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DIAGNOSTIC TESTS FOR WICK-TYPE PAYLOADS AND HIGH VISCOSITY LIQUIDS

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During Phase I, a group of yawsonde-instrumented projectiles was fired at Wallops Island, Virginia, on 27 September 1977 to test a non-toxic simulant for liquid white phosphorous (WP) and to examine the flight stability of two diagnostic wick-type configurations. Tests were conducted at Charge 4W with yaw induction. Yaw levels of up to 15 degrees were achieved. The simulant and the diagnostic payloads reproduced wick-type instabilities with unstable coupled spin-yaw behavior for fill ratios of 90% and 100%. It was concluded

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that the presence of a liquid free surface is not required for poor flight behavior and that the WP simulant should be used in future testing.

During Phase II, eight projectiles were tested at Dugway Proving Ground, Utah, on 14 March 1978 to examine the flight stability of three diagnostic payloads. Standard wick payloads, were impregnated with water and launched with yaw levels of 8.5 and 11.5 degrees produced stable and unstable flights, respectively. This type of behavior was very similar to WP/wick payloads. Next, two other payloads attempted to isolate the importance of the liquid flow through the wicks. Solid flexible rods and cigar-shaped rigid felt wicks replaced the cotton wicks. Two WP similant/felt wick projectiles were launched with initial yaws slightly over 10 degrees and were unstable, while two WP simulant/rubber rod payloads produced constant amplitude flights with nearly 10 degrees of yaw. These data indicate that the elimination of flow through the wicks does not automatically produce a well-damped flight behavior. Also, the use of a random fiber matrix versus the rope-like cotton wicks does not alleviate the adverse payload-projectile interaction.

During Phase III, clean cylinders without wicks were loaded with liquids whose viscosities were one thousand to ten million times above that of water. Unstable, wick-like instabilities occurred for a viscosity of approximately one million times above water, with all other flights exhibiting stable behavior. It is possible that the WP/wick payload can be represented by an artificial viscosity, and such a viscosity would probably be very large. It can not be established that the unstable high viscosity rounds model the wick-type instability.

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I. INTRODUCTION

The 155mm XM761 projectile carried a single payload canister that was loaded with white phosphorous (WP) impregnated cotton wicks (Figure 1). When the WP was conditioned above its melting point of 44.1°C, unstable flight behavior was the result with a strong coupling of the spin and yaw. Flight tests demonstrated that the cotton wicks produced the flight instability, but the physical mechanisms for the instability were never isolated. Hence, development of the projectile was terminated in October 1976. The BRL, however, considered it important to identify the instability mechanism for the wick/WP payload.

During Phase I, a non-toxic flight simulant for WP and diagnostic hardware were tested in an attempt to reproduce wick-like instabilities. Five wick-loaded projectiles which were representative of the original XM761 hardware were tested at Wallops Island, Virginia, on 27 September 1977. A WP simulant was blended from E-series Freons* and was used in this test. Three projectiles were filled to 100% of the available canister/wick volume, while two projectiles were filled to only 90%. All projectiles were instrumented with fuze-configured yawsondes and were launched at Charge 4W with yaw induction. All projectiles demonstrated a rapid growth in yaw and a large decay in spin and achieved only about one-third the expected range. These flight results indicate that the WP simulant and the diagnostic hardware can reproduce the wick-like instability shown by the original XM761 projectile. A second group of three wick shell were also tested on 27 September 1977 at Wallops Island for the Chemical Systems Laboratory (CSL). These shell, called the pentamerous design, carried canisters with metal cylinders that were drilled with longitudinal core holes. Wicks were inserted into the core holes, and the canisters were filled with the WP simulant. These projectiles were also yawsonde instrumented, were launched under conditions similar to the Phase I shell, and also fell short.

Phase II was conducted at Dugway Proving Ground (DPG), Utah, on 14 March 1978 and examined a water/wick payload and payloads that substituted flexible rubber rods and cigar-shaped rigid felt wicks for the standard cotton wicks. All projectiles were launched at Charge 4W with yaw induction. The water/wick projectiles exhibited flight characteristics that were similar to the XM761 WP/wick projectile with a critical launch yaw of approximately 10 degrees. Two felt wick projectiles were launched with initial yaw levels above 10 degrees and produced short flights with coupled spin-yaw histories. Since the cotton wicks consisted mainly of longitudinally oriented fibers, "wicks" were fabricated from a random fiber rigid felt. The unstable flight behavior of the felt wick projectiles indicates that a simple change to a random fiber wick would not eliminate the instability.

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*Trade name of the DuPont de Nemours & Co.

With the realization that the ill-fated pentamerous design essentially eliminated the free liquid between the wicks, a diagnostic configuration was designed to eliminate the flow through the wick by replacing the cotton wick with an impervious, flexible rod. Two flexible rod payloads were launched with initial yaws of 8 and 12.5 degrees. Both flights maintained their initial yaw amplitudes while the precessional component damped and the nutational component grew to produce a total yaw envelope approximately equal to the initial total yaw amplitude. These data indicate that the liquid flow around the rods did not provide a reduction in the initial yaw amplitude and do not prevent nutational growth. However, the flow through the wicks is evidently required to achieve the very large amplitude motion and coupled spin-yaw behavior exhibited by the cotton or felt wick payloads.

