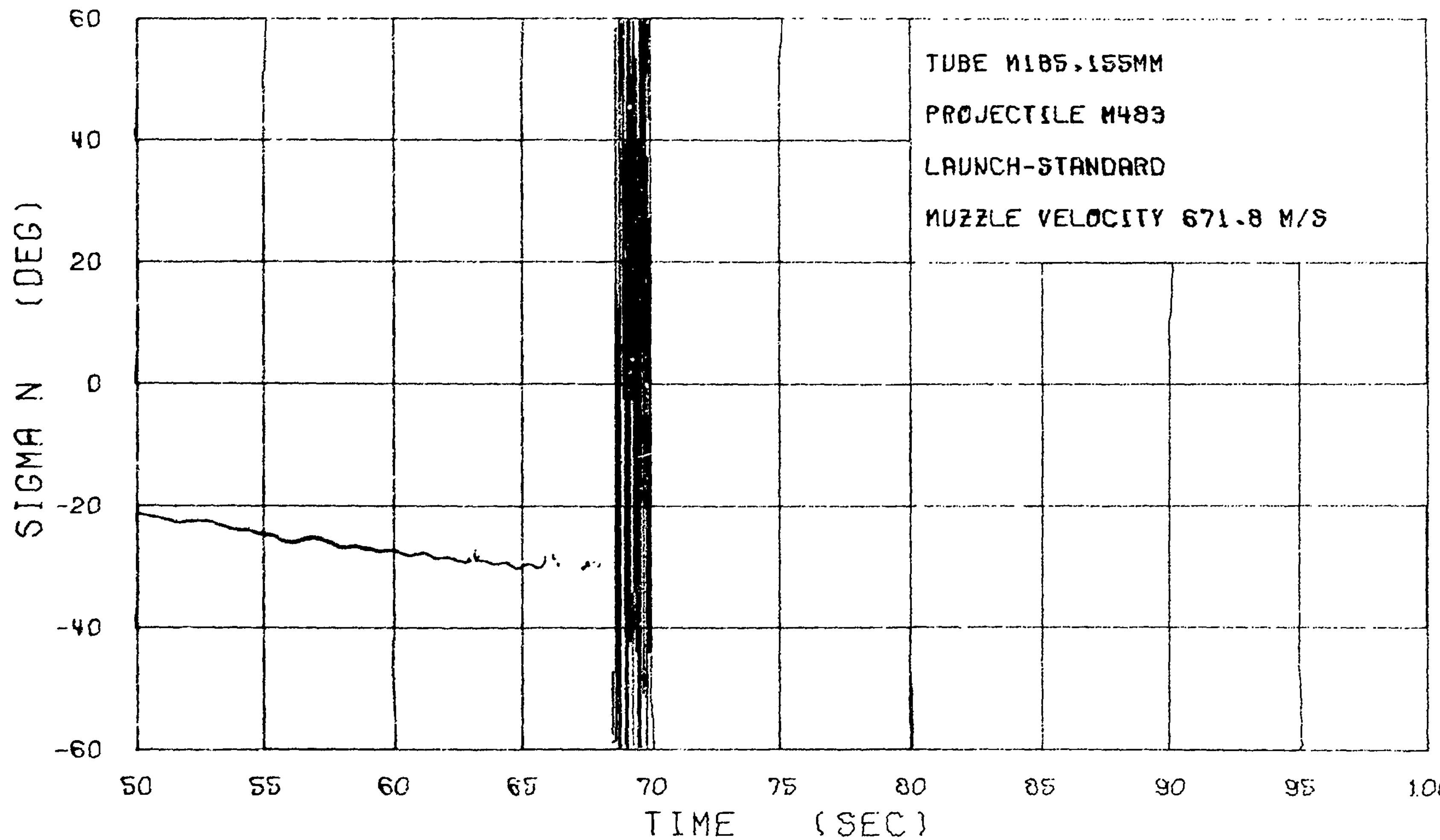

FIGURE 25. SIGMA N VS TIME ROUND E1-9195

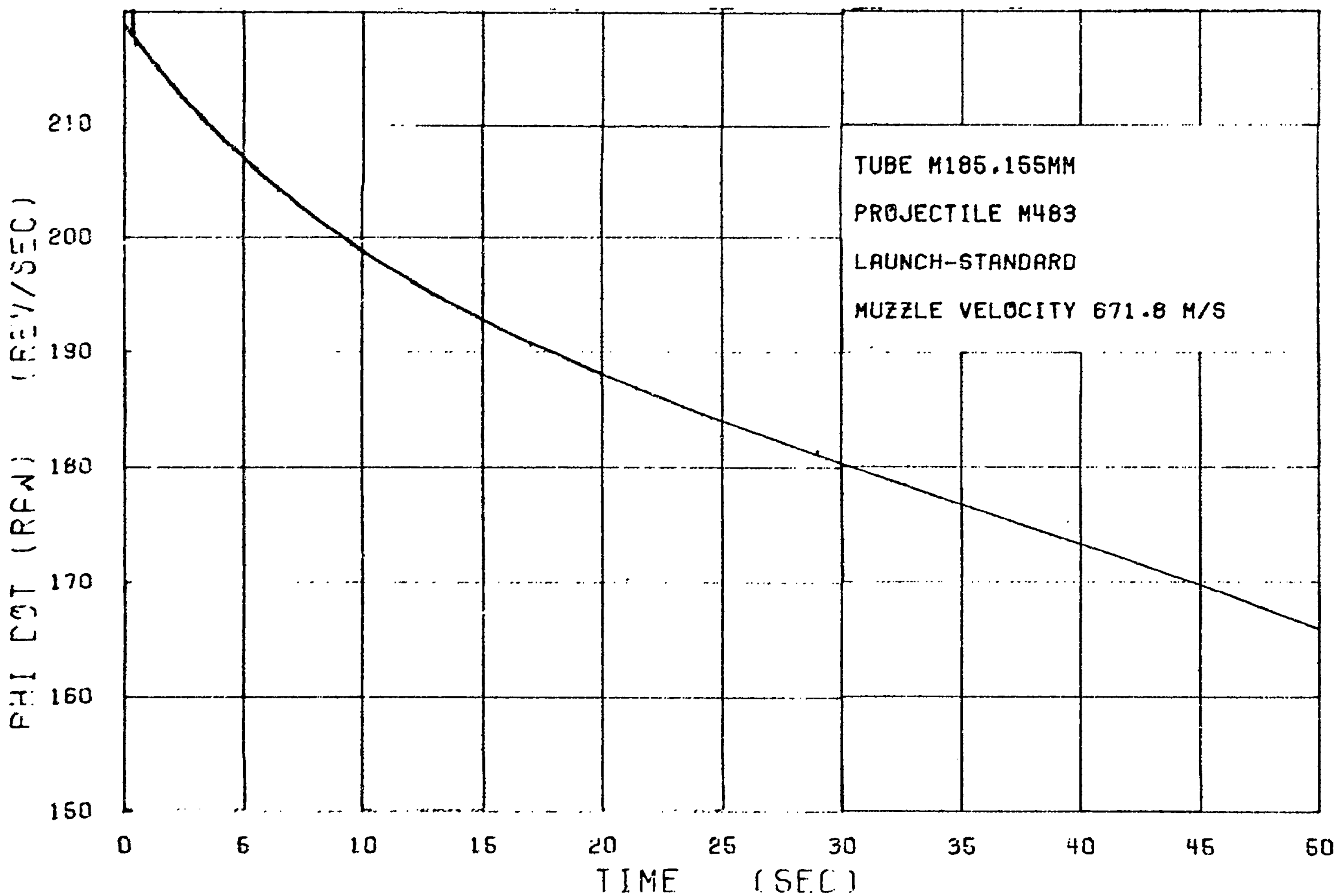

FIGURE 26. PHI DOT (RAW) VS TIME ROUND E1-9195

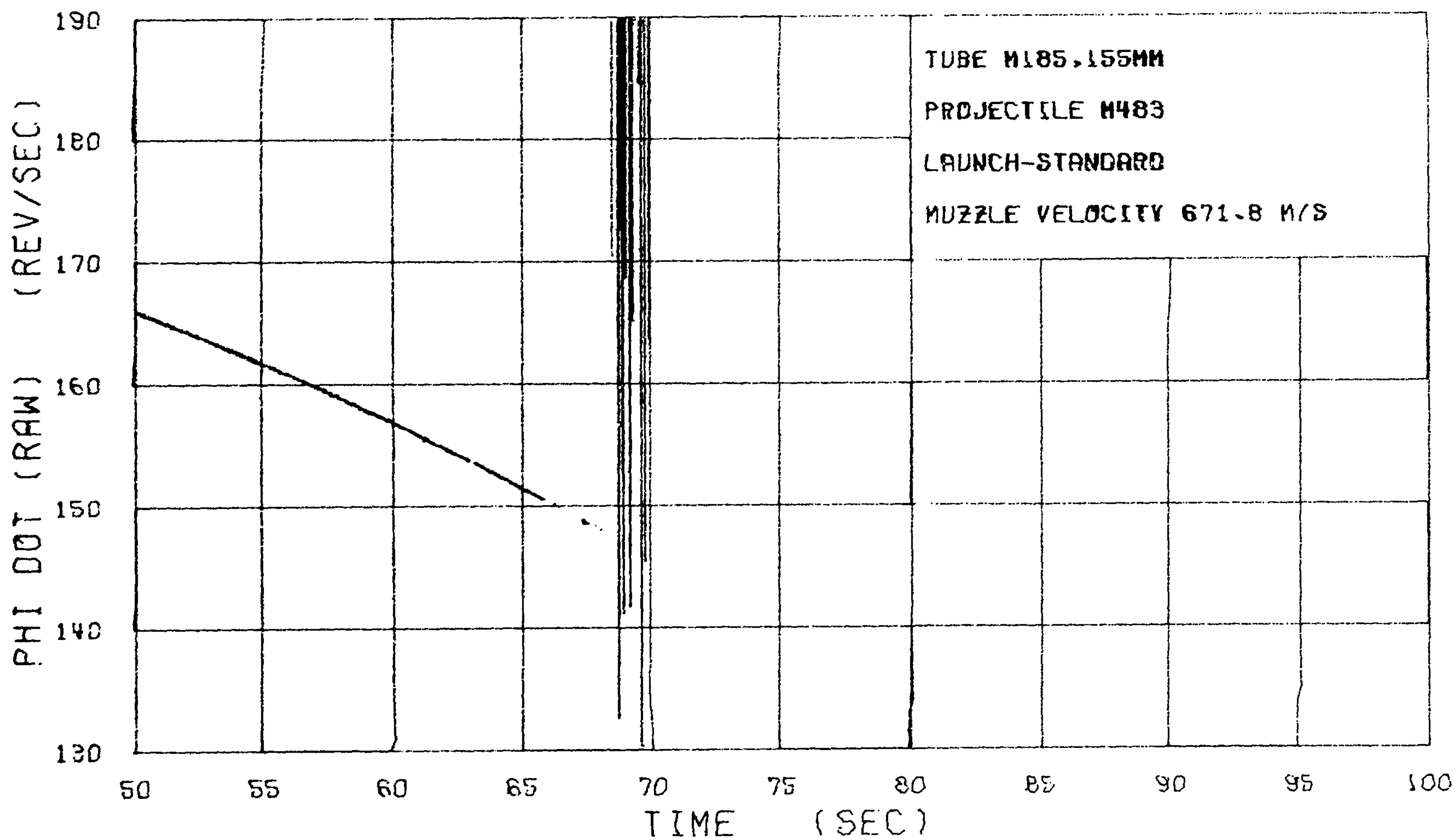

FIGURE 27. PHI DOT (RAW) VS TIME ROUND E1-9195

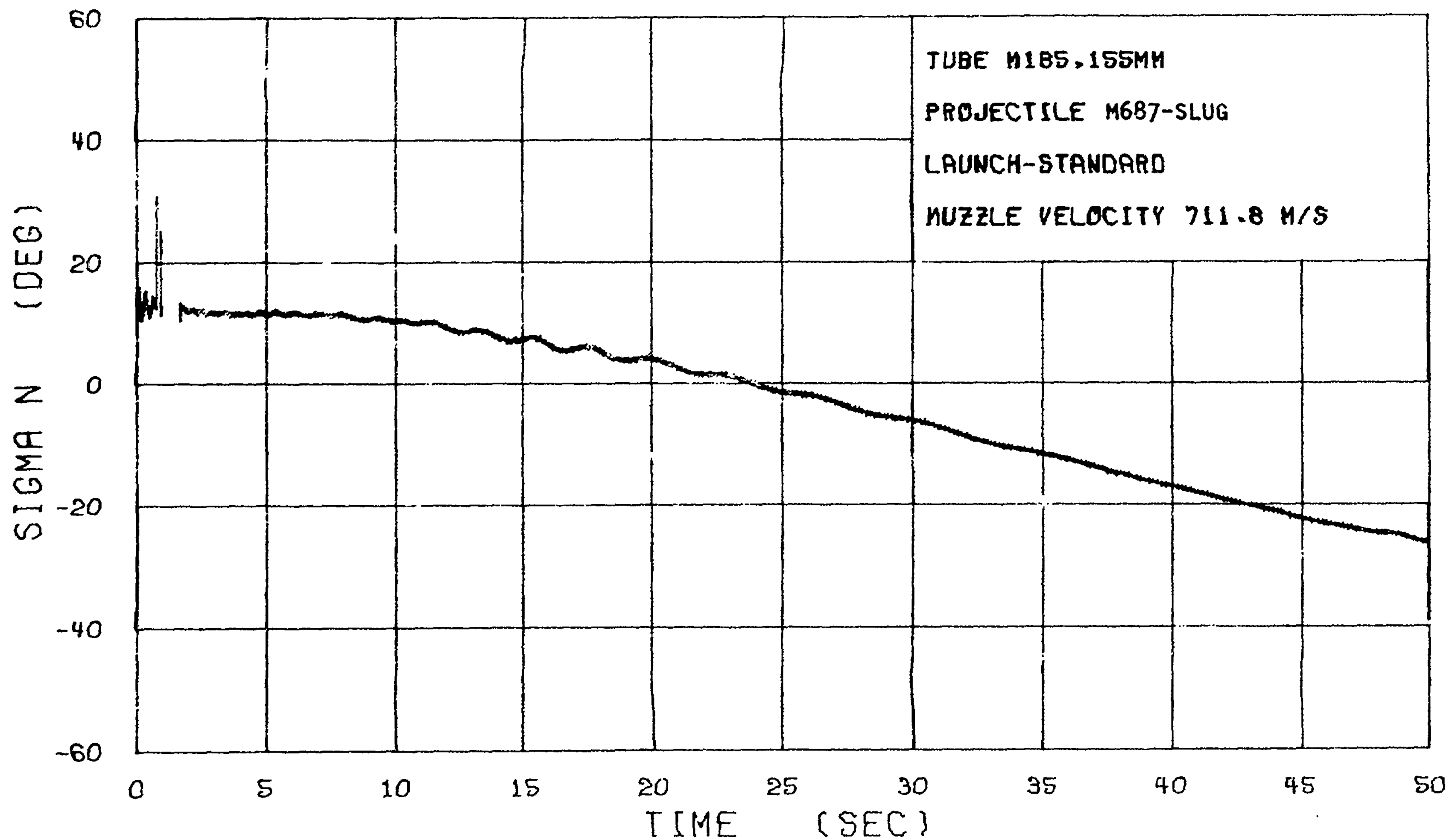

FIGURE 28. SIGMA N VS TIME ROUND E1-9196

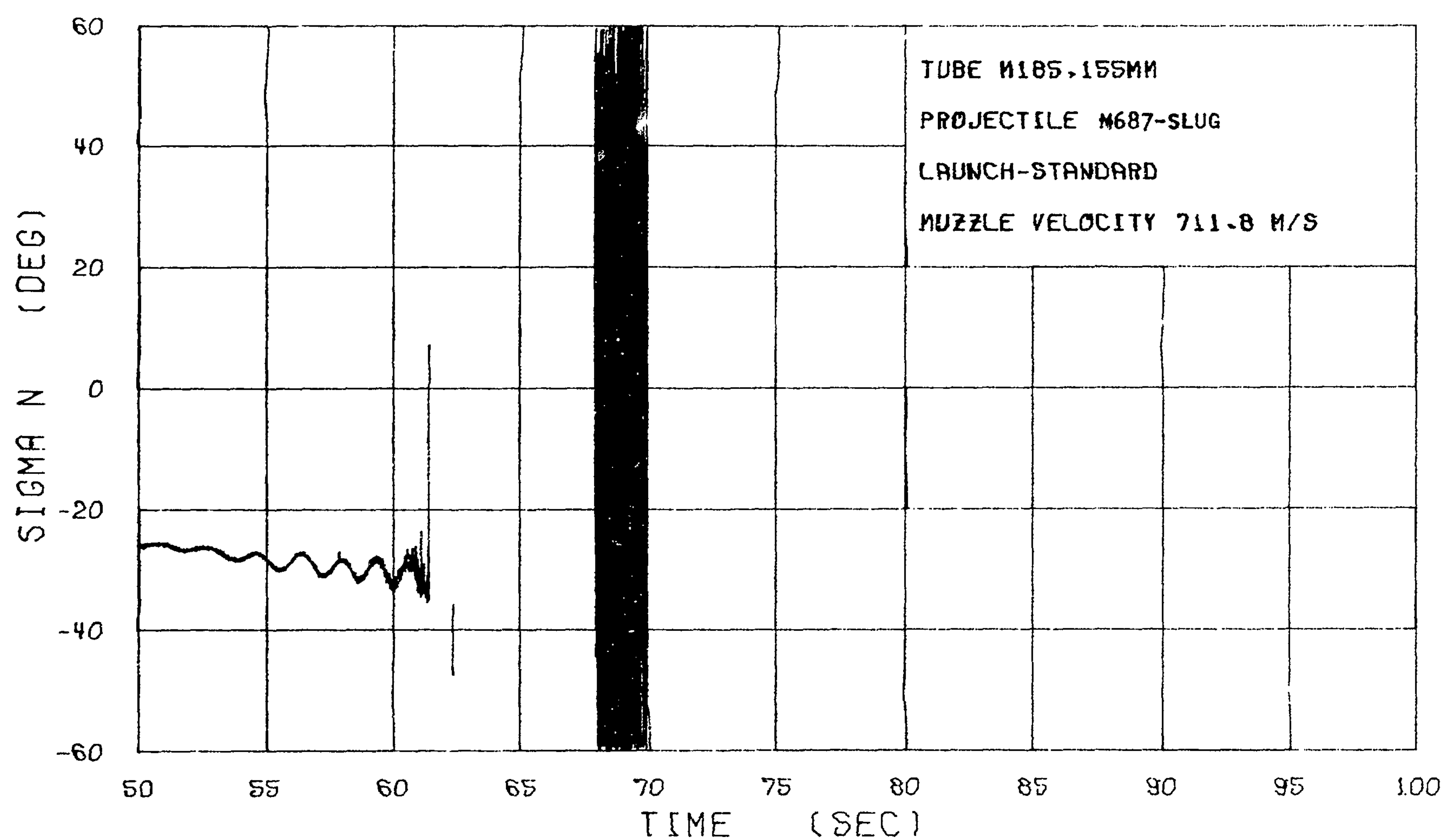

FIGURE 29. SIGMA N VS TIME ROUND E1-9196

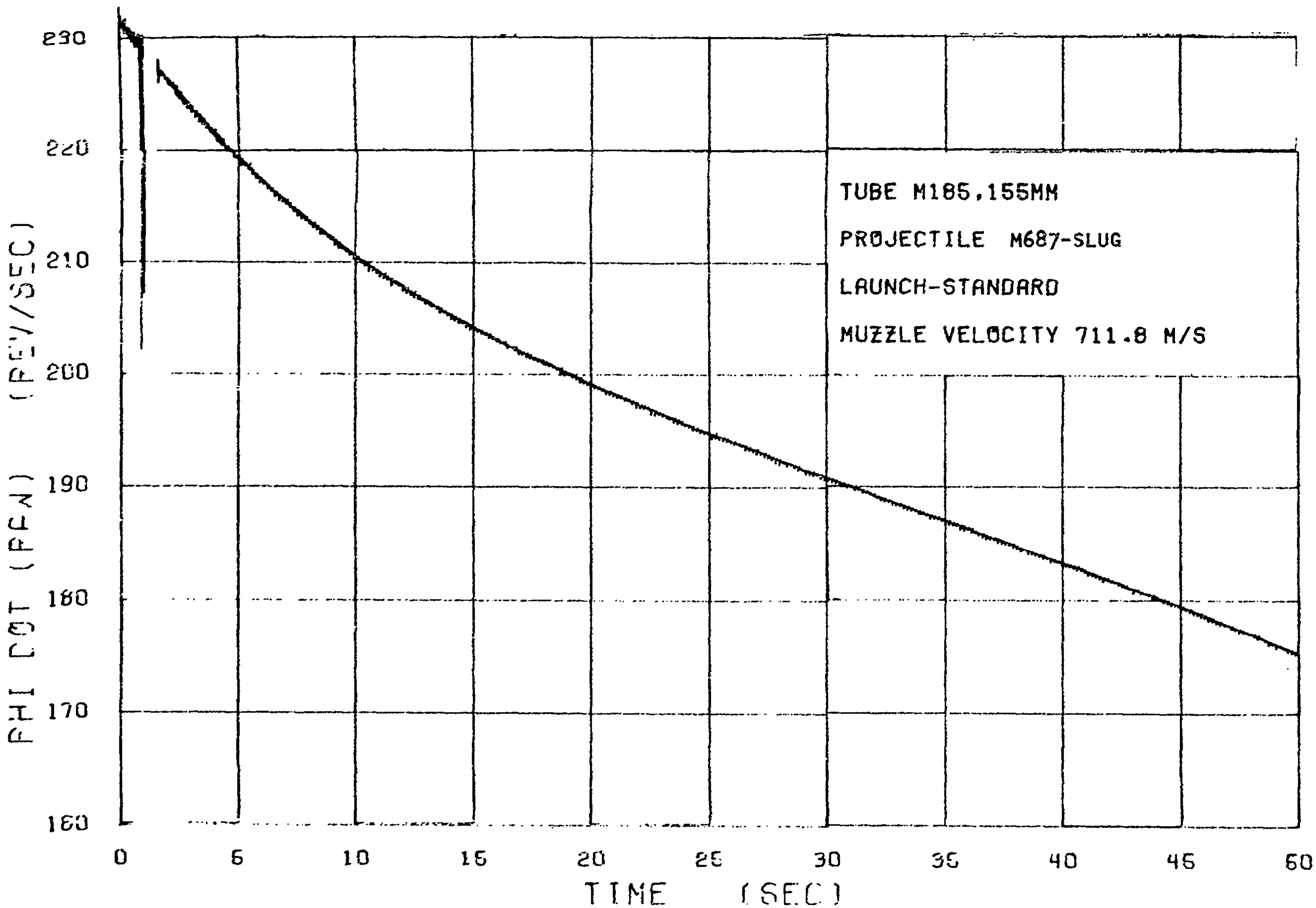

FIGURE 30. PHI DOT (RAW) VS TIME ROUND E1-9196

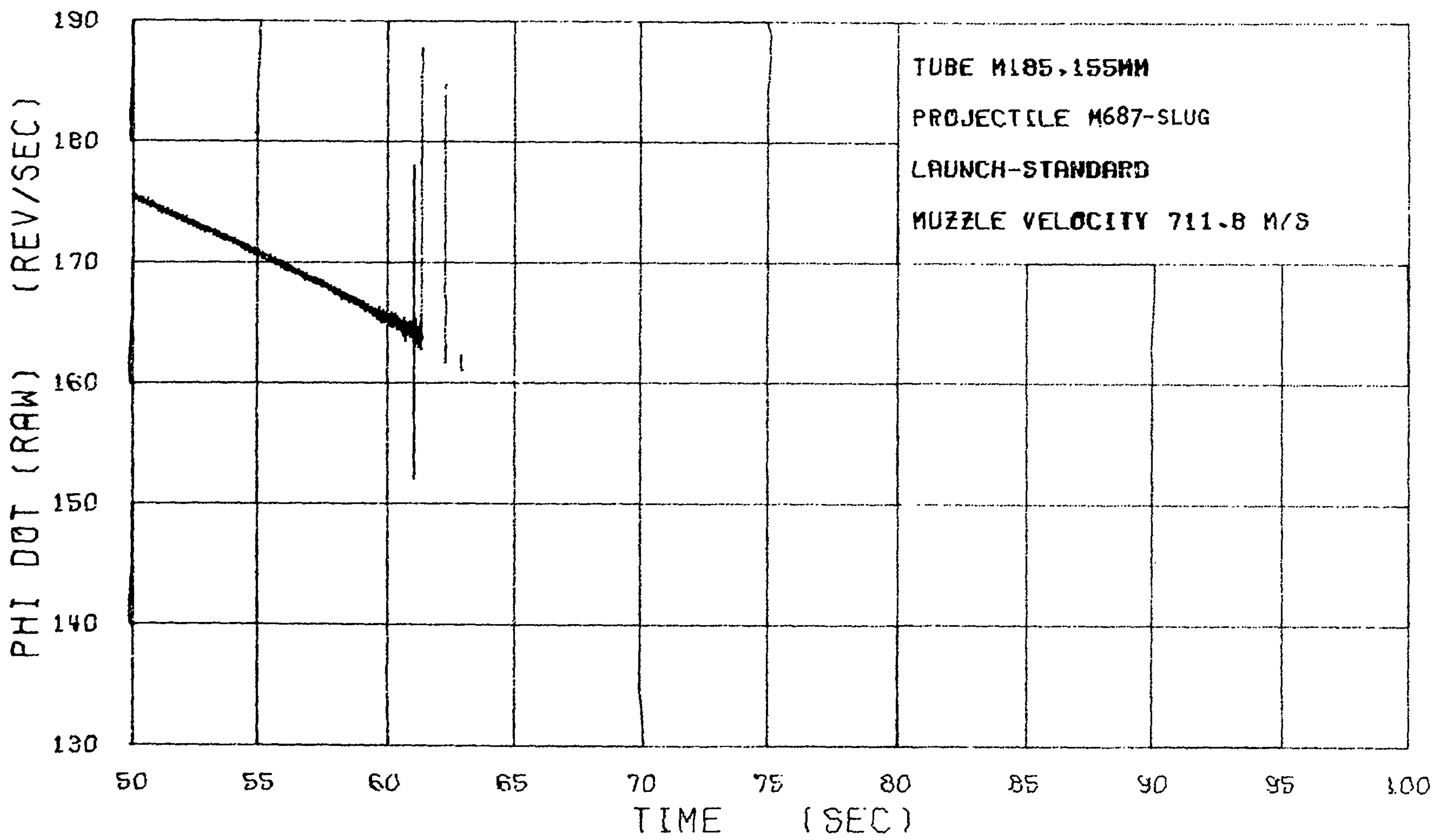

FIGURE 31. PHI DOT (RAW) VS TIME ROUND E1-9196

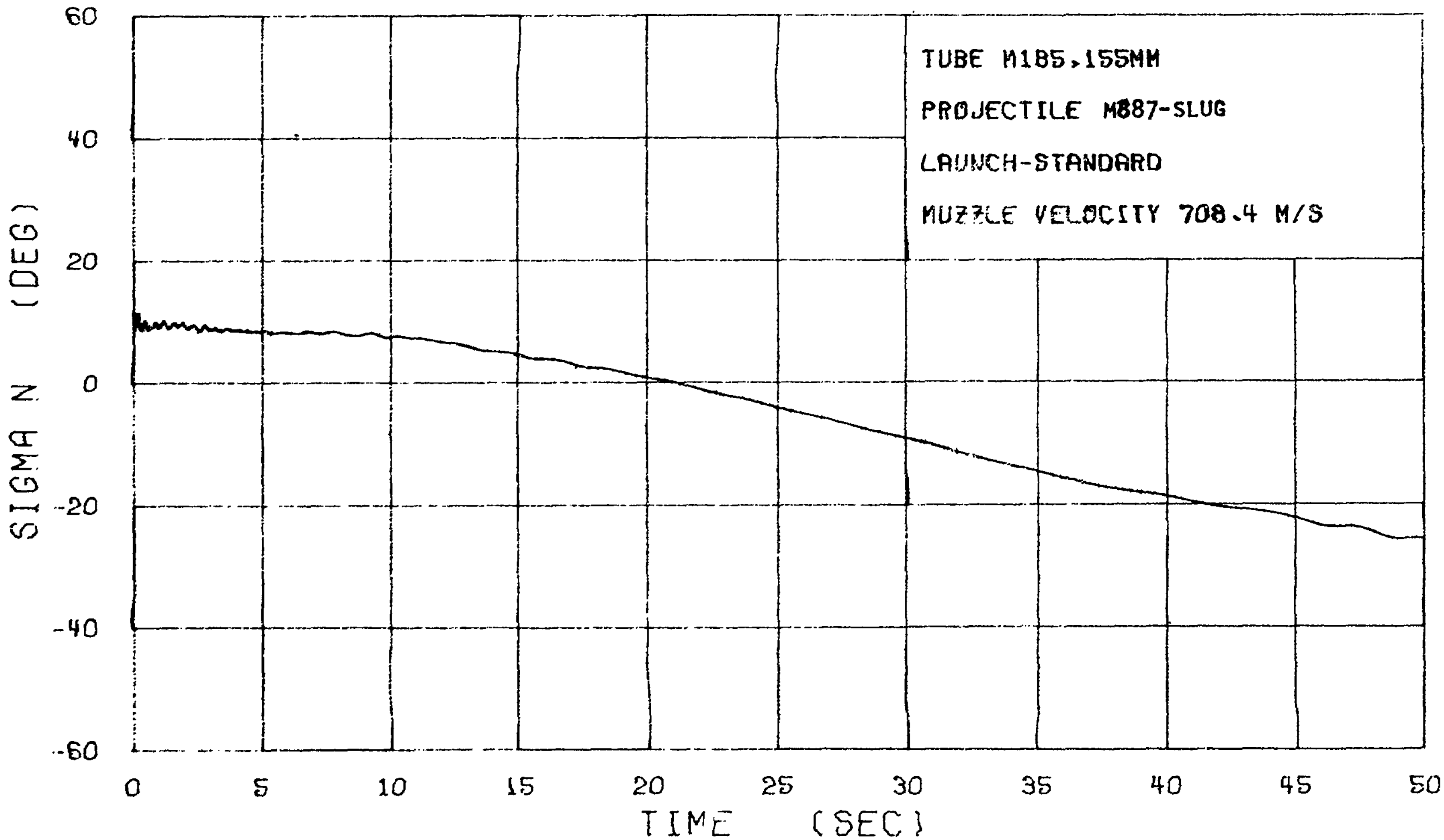

FIGURE 32. SIGMA N VS TIME ROUND E1-9197

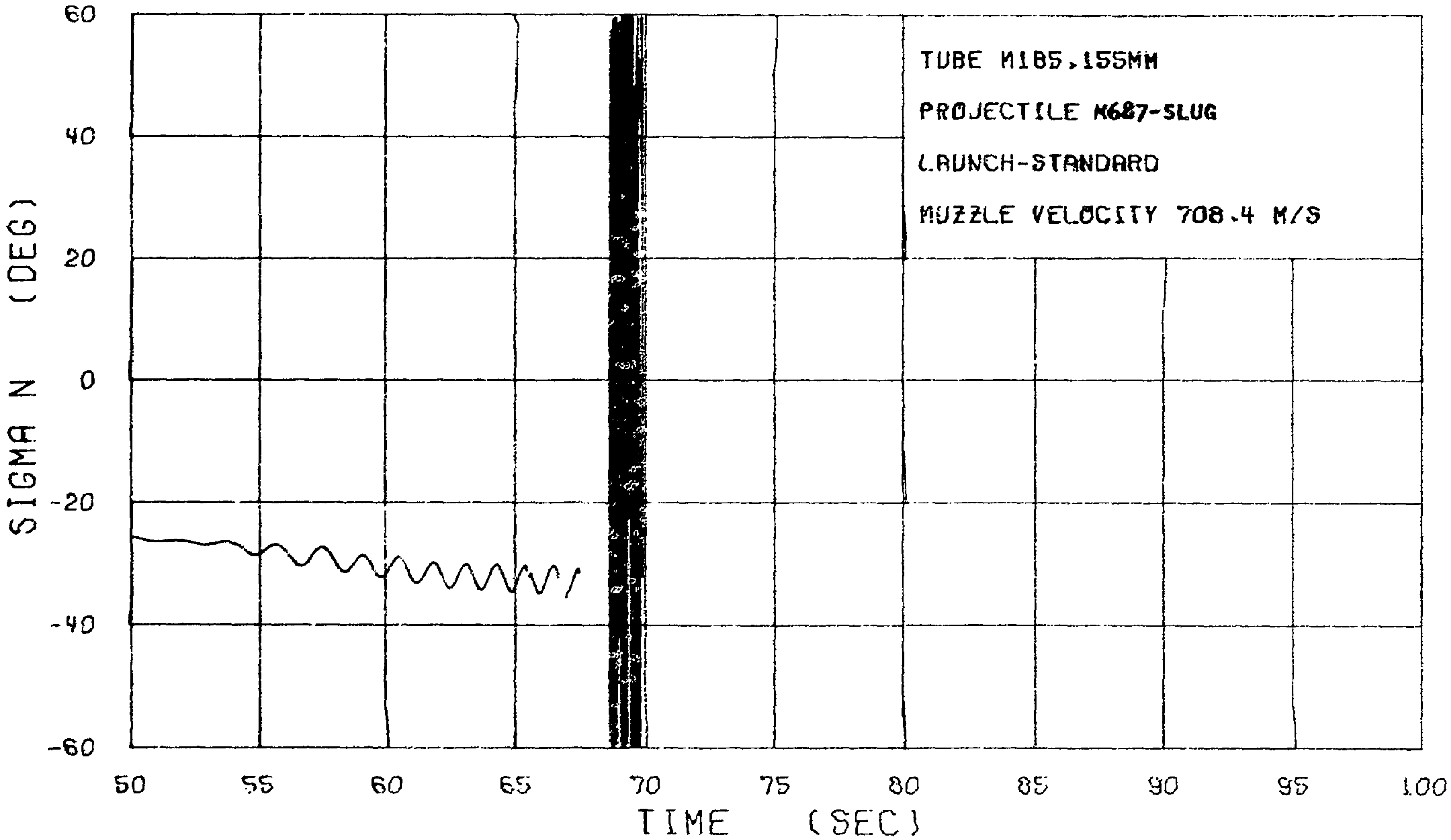

FIGURE 33. SIGMA N VS TIME ROUND E1-9197

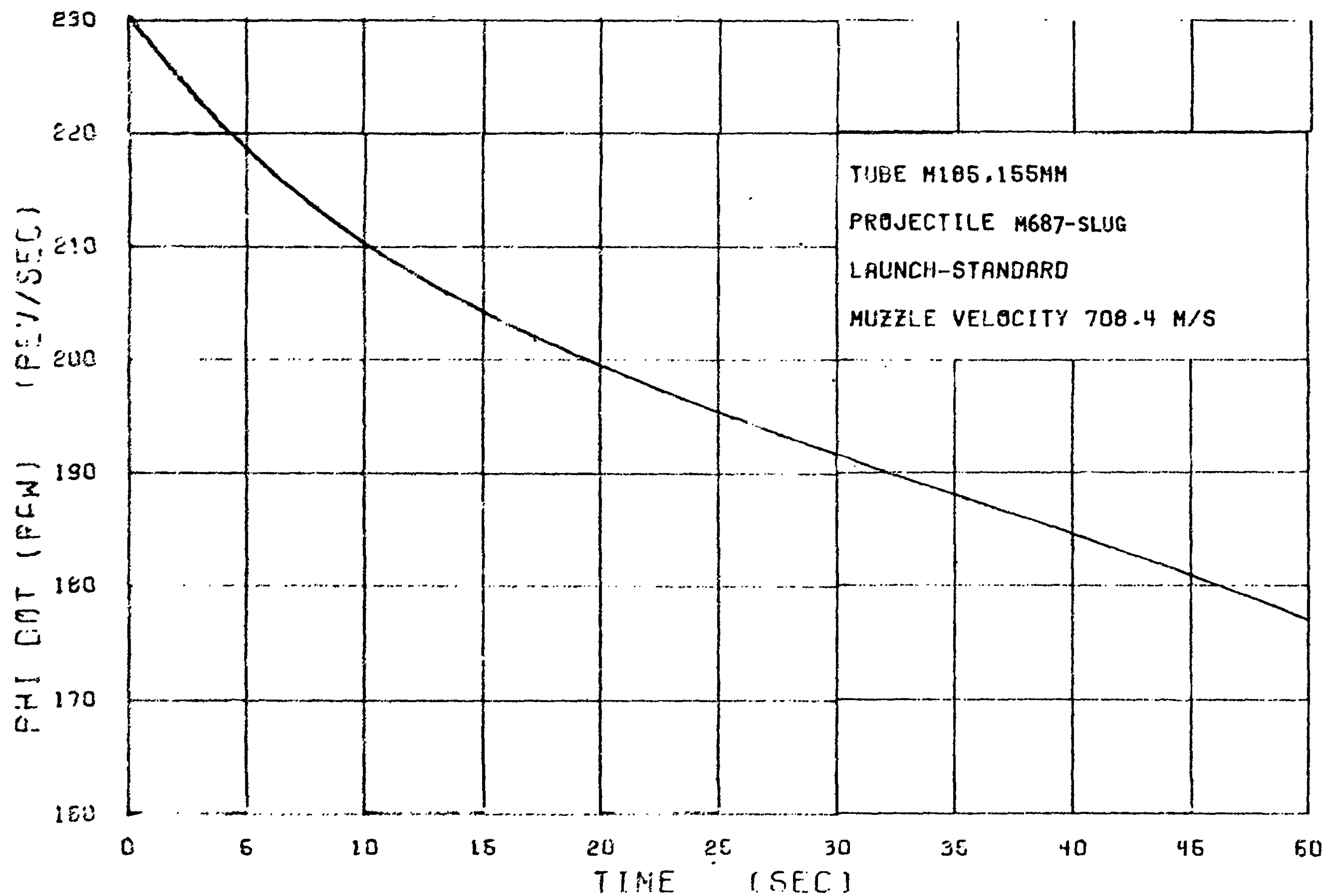

FIGURE 34. PHI DOT (RAW) VS TIME ROUND E1-9197

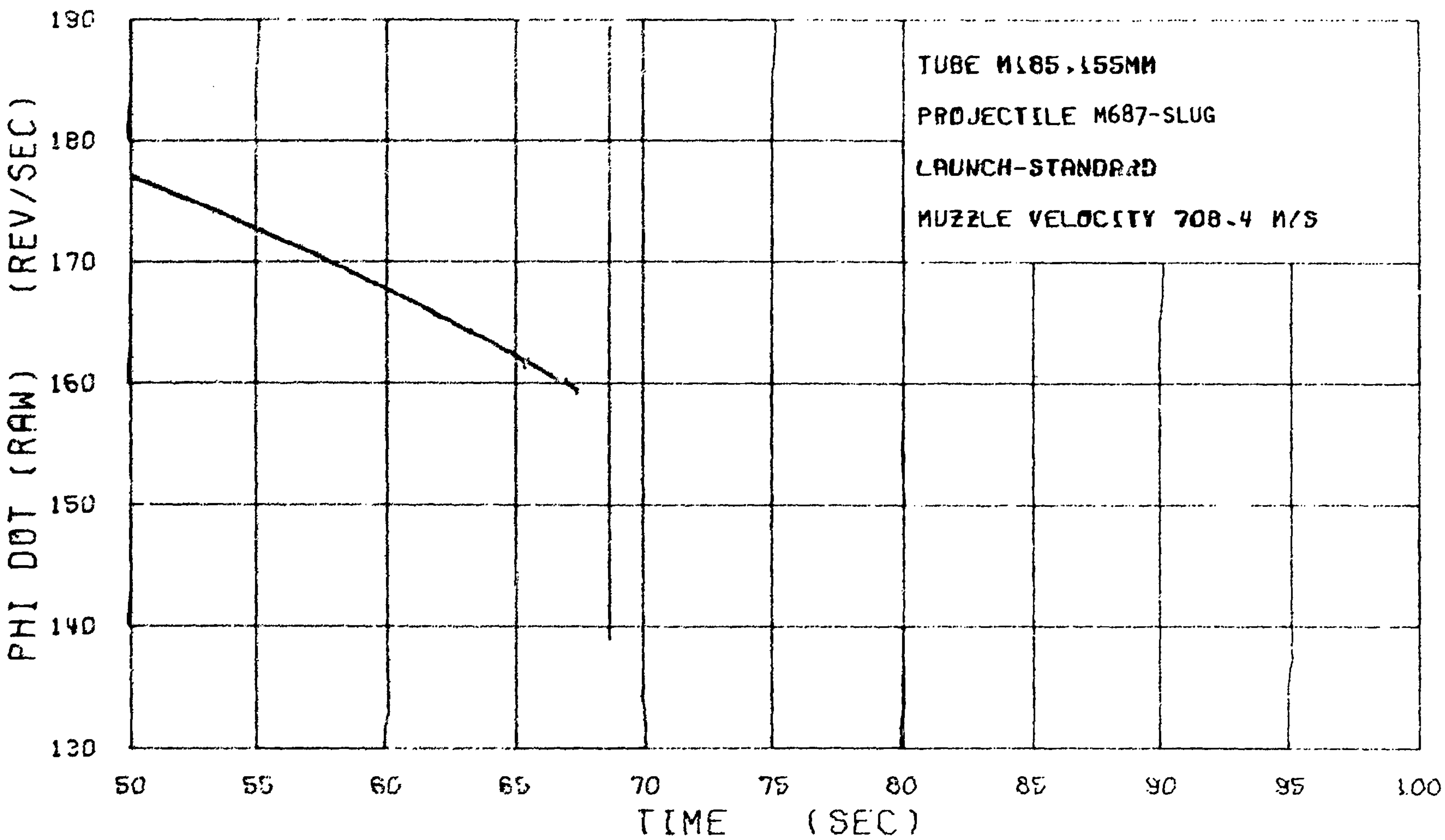

FIGURE 35. PHI DOT (RAW) VS TIME ROUND E1-9197