In Phase III, the XM761 hardware was modified so that only clean cylinders (no x-ribs) without wicks were tested. Liquids over a wide range of viscosities were tested for a fill ratio of 100%. This type of payload geometry is similar to the 155mm binary projectiles; however, the binary-type payloads have viscosities that are similar to water, while the Phase III liquids were one thousand to ten million times more viscous than water. In a very simple model, the WP/wick payload could be represented as a very viscous bulk liquid. Hence, the Phase III liquids were selected to investigate this simple concept. These projectiles also provided basic data for the classical instabilities often encountered by liquid-filled shell. All previous flight data is for liquids of substantially lower viscosities.

All hardware and flight data for all phases will be described in detail in later sections. A round-by-round summary of launch data and projectile physical characteristics are provided in Tables 1 and 2.

II. BACKGROUND

During the period December 1975 to May 1976 three field tests of the XM761 projectile were conducted[1,2,3]. During these trials simple modifications to the initial XM761 hardware, shown in Figure 1, were investigated. These tests all produced dramatically unstable flights of the XM761. Various internal baffle and fill ratio modifications were

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1. W.P. D'Amico, "Early Flight Experiences With the XM761," Ballistic Research Laboratory Memorandum Report 2791, September 1977. AD B024976L.

2. W.P. D'Amico, "Field Tests of the XM761: First Diagnostic Test," Ballistic Research Laboratory Memorandum Report 2792, September 1977. AD B024978L.

3. W.P. D'Amico, "Field Tests of the XM761: Second Diagnostic Test," Ballistic Research Laboratory Memorandum Report ARBRL-MR-02806, January 1978. AD #B025305L

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

Round Number	BRL Number	Projectile Type	Muzzle Velocity (m/s)	Range (m)	FMA[2] (deg)	Comments
		Phase I - 27 September 1977				
E1-9180	1284	Pentamerous	303.6	2725	14	Unstable
E1-9181	1285	Pentamerous	299.6	3052	16.5	Unstable
E1-9182	1286	Pentamerous	298.3	2974	16	Unstable
E1-9183	1288	Mod 1C	299.3	3028	15.5	Unstable
E1-9184	1289	Mod 1C	305.6	3000	14	Unstable
E1-9185	1290	Mod 1C	303.8	2926	14.5	Unstable
E1-9186	1291	Mod 1D	311.2	3175	15	Unstable
E1-9187	1292	Mod 1D	306.6	3084	14.5	Unstable
		Phase II - 14 March 1978				
DPG 1	1384	Mod 1E	333.2	n/a	-	-
DPG 2	1385	Mod 1E	332.5	n/a	11.5	Unstable
DPG 3	1386	Mod 1E	331.9	n/a	8.5	Unstable
DPG 4	1387	Mod 1E	333.4	n/a	11.5	Unstable
DPG 8	1388	Mod 2A/Rods	324.5	n/a	8	Constant Yaw
DPG-9	1389	Mod 2A/Felt	326.1	n/a	11.5	Unstable
DPG-10	1390	Mod 2A/Felt	325.3	n/a	12.5	Unstable
DPG-11	1391	Mod 2A/Rods	326.1	n/a	10	Constant Yaw
		Phase III - 2 May 1978				
E1-9191	1313	Mod 4A	317.1	3447	14	Unstable
E1-9392	1080	Mod 4A	321.4	6955	12	Stable
E1-9393	1190	Mod 4A	317.6	3691	-	No Data
E1-9394	1293	Mod 4A	316.3	3392	14.5	Unstable
E1-9395	1312	Mod 4A	319.9	7217	10.5	Stable
E1-9396	1008	Mod 4A	320.4	6557	13	Constant Yaw

1. *All projectiles were fired from an M185 tube at Charge 4W and were conditioned to ambient temperatures except for E1-9395 and E1-9396 were conditioned to 4°C. Yaw induction was also used.*

2. *First maximum angle (FMA) of yaw is half of the first recorded peak-to-peak excursion of Sigma N.*

TABLE 2. PROJECTILE PHYSICAL MEASUREMENTS[1]

Round Number	Weight[2] (kg)	CG[3] (m)	Moments of Inertia Axial ($kg \cdot m^2$)	Moments of Inertia Transverse ($kg \cdot m^2$)	Shot Weight (kg)
E1-9180	45.82	.323	.1698	1.784	45.82
E1-9181	45.96	.324	.1704	1.789	45.96
E1-9182	45.98	.323	.1706	1.791	45.98
E1-9183	42.52	.331	.1683	1.702	49.37
E1-9184	42.53	.330	.1683	1.701	49.20
E1-9185	42.44	.330	.1680	1.696	49.24
E1-9186	42.34	.330	.1674	1.693	48.50
E1-9187	42.46	.331	.1678	1.697	48.62
E1-9391[4]	39.16	.328	.1649	1.617	46.89
E1-9392	39.16	.328	.1649	1.617	45.94
E1-9393	39.16	.328	.1649	1.617	46.91
E1-9394	39.16	.328	.1649	1.617	46.89
E1-9395	39.16	.328	.1649	1.617	46.93
E1-9396	39.16	.328	.1649	1.617	45.97

1. *All projectile canisters regardless of configuration had the same internal dimensions for length and diameter, 50.8cm and 11.75cm. Where applicable, x-ribs were inserted and end plates were slotted for support. The MOD 4A configurations were cylindrical containers without x-ribs or slotted end plates.*
2. *Rounds 9180, 9181, and 9182 were measured with liquid simulant added since the canisters had been prefilled by CSL. All others were measured dry.*
3. *Center of gravity (CG) is measured from the base.*
4. *Data for E1-9391 through E1-9396 are average values based upon measurements from two rounds, except for shot weight.*

tried, but little or no improvement occurred. Also, a so-called rigid-wick payload was built and tested. Within this concept the wicks were individually held by metal supports thereby eliminating gross movement of the wicks. The rigid wick concept still produced flight instabilities, however. Unstable behavior was observed for yaw induced Charge 4W and standard Charge 6 launches. Upon termination of the XM761 program, the development of three other improved smoke projectiles, the XM801, XM802, and XM803, was initiated. The XM801 used a WP/epoxy payload that operational temperatures. However, this payload concept produced poor smoke characteristics and development was terminated. The XM802 was developed for CSL by a contractor and utilized a red phosphorous (RP) payload. Red phosphorous does not melt over the range of military operational temperatures. A third round, the XM803 is under development by the Large Caliber Weapon Systems Laboratory, Dover, New Jersey. It also uses an RP payload and is quite similar to the XM802. Most recently the XM825 has been tested. This WP payload does not involve a wick, but rather utilizes a felt wedge.[4] In effect, the original XM761 hardware is retained as shown in Figure 1, but 93 stiff felt wedges are located between the x-ribs, 23 wedges per quadrant. Approximately 5.5 kg of WP can be absorbed by the wedges.

After the termination of the XM761, a spin fixture (Figure 2) was built by the Weapons Systems Concept Team (WSCT), Edgewood Area.* It was designed to investigate wick-like instabilities in the laboratory and to screen new payload concepts prior to flight testing. Appendix A reviews the design, construction, and operation of the fixture. Several payload concepts have been tested on the fixture, and the results for some configurations have indicated a substantial reduction in the payload despin moment when compared to the XM761. One such concept was the pentamerous concept, tested in Phase I, that employed a solid core of aluminum with longitudinal core holes (2.22 cm in diameter). A single wick was located in each hole. There were three decks of aluminum, each containing 18 wicks. The three decks hold approximately 5 kg of WP and were inserted into a single canister that was loaded into the projectile body. The pentamerous concept and the felt wedges employed in the XM825 have been tested in the WSCT spin fixture, and data are provided in Figure 3. The data provide the despin moment as a function of the nutation angle in 5 degree increments from 5 to 20 degrees. Curves are faired between the data points. Table spin rate and canister spin rates are established for the nutation and spin frequencies of an XM761 projectile fired at Charge 4W (one Charge 6 condition is also included). Shown are despin moments measured for payload canisters of an XM761 x-rib canister with and without wicks, for an M687 binary canister, and for prototype canisters of the pentamerous and felt wedge concepts. Presently, only a qualitative

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**Contact Miles C. Miller.*

4. *W.P. D'Amico and W.H. Clay, "Flight Tests for Prototype Felt Wedge/White Phosphorous Improved Smoke Concept," Ballistic Research Laboratory Memorandum Report No. ARBRL-MR-02824, April 1978.* AD #A054643

estimation of flight behavior can be extracted from the data in Figure 3. For example, the pentamerous showed nominally the same behavior as the XM761 without wicks. Similarly, the felt wedge produced despin moments that were comparable to the M687. Hence, one would expect the felt wedge concept to have a higher probability of success than the pentamerous concept.

III. FIELD TESTS

The diagnostic tests were conducted to investigate the basic wick-induced instability and to provide a comparison between yawsonde data and the WSCT spin fixture. Table 3 lists the various projectile configurations that were tested. Yawsonde data are presented in the form of solar angle and spin histories[5]. Sigma N is the complement of the solar angle which is the angle between a vector drawn from the center of gravity of the projectile to the sun and a vector aligned with the spin axis of the projectile. Spin data from the yawsonde are presented in terms of the derivative of the Eulerian roll angle of the projectile, PHI DOT. The true spin of the projectile is only approximately by PHI DOT, but this approximation is very good as long as the angular motion of the projectile or the spin do not vary rapidly. A properly reduced PHI DOT requires the use of data from both optical sensors of a yawsonde, and such methods are outlined by Murphy.[6] When the methods of Reference 6 are not applied, the spin data are labeled PHI DOT (RAW). A spin history derived from raw yawsonde pulses produces a smooth curve with small oscillations superimposed. These small oscillations are a result of the yawing motion. The mean of such oscillations should be regarded as the actual spin of the projectile.

A. Instrumentation

Phase I and Phase III of the diagnostic tests were conducted at the NASA Launch Facility, Wallops Island, Virginia. Figure 4 is a sketch of the launch area at Wallops Island, Virginia. The area is located at PAD 2. A time-position radar and a break-wire time-zero system were operated by Wallops Island personnel, while the gun, a muzzle chronograph, a smear camera and a mobile telemetry van were manned by ARRADCOM personnel. Main base telemetry from Wallops Station (approximately ten miles from the launch site) also monitored the yawsondes, but only data from the mobile site were reduced. A fixed position sleigh was mounted with an M185 155mm

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

6. 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. 2581, February 1976. AD B009431O.

TABLE 3. CONFIGURATION TYPES FOR THE BRL DIAGNOSTIC PROGRAM

	MOD A NO WICKS 100%	MOD C 48 WICKS 100%	MOD D 48 WICKS 95%	MOD E 48 WICKS 95%
MOD 1 X-RIB		PHASE I 3 RDS WP SIMULANT	PHASE I 2 RDS WP SIMULANT	PHASE II 4 RDS WATER
MOD 2 X-RIB	PHASE II RODS/WP SIMULANT 2 RDS FELT WICK/WP SIMULANT 2 RDS			
MOD 4 CLEAN CYLINDER (PHASE III)	PHASE III 6 RDS HIGH VISCOSITY			

tube, and yaw induction was produced by the use of a modified muzzle brake. The type of yaw inducer used is shown in Figure 5. The side plates that were located between the threaded section of the brake and the first baffle were approximately 13 cm high. Yaw levels over ten degrees were expected.