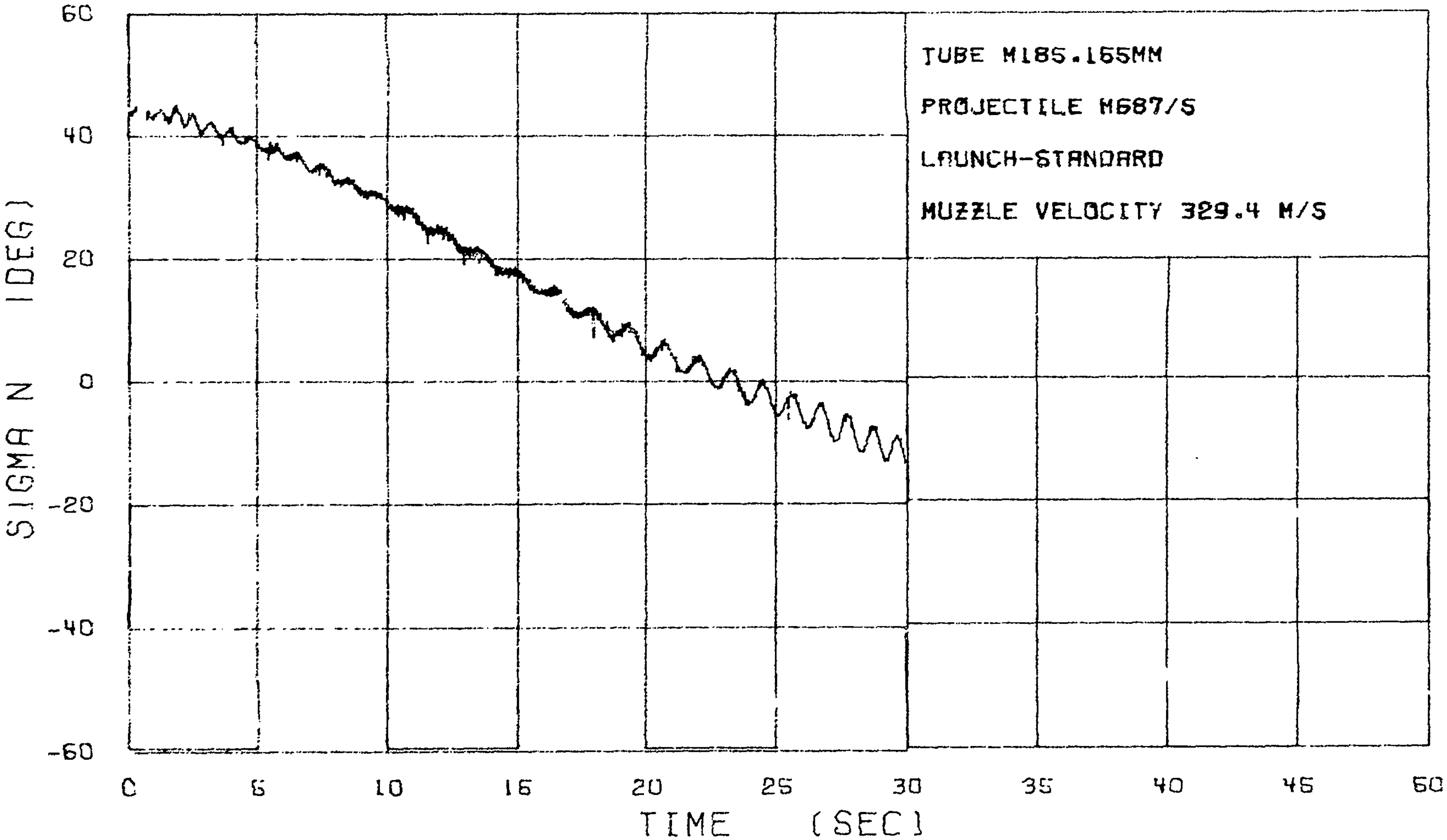

FIGURE 36. SIGMA N VS TIME ROUND E1-9383

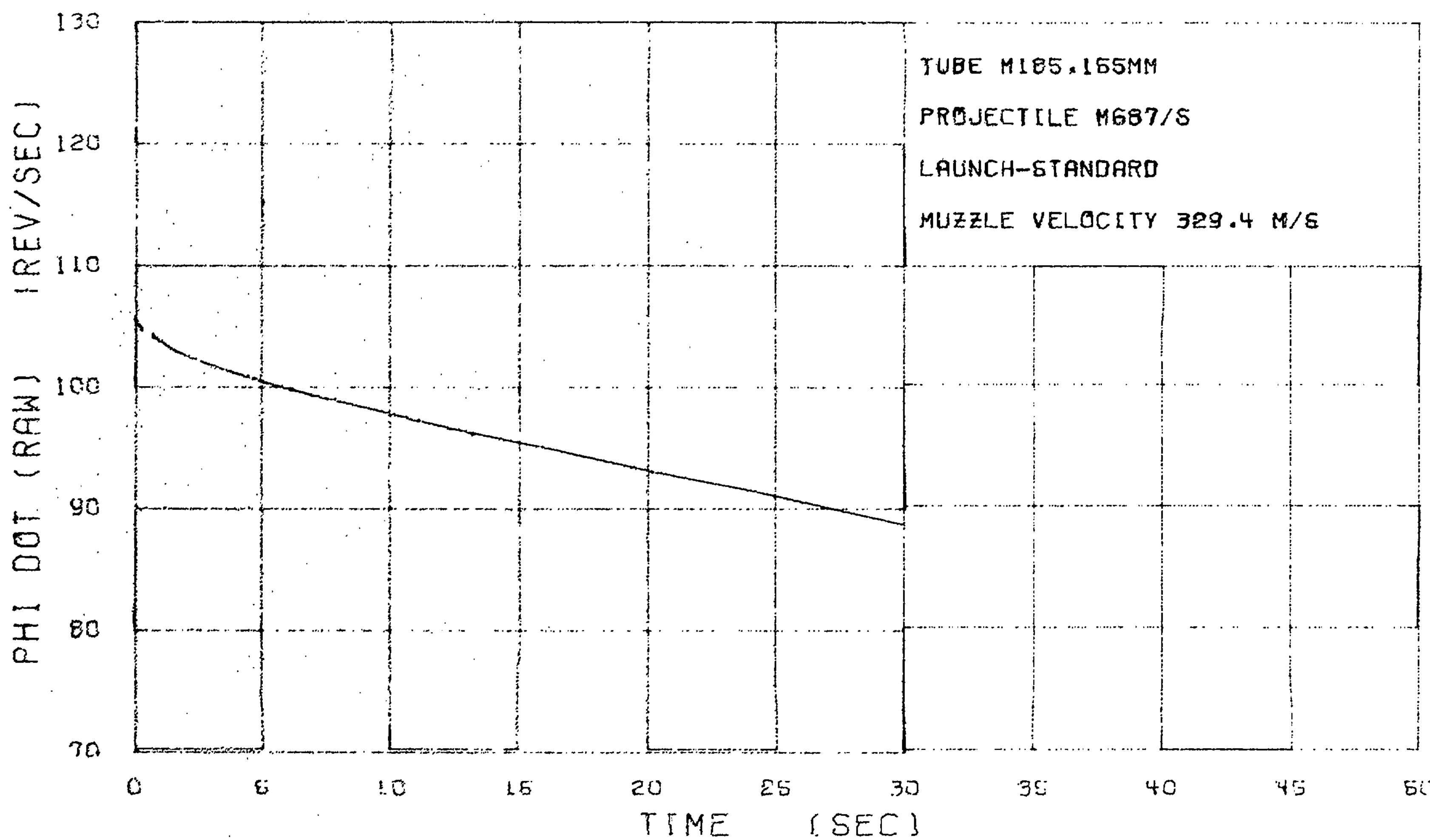

FIGURE 37. PHI DOT (RAW) VS TIME ROUND E1-9383

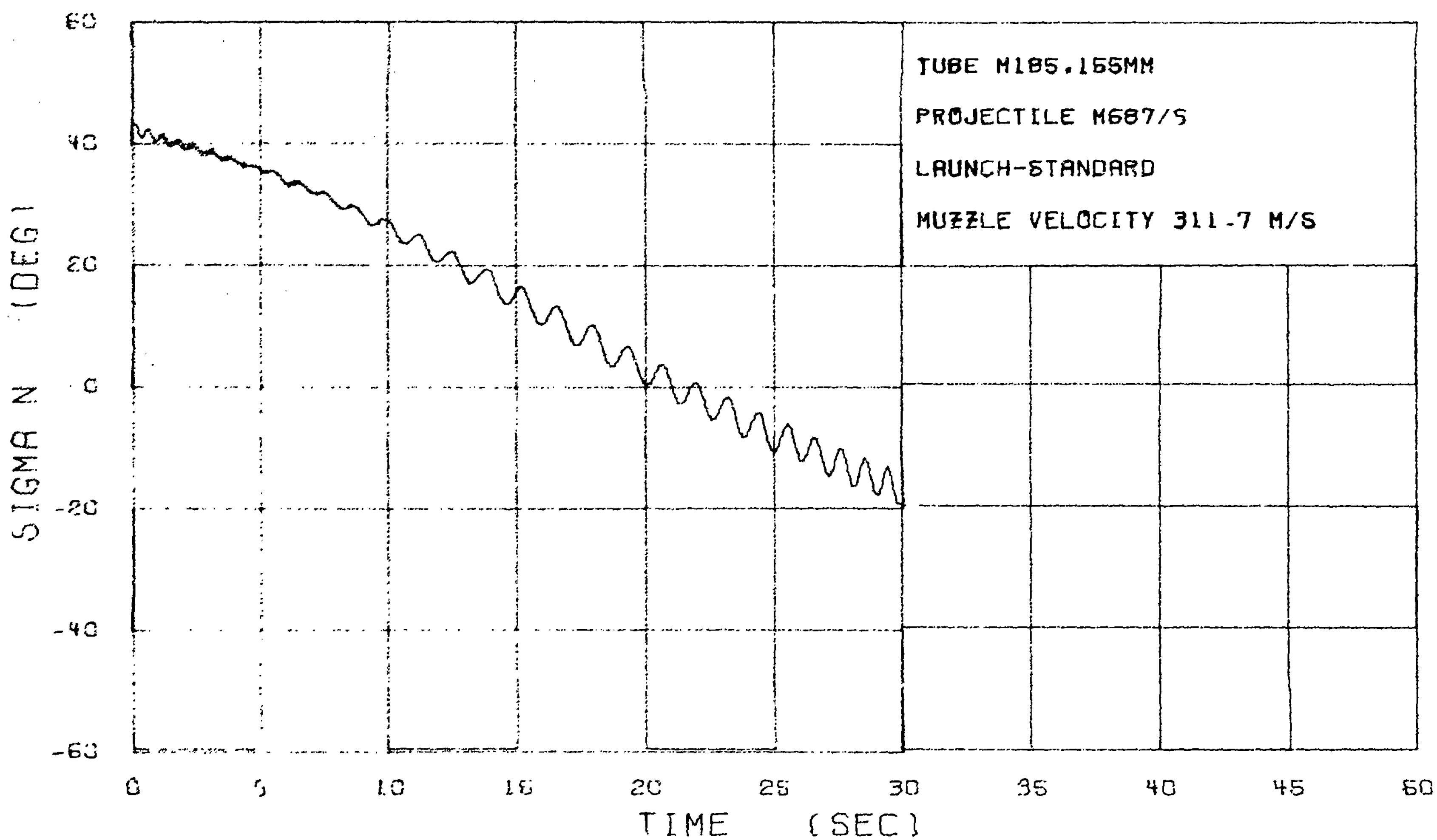

FIGURE 38. SIGMA N VS TIME ROUND E1-9384

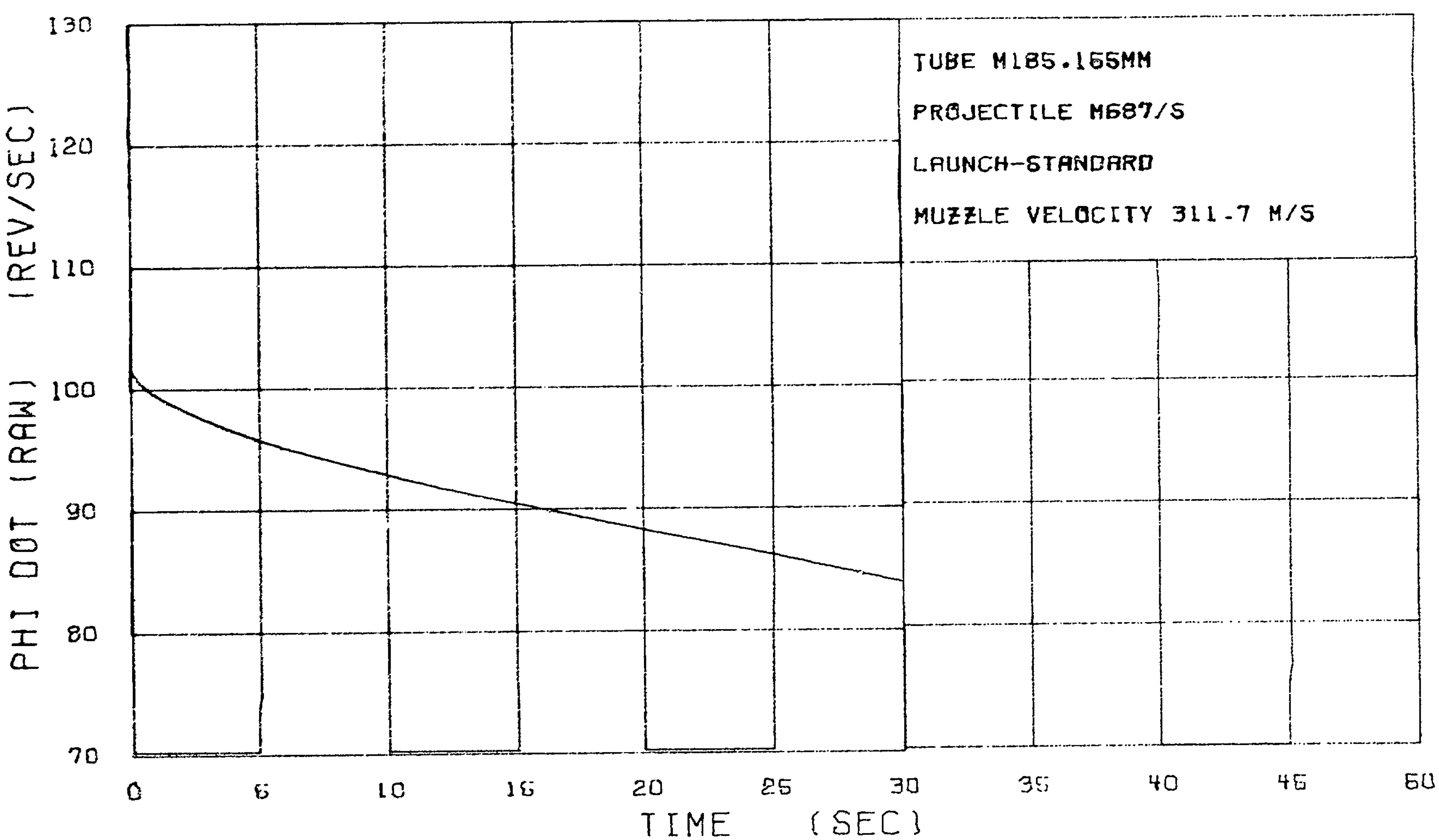

FIGURE 39. PHI DOT (RAW) VS TIME ROUND E1-9384

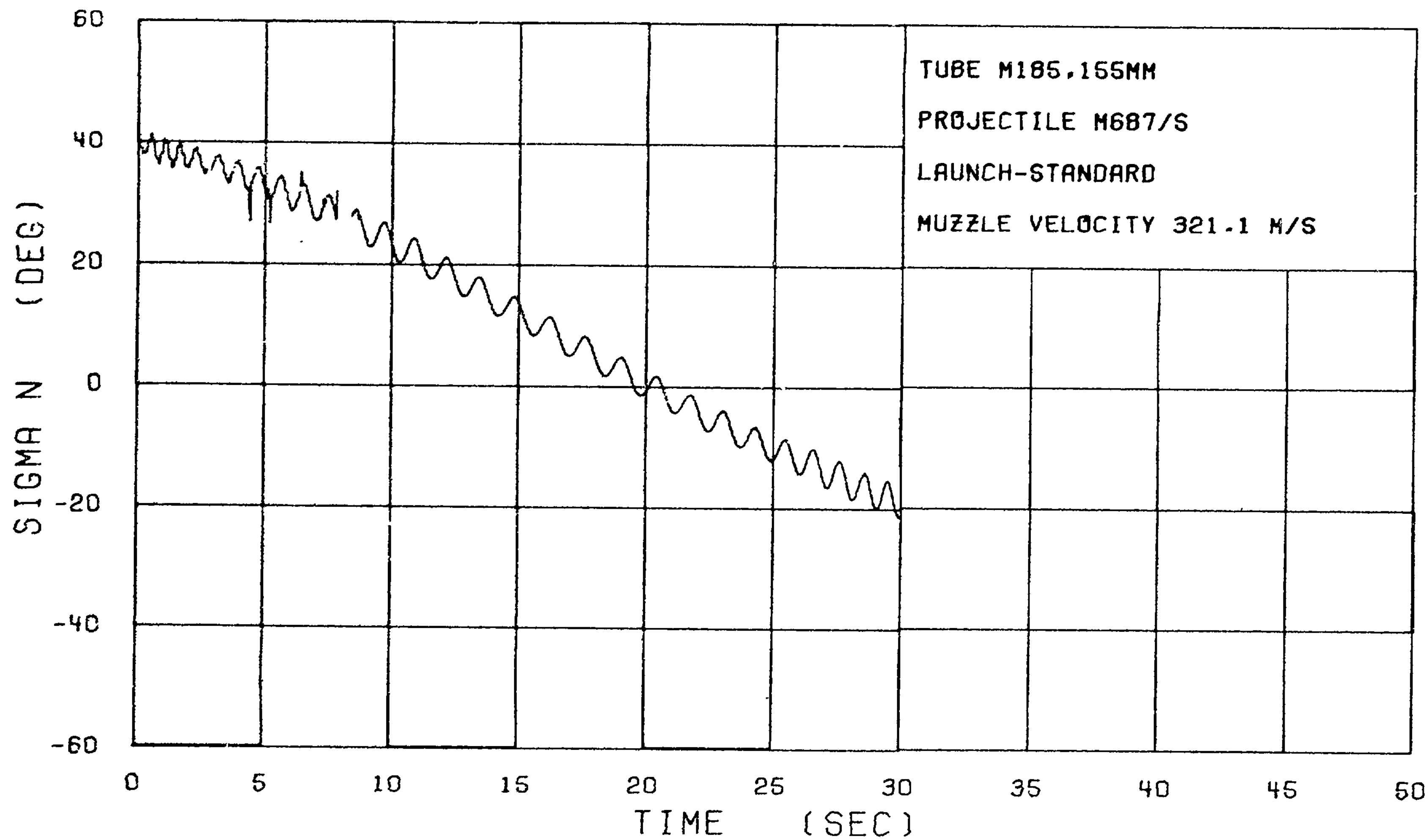

FIGURE 40. SIGMA N VS TIME ROUND E1-9385

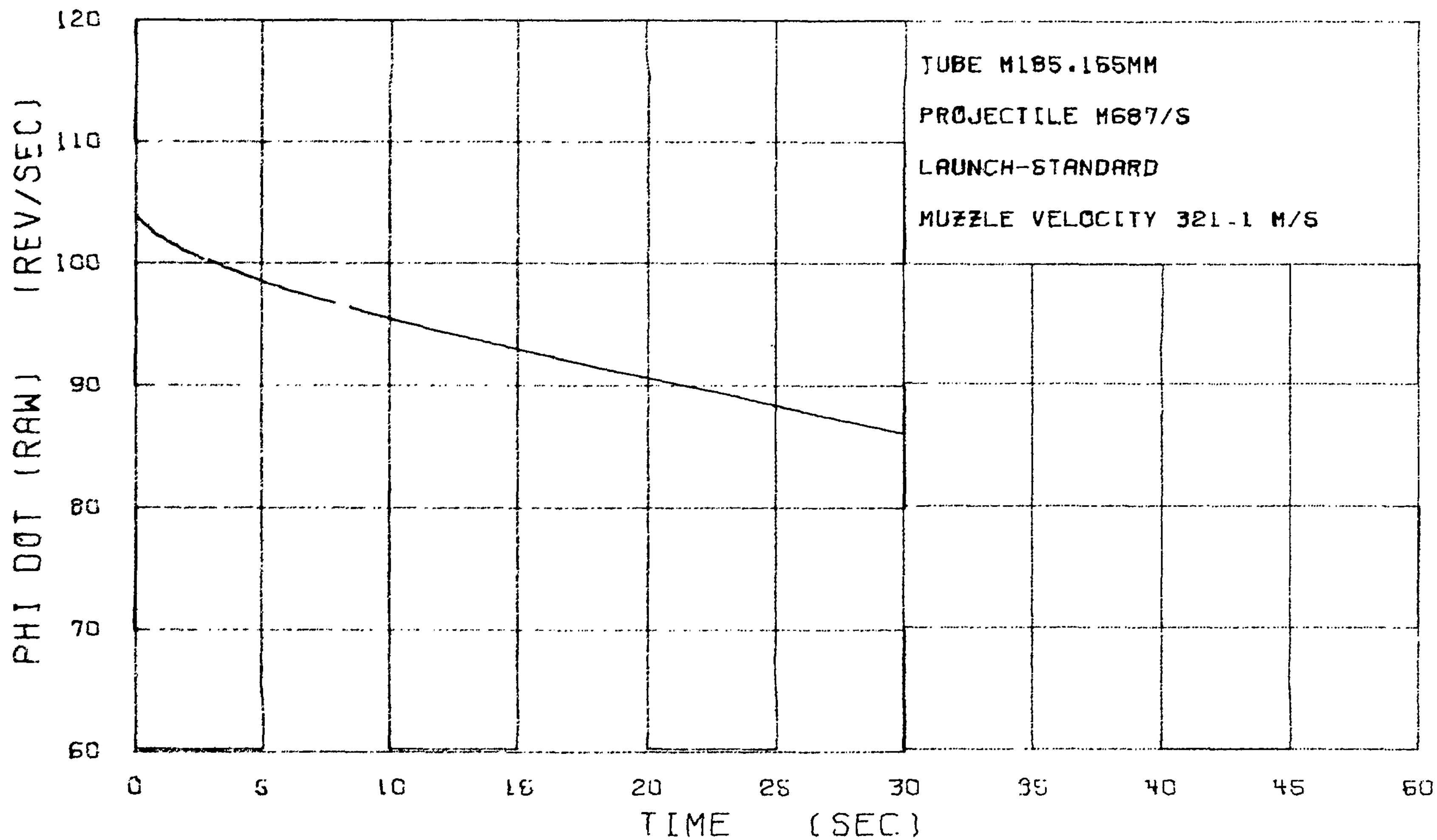

FIGURE 41. PHI DOT (RAW) VS TIME ROUND E1-9385

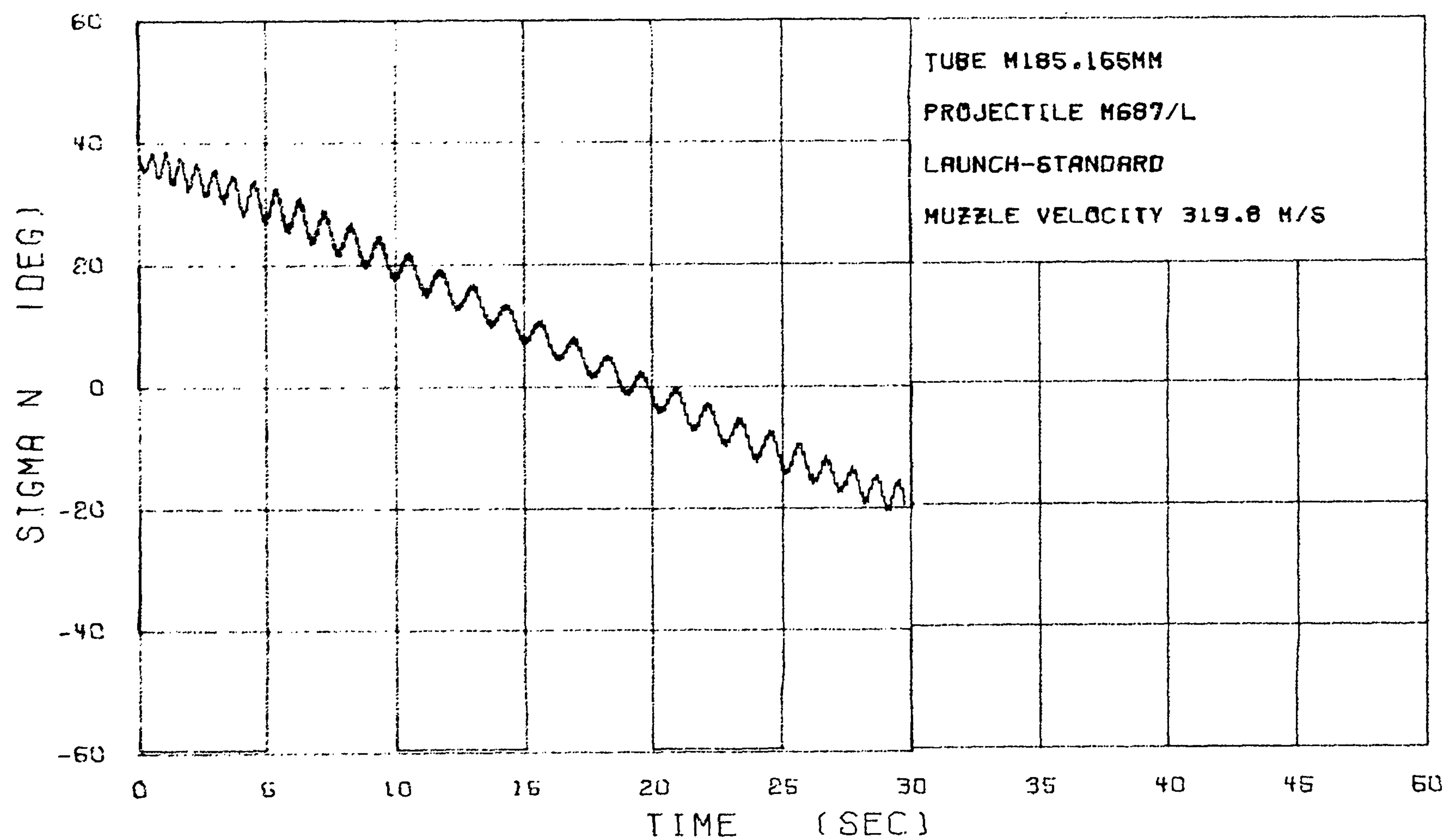

FIGURE 42 SIGMA N VS TIME ROUND E1-9386

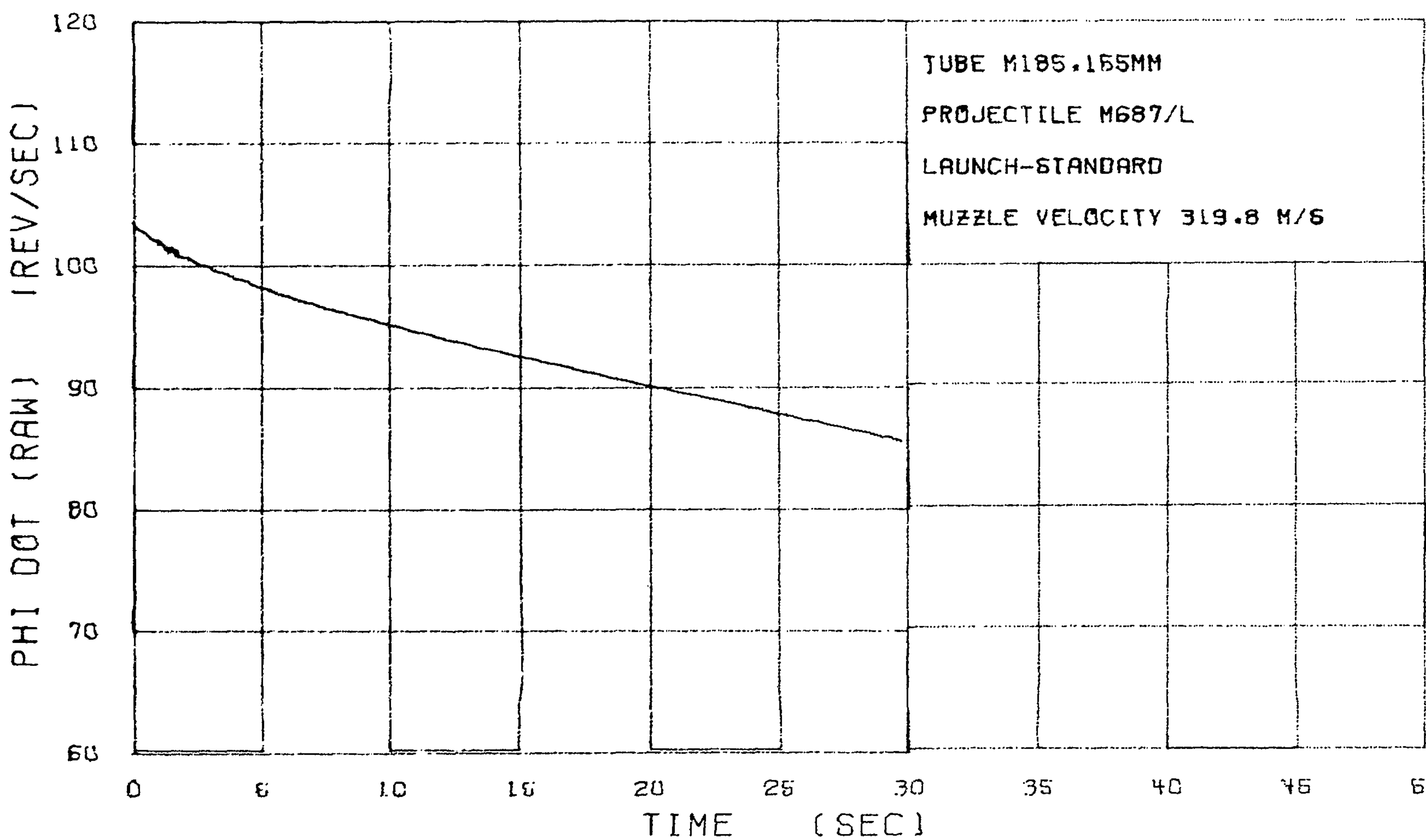

FIGURE 43. PHI DOT (RAW) VS TIME ROUND E1-9386

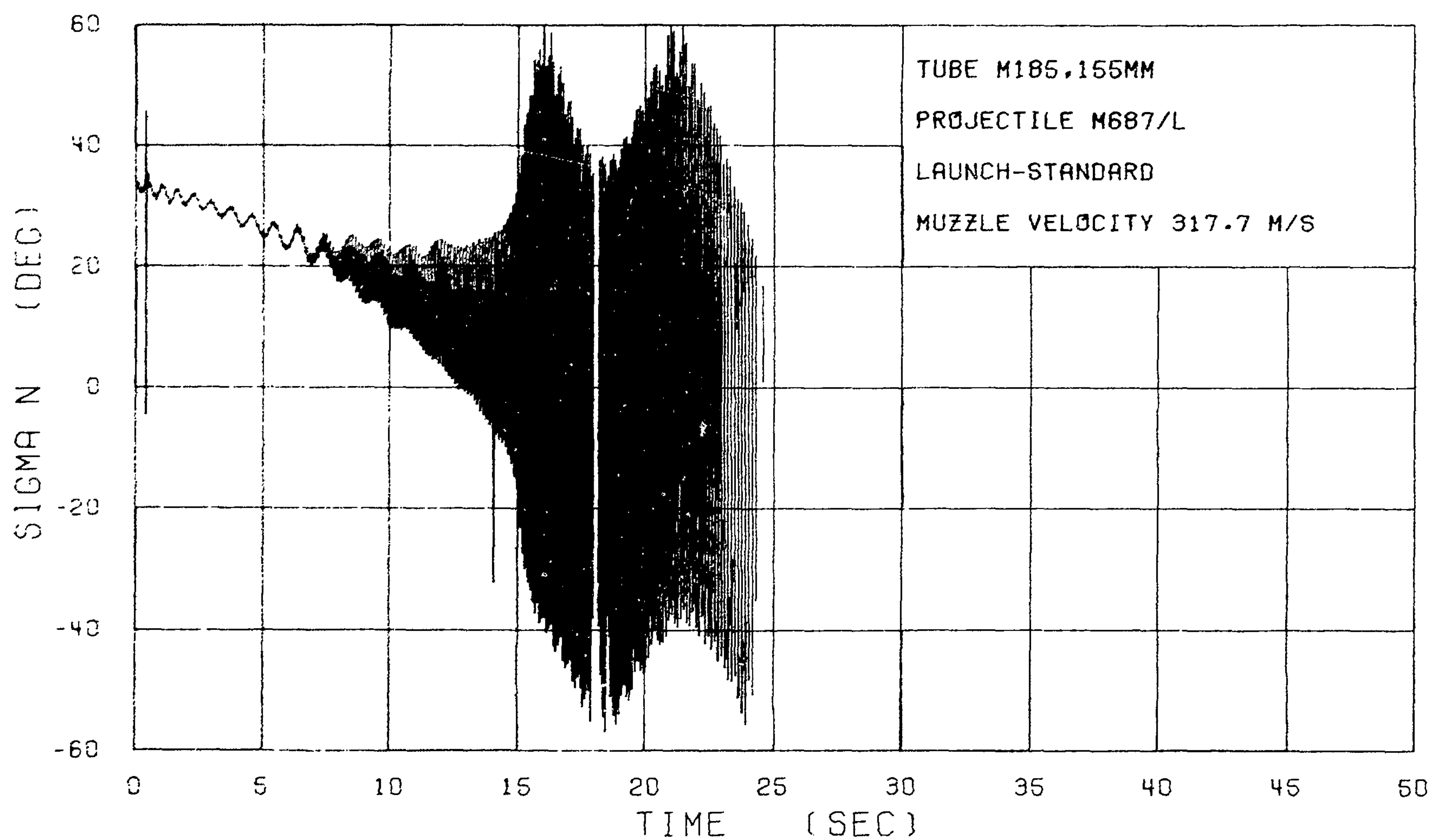

FIGURE 44. SIGMA N VS TIME ROUND E1-9387

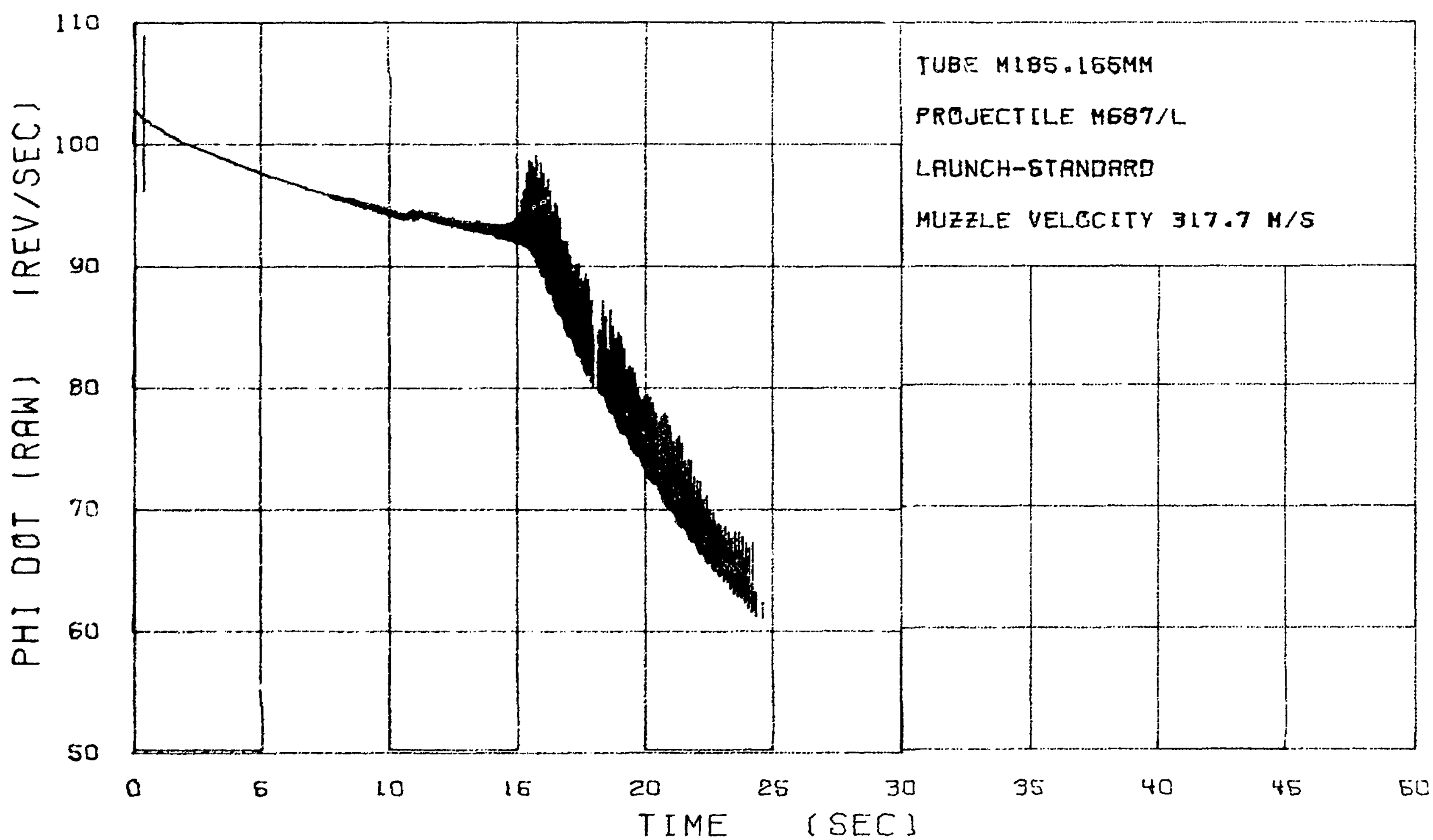

FIGURE 45. PHI DOT (RAW) VS TIME ROUND E1-9387

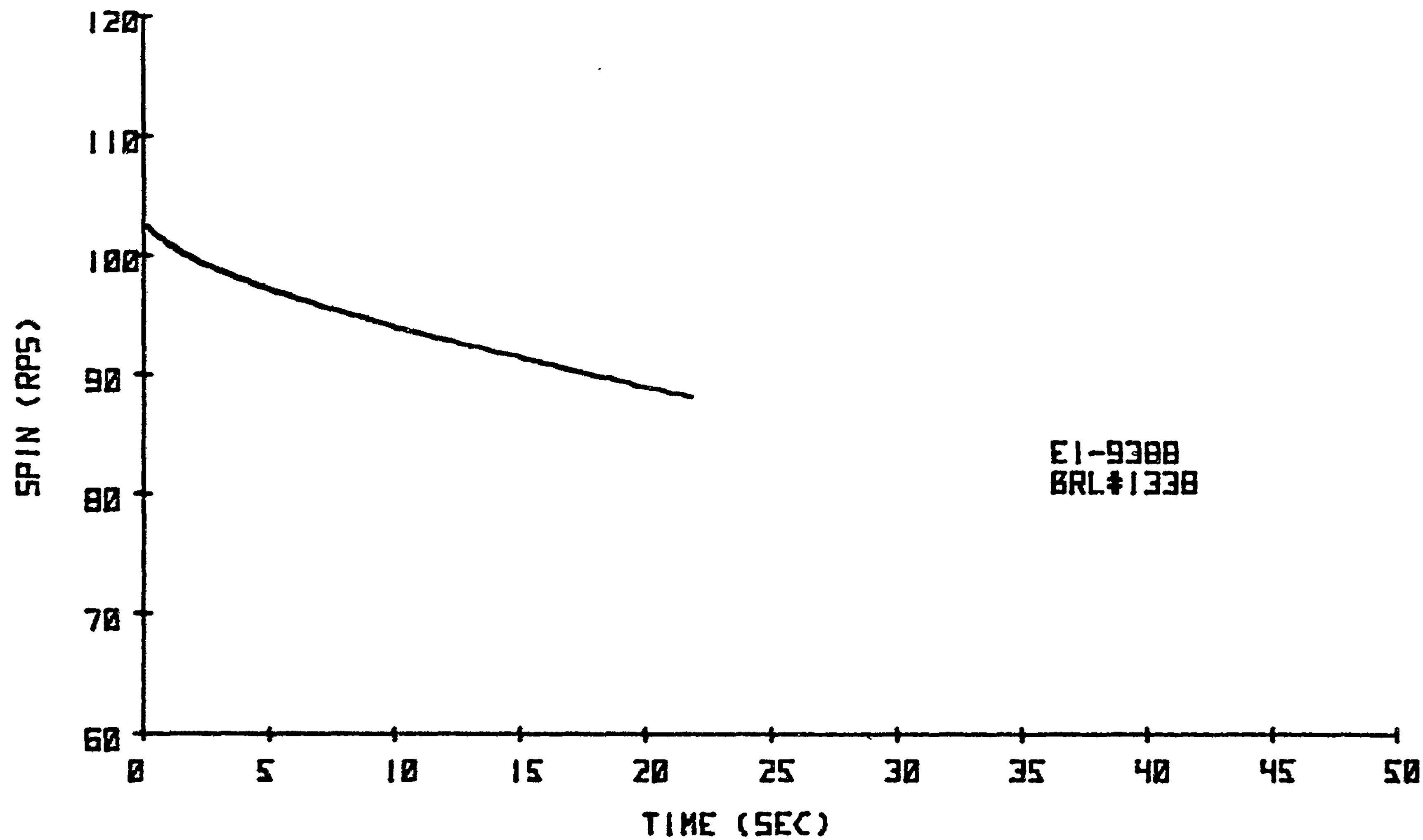

Figure 46. Phi Dot (Raw) Vs Time Round E1-9388

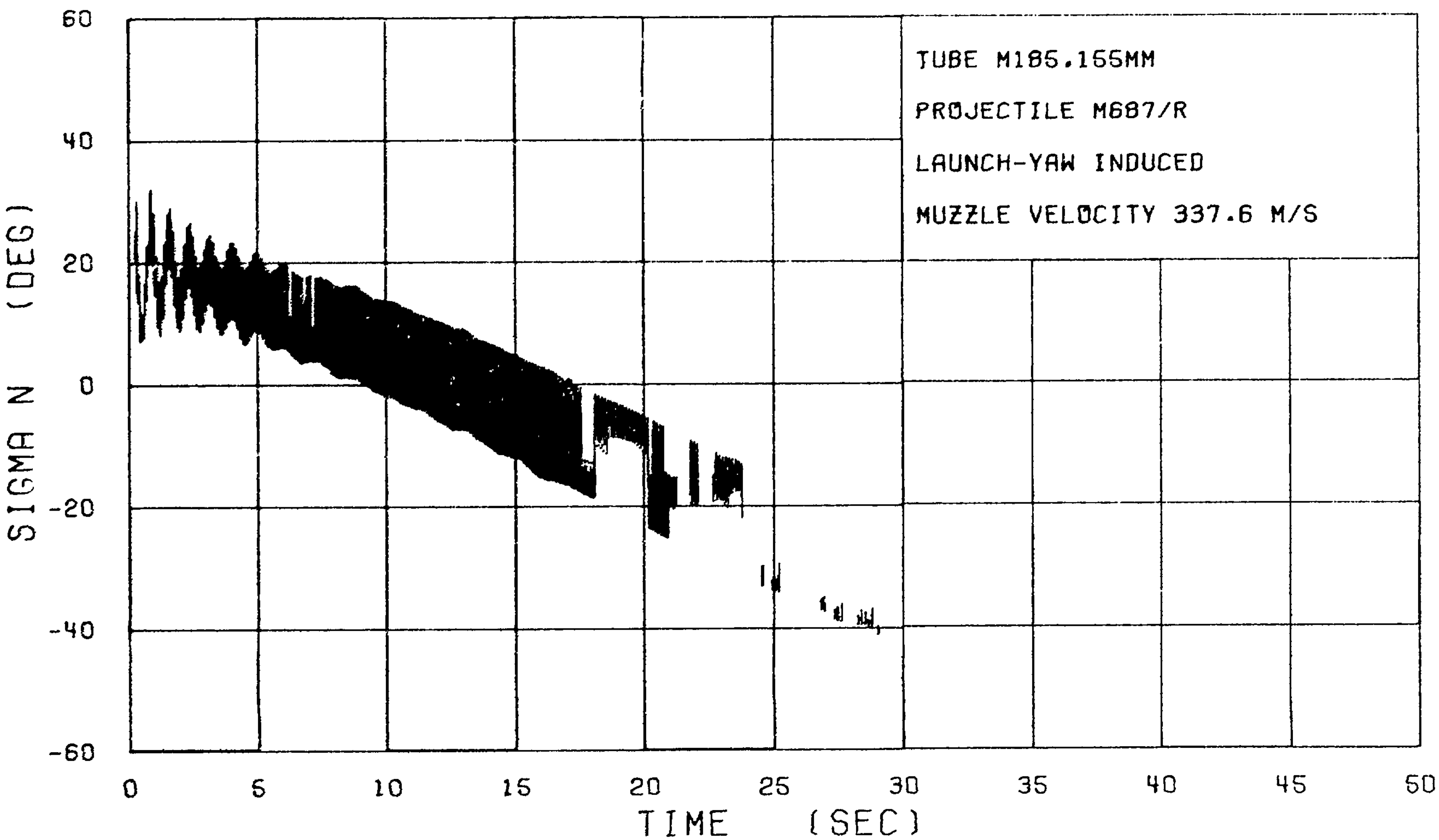

FIGURE 47. SIGMA N VS TIME ROUND E1-9389

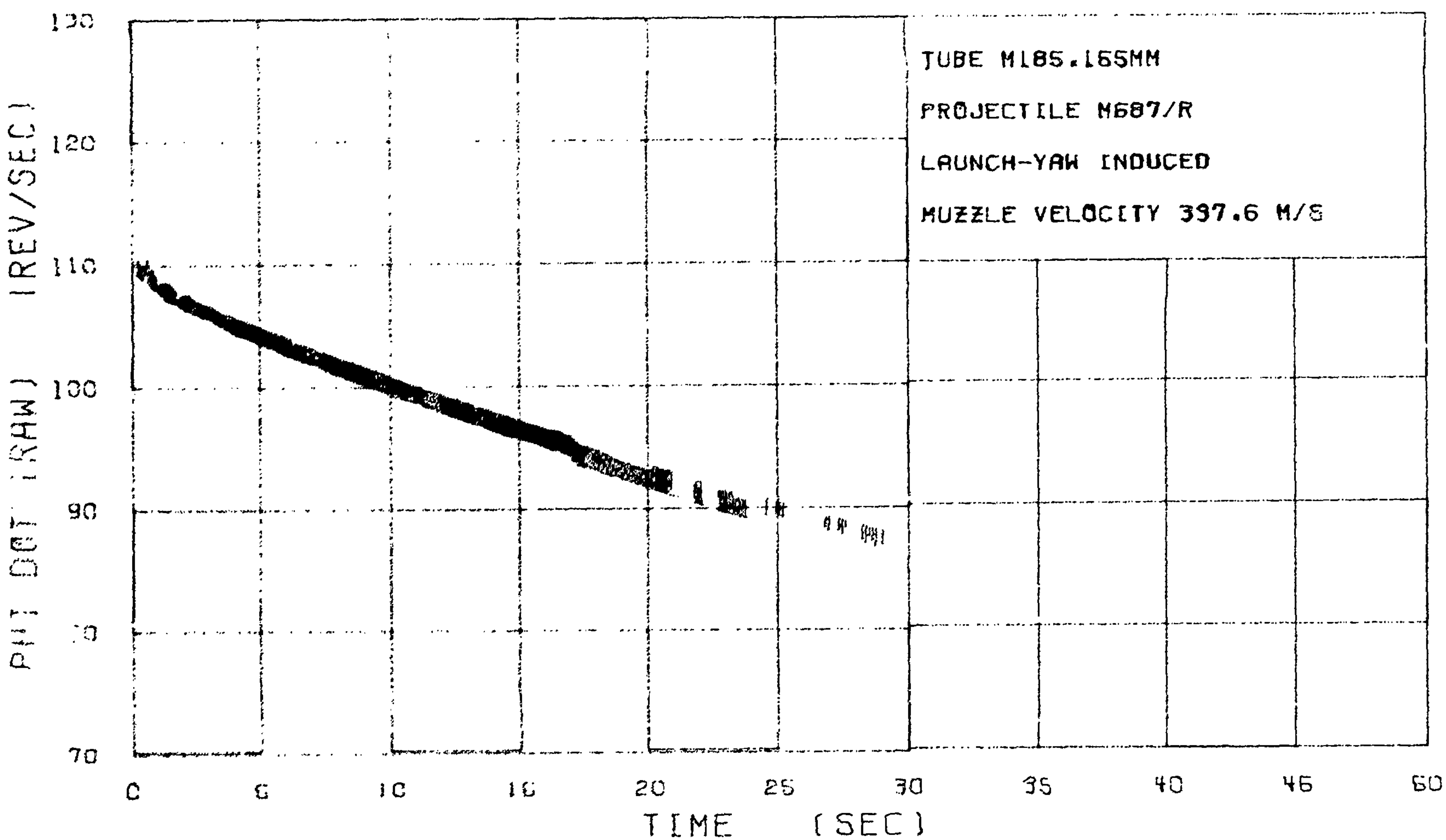

FIGURE 48. PHI DOT (RAW) VS TIME ROUND E1-9389

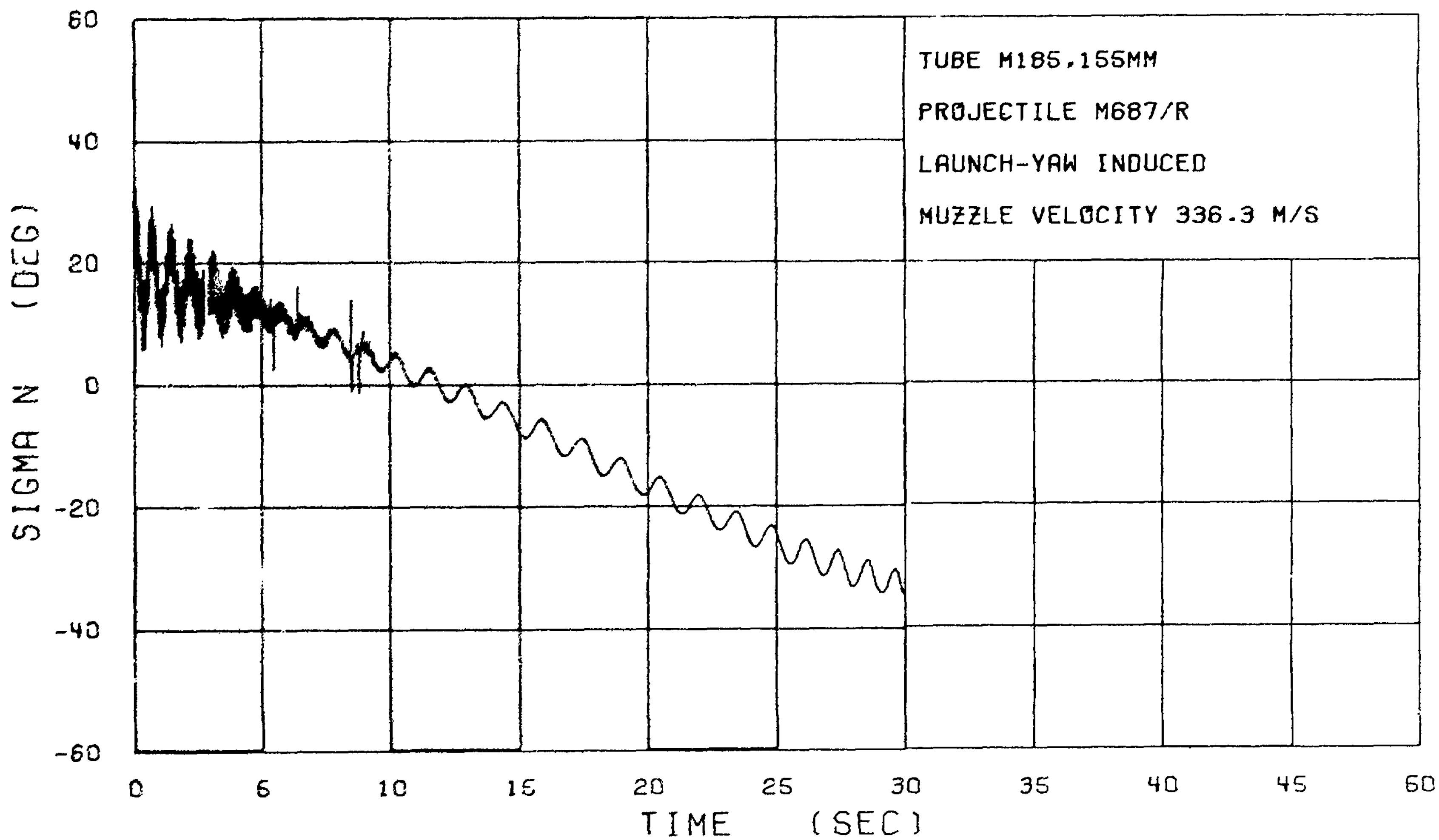

FIGURE 49. SIGMA N VS TIME ROUND E1-9390

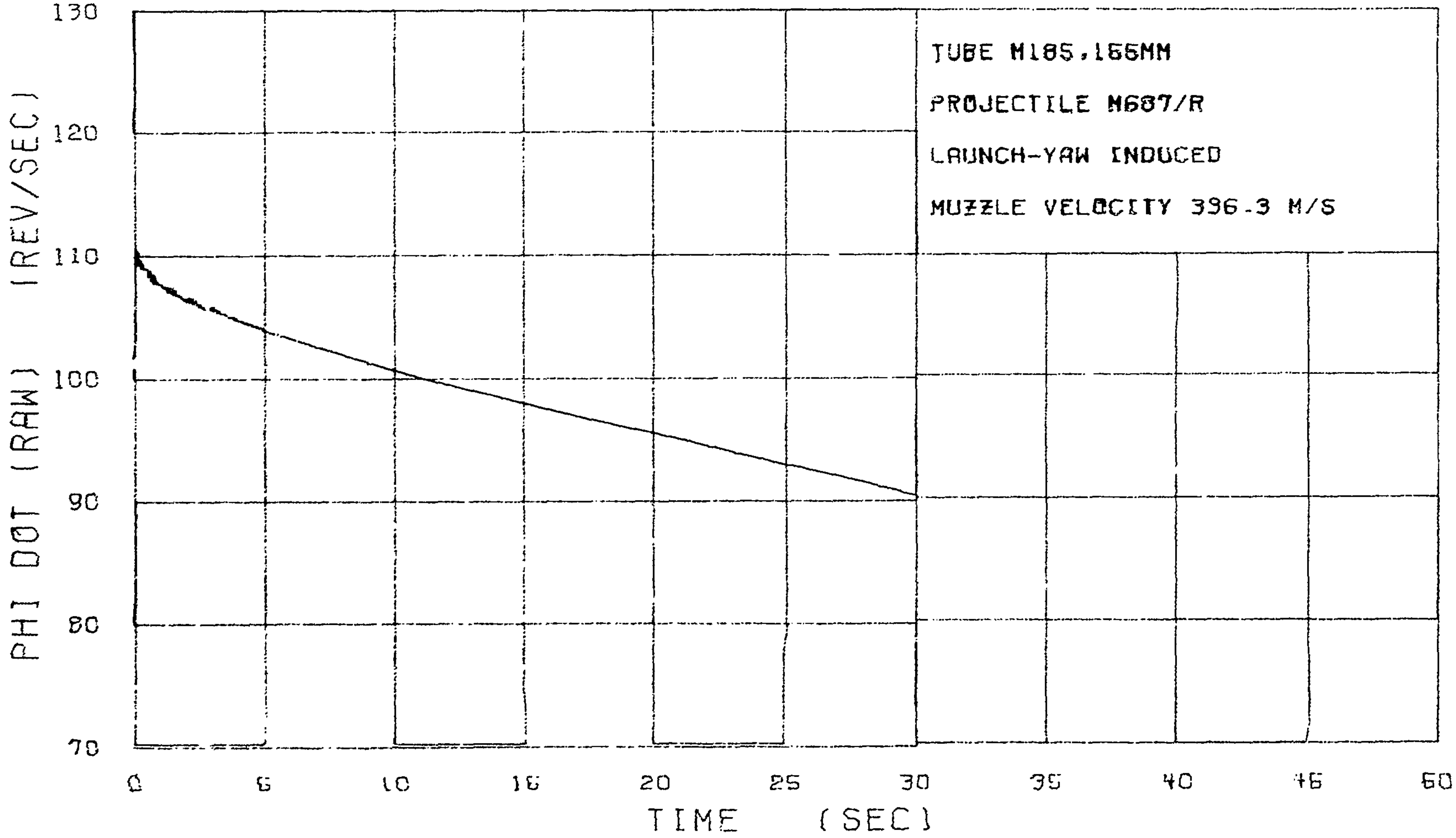

FIGURE **50.** PHI DOT (RAW) VS TIME ROUND E1-9390

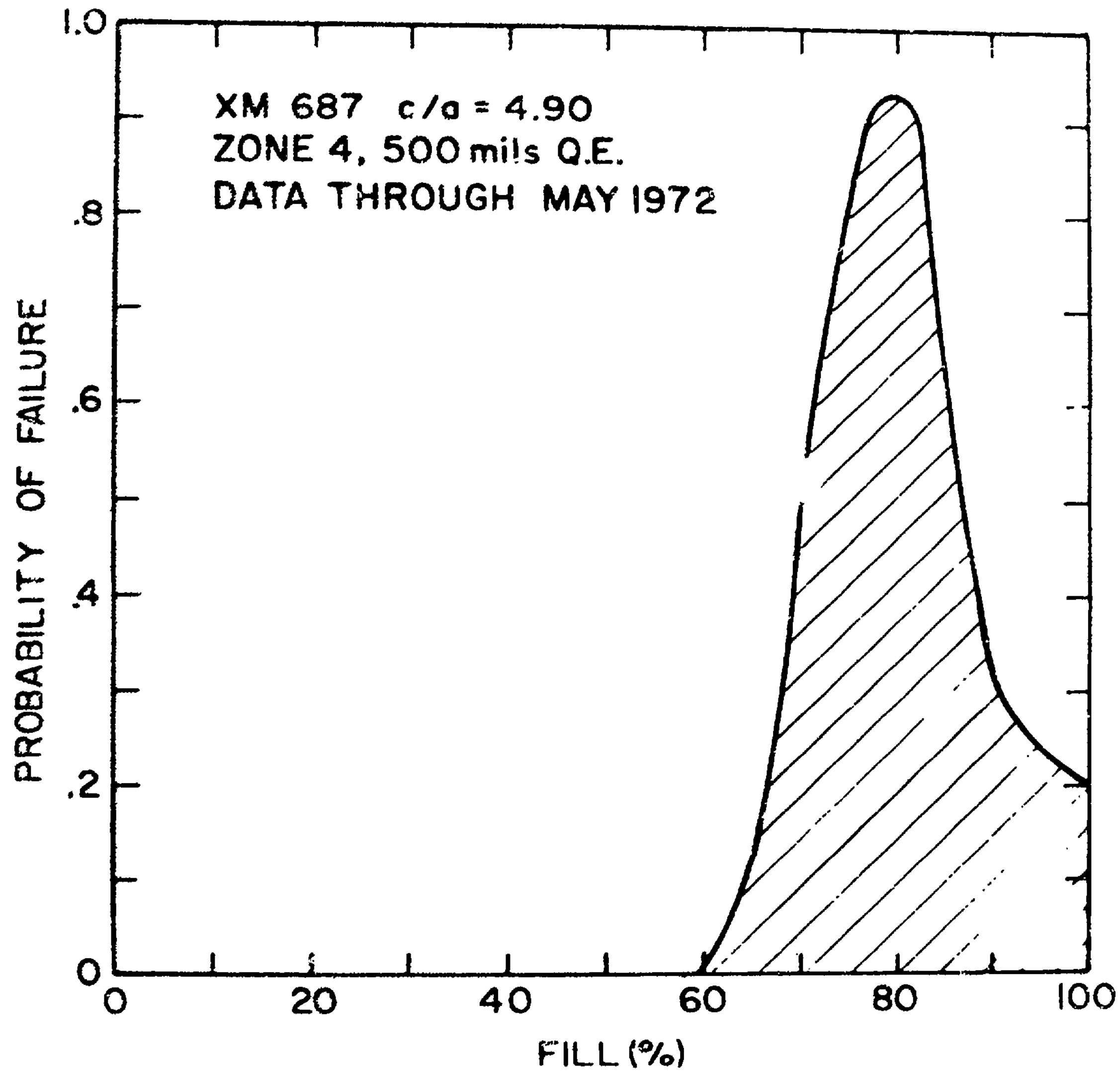

Figure 51. Probability of Failure of XM687

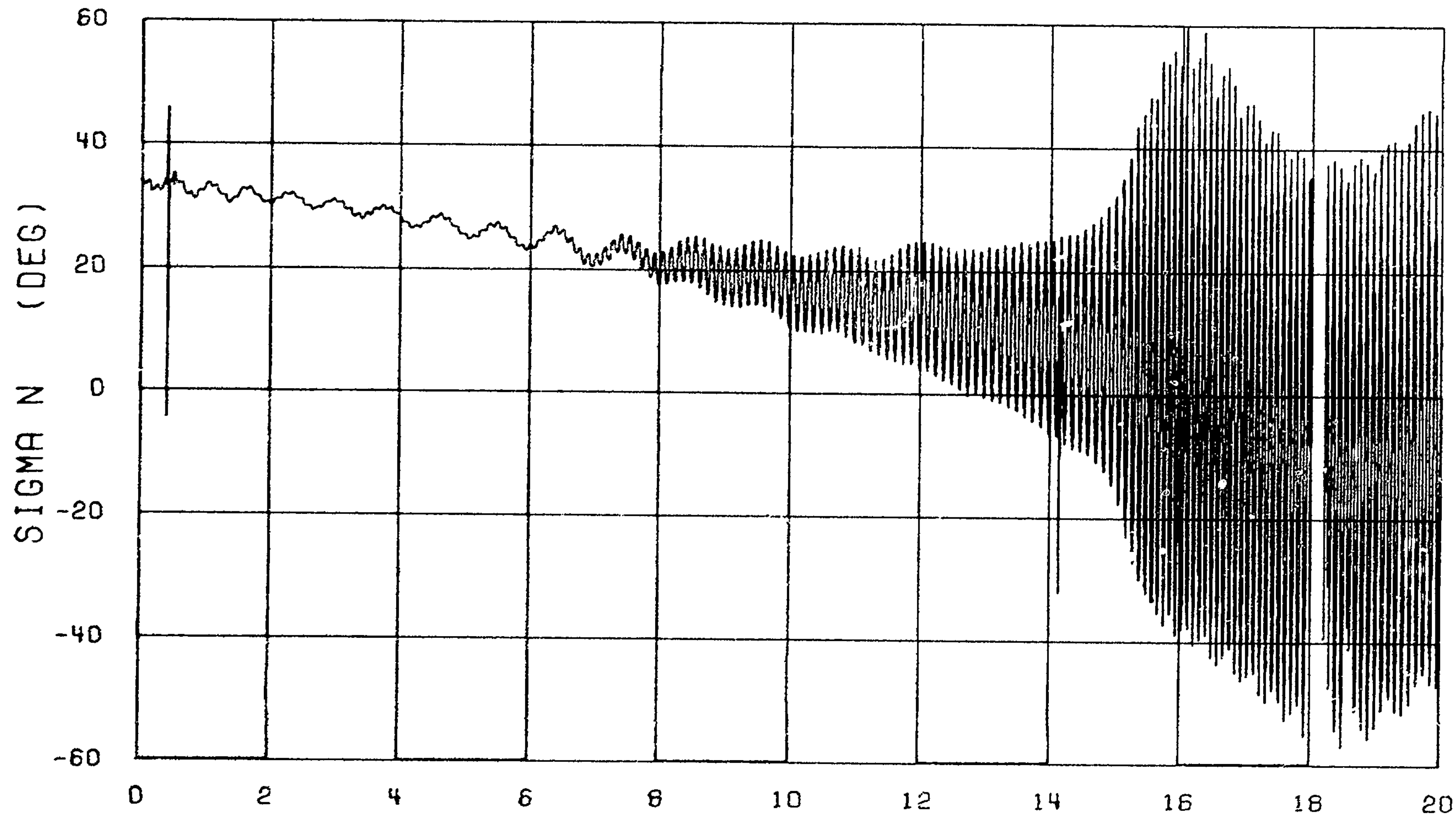

FIGURE 52. SIGMA N VS TIME ROUND E1-9387

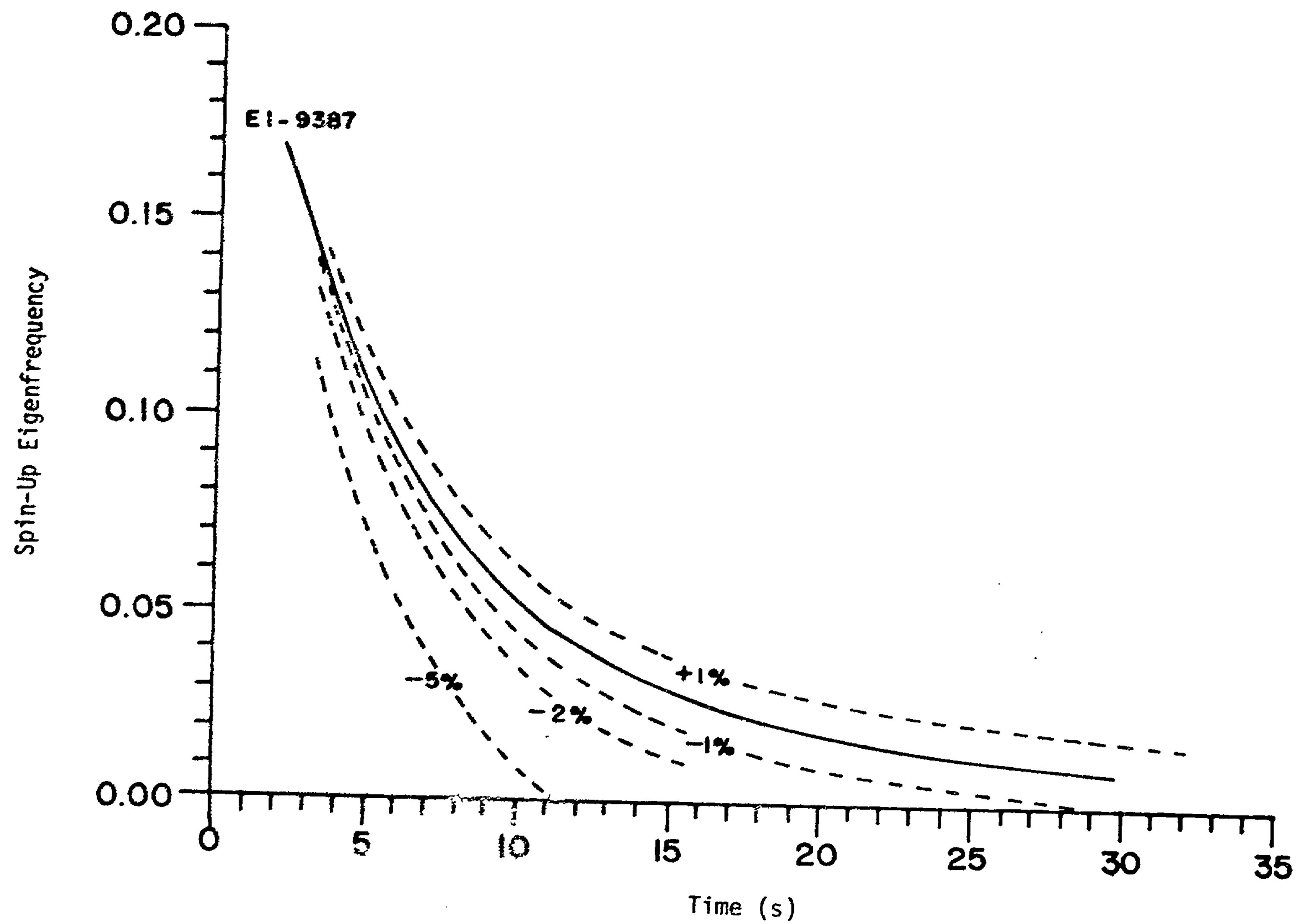

Figure 53. Spin-Up Eigenfrequency History for EI-9387 for the n=1 and j=2 Mode

TABLE 1. ROUND-BY-ROUND SUMMARY[1]

Round Number	Projectile Type	Launch Time (UT)	Muzzle Velocity[2] (m/s)	Radar Range (m)
		28 September 1977		
E1-9188	M687/R	1641	-	6,573
E1-9189	M687/R	1656	290.0	6,180
E1-9190	M687/R	1710	313.0	6,987
E1-9191	M687/R	1759	306.2	7,002
E1-9192	M687/R	1816	305.6	6,805