Phase II was conducted at the German Village range at DPG (Figure 6). A ground receiving station was located 50 metres to the north and 50 metres behind the M109A1 weapon. A time zero system and a muzzle chronograph were also utilized. All equipment was provided and operated by DPG personnel. A yaw inducer similar to the type used in Phases I and III was employed.

B. Hardware Description

Table 3 shows a configuration chart for the BRL diagnostic program. Hardware to be built and tested are identified by a combination of a canister MOD and a payload MOD. For example, a MOD 1C consists of an x-rib within the canister and a payload of 48 wicks with a fill ratio equal to 100% of the available volume. Table 3 provides the number of rounds of a particular configuration that were fired in the various phases. For example, two rounds of MOD 1D were fired in Phase I. The MOD 2 hardware utilized the canister and x-rib of the MOD 1 design, but flexible rods and felt wicks were substituted for the cotton wicks. The MOD 4 hardware consisted of the same canister as the other MOD designs but no x-ribs or wicks were incorporated.

C. Phase I Test Results

The objectives of Phase I were to flight test a simulant for WP and to investigate the case of 100% fill. Both of these objectives were met. A summary of a CSL program that led to the determination of a flight simulant for WP is provided within Appendix B.* A solution of two E-series Freons was blended to reproduce the density and kinematic viscosity of liquid WP. This simulant reproduced wick-like instabilities in the WSCT spin fixture and in Phase I, hence the Freon blend will be used as a simulant in future efforts. Hardware used for the diagnostic tests was, however, not identical to the original XM761. M687 bodies (1/4 caliber boattail) were used in the original XM761 and for the diagnostic tests, but the canister designs were not identical. A detailed view of an XM761 canister and the internal x-rib is shown in Figure 7. The x-rib consisted of four angle irons that were loosely seated into the front and rear plates (also shown in Figure 1). It was felt that this type

*Comparison of data with a felt wedge/WP projectile and a felt wedge/WP simulant projectile indicate slight differences may exist between WP and the blended Freons as per flight stability.

of assembly could interact with the motion of the liquid payload and the projectile and produce results that would be hard to interpret. Hence, a solid x-rib was cut from an extruded section of fin stock. The solid x-rib was mounted into the canister end plates with an interference fit, thus producing a rigid payload canister. Also, the canisters were shortened by 1.27 cm to assure proper keying of the canister. The canister depicted in Figure 8 is identified in Table 3 as MOD 1 X-RIB and was the canister hardware tested in Phase I. Canisters were loaded with 48 wicks and filled to 100% or 95% of the available volume, thus producing MOD 1C and MOD 1D configurations, respectively. The fill ratio of 100% was achieved by repeatedly filling and centrifuging the canister on a lathe until no free surface appeared at the fill hole at the top of the canister.

Yawsonde data for two diagnostic payloads, Rounds E1-9183, E1-9184, E1-9185, E1-9186, E1-9187, are shown in Figures 9-18. The first three projectiles fired were MOD 1C types (100% filled). Figure 9 shows the solar angle data for E1-9183. A first maximum angle (FMA) of yaw of 15.5 degrees was induced, and within 3-4 seconds the motion of the projectile degenerated into pure nutation with a peak-to-peak (PTP) motion of more than 90 degrees. The rapid increase in yaw was accompanied by a rapid decrease in spin, as shown in Figure 10. This type of flight history is identical in nature to the instabilities recorded in References 1-3 for the original XM761. The other two MOD 1C projectiles had slightly different levels of FMA and PTP motion, but their fates were identical. Subsequently, two MOD 1D rounds were tested, E1-9186 and E1-9187. Both rounds were launched with FMA values of approximately 15 degrees and produced unstable flights with coupled spin-yaw histories. Figures 15 and 17 show the solar angle data for E1-9186 and E1-9187 to be the same. The spin histories for both rounds, shown in Figures 16 and 18, are also quite similar. In fact, there are no apparent differences in the flight behavior of the MOD 1C and MOD 1D configurations.

Also on 27 September 1977 the pentamerous concept was flight tested for CSL. Three rounds, E1-9180, E1-9181, E1-9182, were fired under the same conditions and with the same instrumentation as the BRL diagnostic rounds. All rounds experienced large initial motion and produced dramatic shorts with a coupled spin-yaw behavior. E1-9180 was launched with an FMA of 14 degrees and an unstable single mode motion was evidenced in Figure 19 within 2 seconds of flight. A substantial loss in spin is shown in Figure 20. E1-9181 was launched with an FMA of 16.5 degrees as shown in Figure 21. This round also exhibited the large reduction in spin as shown in Figure 22. E1-9182 was launched with an FMA of 16 degrees and suffered a fate similar to the two previous rounds, as the data in Figures 23 and 24 indicate.