E1-9193	M687/R	1831	294.7	6,521
E1-9194	M687/R	1857	295.8	6,596
E1-9195	M483	1933	671.8	19,528
E1-9196	M687-SLUG	1951	711.8	18,107
E1-9197	M687-SLUG	2008	708.4	18,663
		3 May 1978		
E1-9383	M687/S	1644	329.4	7,696
E1-9384	M687/S	1657	311.7	7,114
E1-9385	M687/S	1712	321.1	7,339
E1-9386	M687/L	1724	319.8	7,272
E1-9387	M687/L	1736	317.7	5,949
E1-9388	M687/L	1751	316.9	7,171
E1-9389	M687/R	1849	337.6	7,034
E1-9390	M687/R	1852	336.3	7,513

1. *All Rounds were fired at a quadrant elevation of 30 degrees.*

2. *Muzzle velocity was measured by a Nera radar chronograph at a distance of approximately 30 metres from the muzzle. This velocity was not extrapolate back to the muzzle.*

TABLE 2. PROJECTILE PHYSICAL MEASUREMENTS[1]

WI Number	Projectile Type[2]	Empty Weight (kg)	CG[3] (m)	Moments of Inertia Axial ($kg \cdot m^2$)	Moments of Inertia Transverse (kg)
		28 September 1977			
9188	M687/R	37.59	0.333	0.1601	1.648
9189	M687/R	37.55	0.333	0.1601	1.650