D. Phase II Test Results

Eight projectiles were tested on 14 March 1978 at DPG and are listed in the round-by-round summary in Table 1. Physical measurements of the Phase II projectiles were inadvertently not taken. Four water/wick projectiles were launched at Charge 4W with yaw induction. The yawsonde did not transmit on DPG 1, but data on the other three flights were excellent. DPG 2 was launched with an FMA of 11.5 degrees, as seen in Figure 25, and exhibited a constant amplitude motion for three cycles of precession. At approximately 5 seconds into the flight the epicyclic motion degenerated into a single mode motion whose amplitude grew rapidly. The spin history, shown in Figure 26 exhibited a strong coupling with the yaw at about 8 seconds, which is slightly later in time then when the single mode motion was observed. DPG 3 was launched with an FMA of 8.5 degrees and was stable. The initial motion damped into a limit cycle behavior, although a slight amount of nutational mode growth was experienced at about 5 seconds. The spin history (Figure 27) showed no unusual behavior. The last water/wick projectile, DPG 4, was launched with an FMA of 11.5 degrees and suffered a fate that was almost identical to DPG 2. Yawsonde data are provided in Figures 29 and 30. The next group of four projectiles were the MOD 2B types. DPG 8 and DPG 11 carried rubber rods and WP simulant and were launched with FMA values of 8 and 10 degrees, respectively. Both shell produced flight histories where the initial amplitude of the motion remained fairly constant throughout the entire flight (Figures 31 and 33). The spin histories (Figures 32 and 34) did not show any unusual behavior. The last two rounds of Phase II were loaded with cigar-shaped felt wicks and the WP simulant. These projectiles, DPG 9 and DPG 10, were both unstable when launched with FMA's of 11.5 and 12.5 respectively. Figures 35 and 37 show, the solar angle data for these rounds, the yaw was increasing immediately after launch. Coning motions of 60 degrees were observed within 5 seconds of launch. The spin data in Figures 36 and 38 show strong coupling with the yaw at approximately the 5 second time frame. Data were not received beyond 7 seconds due to the large amplitude motion moving the optical sensors out of view of the sun.

E. Phase III Test Results

The final portion of the program was conducted on 2 May 1978 at WI. Six projectiles were tested. The hardware was the MOD 4A configuration and utilized canisters that were clean cylinders and were loaded only with homogeneous liquids. Two liquids were tested at two temperatures, corn syrup and glycerol at 4°C and 22°C. All projectiles were launched with induced yaw. The first projectile was El-9391. This corn syrup-filled (22°C) projectile was unstable when launched with an FMA of 14 degrees. Large amplitude motion (Figure 39) was experienced from shot exit, and coupled spin-yaw behavior was evident (Figure 40) over the entire flight history. El-9392 was filled with glycerol (22°C), was launched with an FMA of 12 degrees, and was stable. Damping of the precessional mode was rapid, while the nutational mode was not. However, by 24 seconds of flight the expected M483A1 limit cycle behavior was realized (Figure 41). The spin history for this flight was quite interesting. At early times the data were noisy, but there is some evidence of a rapid spin decay at shot exit (Figure 42). The reduction in spin is approximately 2.5 rps. No data was received for E1-9393, which was a corn syrup loaded projectile, hence, another projectile of this type was fired. E1-9394 experienced an FMA of 14.5 degrees and was unstable. The yawsonde data for E1-9394 (Figures 43 and 44) were essentially the same as those for E1-9391. The last two projectiles were conditioned to 4°C. E1-9395 was loaded with corn syrup. The FMA level was 10.5 degrees and a stable flight was observed (Figure 45) with a smooth spin history (Figure 46). E1-9396 was filled with glycerol, launched with an FMA of 13 degrees, and was unstable. The yawsonde data are probably only good for the first twenty seconds of flight since the despin of the projectile produced a torque that unscrewed the yawsonde from the ogive. Radar observed two targets at 32 seconds into the flight. Figures 47 and 48 indicate very unexpected behavior beyond 20 seconds. The amplitude of the yaw decreased subsequent to shot exit where the precessional mode rapidly damped and the nutational mode rapidly undamped. By 20 seconds, however, the amplitude of the yaw reached the FMA level. The spin history was smooth at shot exit, but at 13 seconds a shift in the spin was observed. No explanation is offered.

IV. DISCUSSION

At present very little is known about the behavior of projectiles with non-rigid internal parts. Substantial work on the stability of projectiles with a bulk liquid payload (WP without wicks, for example) has been done.[7] Also, recent experience on projectiles with solid but nonfixed payloads has produced a useable theory.[8] However, a wick/WP payload embodies both of these subject areas. Prior to a discussion of the flight data, however, test data from the WSCT spin fixture will be reviewed since many configurations were tested both in the laboratory and with yawsonde instrumented projectiles. Figure 49 gives the spin fixture results for configurations that were tested within Phase II. None of the configurations produced a large despin moment when compared with the XM761 results, and in fact the pentamerous design provided a crude upper bounds for the Phase II configurations. Hence, one would expect that poor flight behavior could result for large values of induced yaw. The data indicate that with the x-rib rigid lexan rods produced a

7. *Engineering Design Handbook - Liquid-Filled Projectile Design* AMC Pamphlet 706-165, April 1969.

8. C.H. Murphy, "Angular Motion of Projectiles With a Moving Internal Part," Ballistic Research Laboratory Memorandum Report No. 2731, February 1977. AD A037338.

slightly larger despin moment than flexible rods. With the x-ribs removed the despin moment for the flexible rods increased significantly. A very surprising result was obtained for the XM761 hardware when water was used in place of the WP simulant. A very small despin moment was measured. The ratio of the mass of the water to the mass of WP simulant for the standard XM761 configuration was approximately 1/3, but the major portion of such a difference in mass or in axial moment of inertia would be scaled properly during the calculation of the moment. Hence, one would expect a water-filled XM761 to be stable. This was not the case for the actual shell tested. Felt wicks were not tested on the spin fixture.

Twenty-two projectiles have been fired in an attempt to determine the details of the instability mechanism for wick-type projectiles. A listing of conclusions based upon yawsonde instrumented projectiles is provided. Included within this list are results from the XM761 flights of References 1-3.

1. WP/wick payload is fully spun up at shot exit. (XM761 tests)

2. Large reduction in the mass of the WP (up to 40%) does not produce stable flights (XM761 tests)

3. Modification as to the packing density of the wicks (48 or 60 per canister) or the type of weave for a wick does not produce stable flights. (XM761 tests)

4. Compartmentalization (transverse baffles or individually sealed quadrants) does not produce stable flights. (XM761 tests)

5. Gross motion of the wicks is not needed to produce unstable flights (rigid wick design). (XM761 tests)

6. A blended Freon simulant that has the same density and kinematic viscosity as liquid WP will reproduce the wick-type instability. (Phase I)

7. Elimination of the liquid free surface does not produce stable flights (Phase I)

8. Elimination of the free liquid surrounding the wicks does not produce stable flights (Phase I)

9. Substitution of a random oriented matrix material for the rope-like wicks does not produce stable flights. (Phase II)

10. Substitution of flexible rubber rods for the cotton wicks does not produce a flight behavior with good damping characteristics. (Phase II)

11. XM761 hardware with 48 water impregnated wicks produced unstable flights. (Phase II)

12. A homogeneous liquid with a large viscosity may produce a wick-type instability. (Phase III)

Items 2-5 indicate that subtle variations to a wick payload can not modify the underlying and unknown mechanism for instability when a wick payload is employed. Further, 5, 7, 8 and 10 indicate that the single elimination of gross wick motion free surface effects, flow around the wicks, or flow through the wicks does not produce satisfactory flight behavior, while 6, 8, and 11 indicate that various combinations of liquids (WP, Freons, water) and fibrous submunitions (cotton or rigid felt) still produce unstable flights. The only glimmer of light is contained within item 12 where bulk-filled homogeneous liquids were launched with induced yaws of approximately 10 degrees and rapid amplitude growth and spin decay was observed. This had not been achieved during the testing of other liquid-filled projectiles, such as the 155mm M687 binary shell. For the M687 coupling between the spin and the yaw were not noted until very large amplitudes (30-40 degrees). Hence, if one could determine an artificial viscosity for the liquid/wick payload then the instability of the very high viscosity rounds of Phase III may provide the key. In order to realize such a goal, several steps must be undertaken. First, the actual physical phenomenon that is involved is the flow of a liquid through a matrix material. Hence, the permeability of the liquid/matrix system must be determined. Then either a model or an empirical correlation based upon flow through porous material must be established so that an artificial viscosity for the wick payload can be achieved. Finally, a detailed understanding of the stability of high viscosity liquids must be achieved through further flights at smaller yaw levels and with a simple mathematical representation for the liquid/projectile system. Figure 50 provides a summary of the WSCT spin fixture data pertinent to Phase III. Calculation of the liquid despin moment from the yawsonde data has not been accomplished as yet, but excellent qualitative agreement between the laboratory data and the flight tests exists. Unstable or constant amplitude flights were observed for viscosities in the range of 8.3×10^3 to 1.9×10^5 centistokes. Table 4 lists large amplitude yawsonde data for bulk liquid shell that have been gathered not just within Phase III but during an investigation of spin-up behavior of the M687 projectile.[9] The cause of the large viscosity instability is poorly understood, and it is not possible to apply available liquid-filled shell theories to this type of high viscosity payload.

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9. *W.P. D'Amico, W.H. Clay and A. Mark, "Yawsonde Data for M687-Type Projectiles with Application to Rapid Spin Decay and Stewartson-Type Spin-Up Instabilities," Ballistic Research Laboratory Memorandum Report in publication.*

V. CONCLUSIONS

A diagnostic program has been fired to investigate the wick induced instability of the XM761 projectile. It has been shown that the stability of liquid/fibrous matrix payload, spin-stabilized projectiles is not well understood. Detailed descriptions of the flight behavior would only be possible after basic investigations into the flow through porous media, and the development of artificial viscosity models or correlations. The testing of a wide variety of porous media and liquids have in general shown very similar behavior, most of which is not well suitable for a spin-stabilized projectile.

TABLE 4. LARGE AMPLITUDE BEHAVIOR OF PROJECTILES WITH HOMOGENEOUS LIQUIDS (FILL RATIO = 100%)

Reference	Projectile Number	Kinematic Viscosity (cs)	Liquid Payload	Flight Behavior
Text	E1-9391	2×10^5	corn syrup (22°C)	unstable
Text	E1-9392	1×10^3	glycerol (22°C)	stable
Text	E1-9393	2×10^5	corn syrup (22°C)	unstable no data
Text	E1-9394	2×10^5	corn syrup (22°C)	unstable
Text	E1-9395	2×10^6	corn syrup (4°C)	stable
Text	E1-9396	6×10^3	glycerol (4°C)	constant amplitude
Ref 7	E1-9188	1	water	stable
Ref 7	E1-9189	500	silicon oil	stable
Ref 7	E1-9190	500	silicon oil	stable