9190	M687/R	37.73	0.333	0.1606	1.656
9191	M687/R	37.30	0.334	0.1599	1.656
9192	M687/R	37.77	0.334	0.1603	1.666
9193	M687/R	37.73	0.333	0.1605	1.654
9194	M687/R	37.69	0.334	0.1601	1.657
9195	M483	46.02	0.367	0.1539	1.770
9196	M687-SLUG	39.64	0.335	0.1540	1.688
9197	M687-SLUG	39.64	0.335	0.1540	1.690
		3 May 1978			
9383	M687/S	38.42	0.367	0.1629	1.726
9384	M687/S	38.20	0.366	0.1622	1.717
9385	M687/S	38.29	0.366	0.1623	1.720
9386	M687/L	37.99	0.368	0.1619	1.706
9387	M687/L	38.15	0.368	0.1620	1.721
9388	M687/L	38.02	0.367	0.1620	1.707
9389	M687/R	37.80	0.334	0.1607	1.660
9390	M687/R	37.79	0.333	0.1607	1.653

1. *M687-type shell were not filled for measurements of CG and moments of inertia.*

2. *The M687/S and M687/L had 1/2 caliber boattails, while all M687/S had 1/4 caliber boattails.*

3. *Center of gravity (CG) is measured from the base.*

TABLE 3. CONFIGURATION DATA

WI Number	Projectile Type	Payload/ % Fill	Kinematic Viscosity[1] (cs)	FMA (deg)	Ekman Number[2,3]