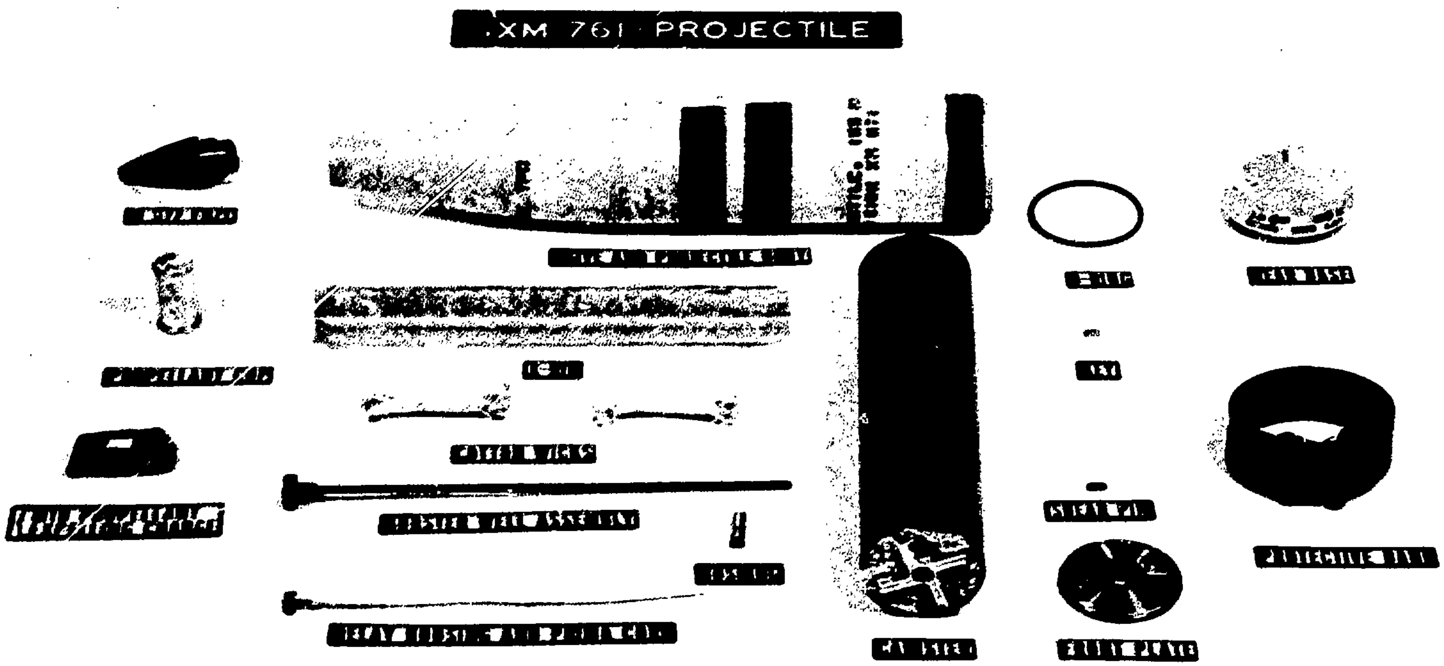

Figure 1. XM761 Wick/WP Projectile

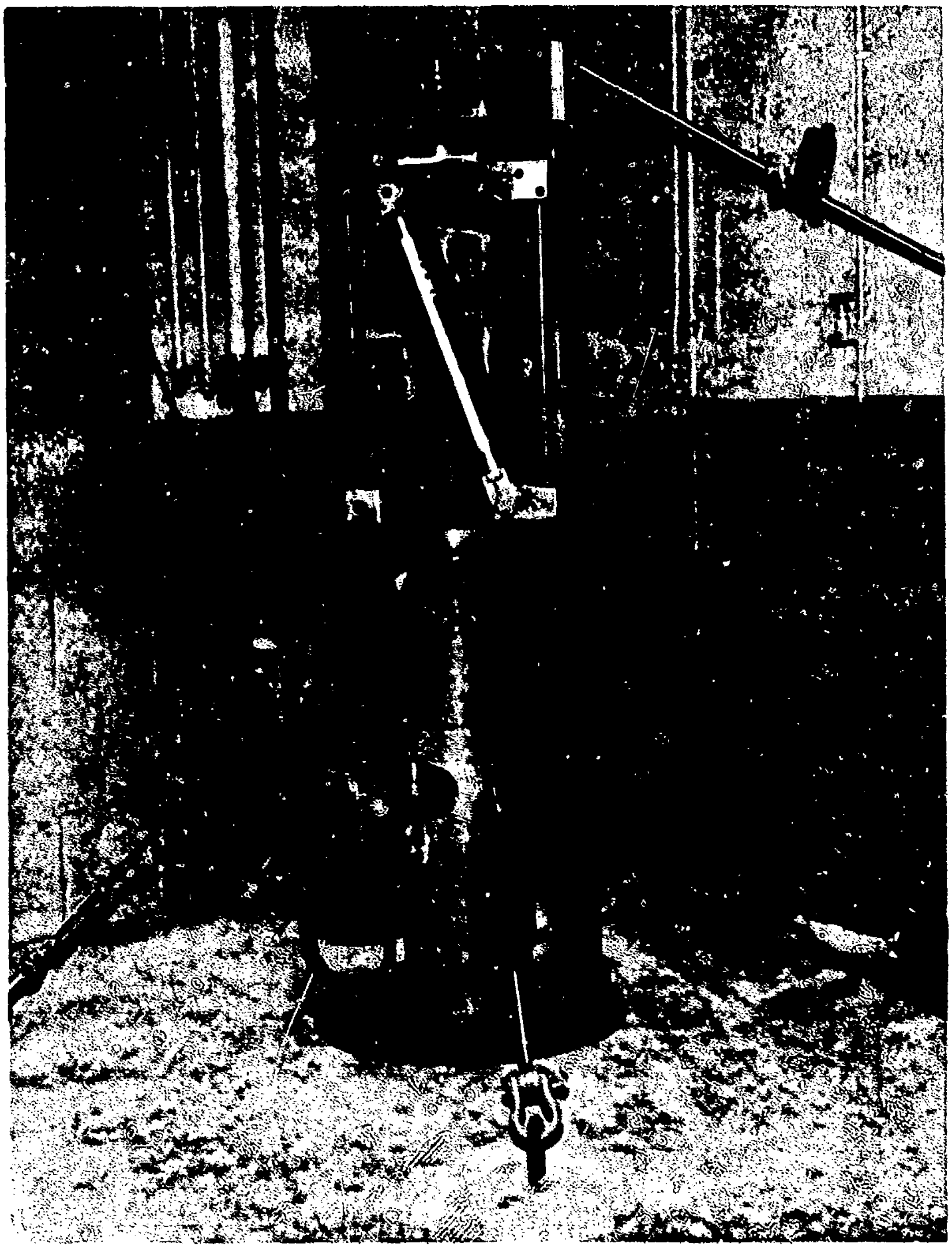

Figure 2. Spin Fixture