		Firings of 28 September 1977			
E1-9188	M687/R	water/100	1.0	< 10	5.57×10^{-7}
E1-9189	M687/R	silicon oil/100	507.8	< 10	2.99×10^{-4}
E1-9190	M687/R	silicon oil/100	507.8	13	2.77×10^{-4}
E1-9191	M687/R	water/100	1.0	3	5.59×10^{-7}
E1-9192	M687/R	water/100	1.0	3	5.60×10^{-7}
E1-9193	M687/R	Freon-E2/100	0.66	3	3.83×10^{-7}
E1-9194	M687/R	Freon-E1/100	0.66	1.5	3.81×10^{-7}
		Firings of 3 May 1978			
E1-9383	M687/S	water/100	1.0	1.5	5.19×10^{-7}
E1-9384	M687/S	water/100	1.0	1.5	5.49×10^{-7}
E1-9385	M687/S	water/90	1.0	2	5.33×10^{-7}
E1-9386	M687/L	water/100	1.0	2	5.35×10^{-7}
E1-9387	M687/L	water/100	1.0	1.5	5.38×10^{-7}
E1-9388	M687/L	water/100	1.0	--	5.40×10^{-7}
E1-9389	M687/R	water/90	1.0	12.5	5.06×10^{-7}
E1-9390	M687/R	water/90	1.0	12	5.09×10^{-7}

1. *A centistoke (cs) is 0.01 cm^2/s.*

2. *Ekman number is defined as $E = \nu/a^2 p_o$, where ν is the kinematic viscosity, a is the canister radius, and p_o is the spin calculated from the muzzle velocity.*

3. *The first measurement of spin from the yawsonde was used as p_o for E1-9188 since the muzzle velocity measurement was not obtained.*

TABLE 4. CANISTER LENGTHS AND ASPECT RATIOS FOR M687-TYPE SHELL*

Projectile Type	Inside Canister Length (cm)	Aspect Ratio: $\frac{c/a}{2j+1}$ j=0	j=1	j=2	j=3
M687/L	53.41	4.972	1.657	0.994	0.710
XM687	52.64	4.901	1.633	0.980	0.700
M687/R or M687	47.16	4.391	1.463	0.878	0.627
M687/S	45.21	4.209	1.403	0.841	0.601

**Inside diameter of all canisters was taken as 10.74cm.*

TABLE 5. STEWARTSON'S TABLES FOR A 100% CYLINDER FIRST RADIAL MODE (n=1)*

Eigenfrequency	Aspect Ratio
0.00	0.995
0.02	1.018
0.04	1.042
0.06	1.066
0.08	1.091
0.10	1.117

**See Reference 10.*

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4. C.W. Kitchens, Jr., and N. Gerber, "Prediction of Spin-Decay of Liquid-Filled Projectiles," Ballistic Research Laboratory Report No. 1996, July 1977. AD A043275.

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APPENDIX

SLIPPAGE OF PLASTIC LINERS IN THE M687 CANISTERS

The percentage loss in spin from shot exit to the elbow for Round 7254 was 3.8%. Table A-I shows that the percentage spin loss required for spin-up of the liquid payload and the plastic liners would be 5.4%. Hence, it is concluded that the liners do not slip.

TABLE A-I. AXIAL MOMENTS OF INERTIA FOR AN M687 PROJECTILE

Liquid Payload ($kg \cdot m^2$)	0.00673
(% of Total)	4.2
Outer Canisters ($kg \cdot m^2$)	0.0245
(% of Total)	15.2
Plastic Inner Canisters ($kg \cdot m^2$)	0.0020
(% of Total)	1.2
Shell Casing ($kg \cdot m^2$)	0.01278
(% of Total)	79.4
Total ($kg \cdot m^2$)	0.1610

The above percentages also indicate that a slippage of both the complete canister assembly and the liquid would produce a very large, and not observed, spin decrement.

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