for Testing Liquid Payloads

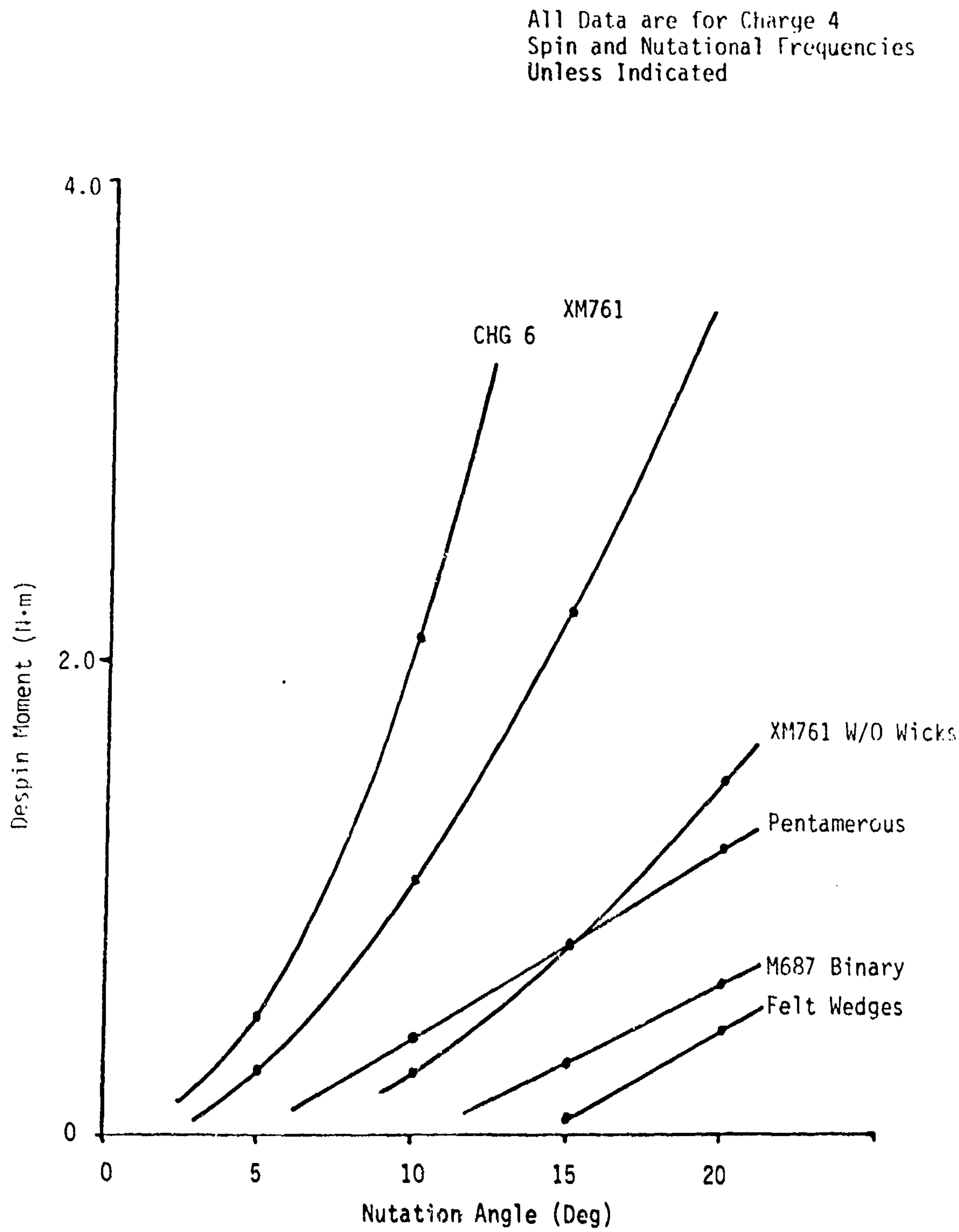

Figure 3. Despin Moment Versus Nutation Angle From The WSCT Spin Fixture

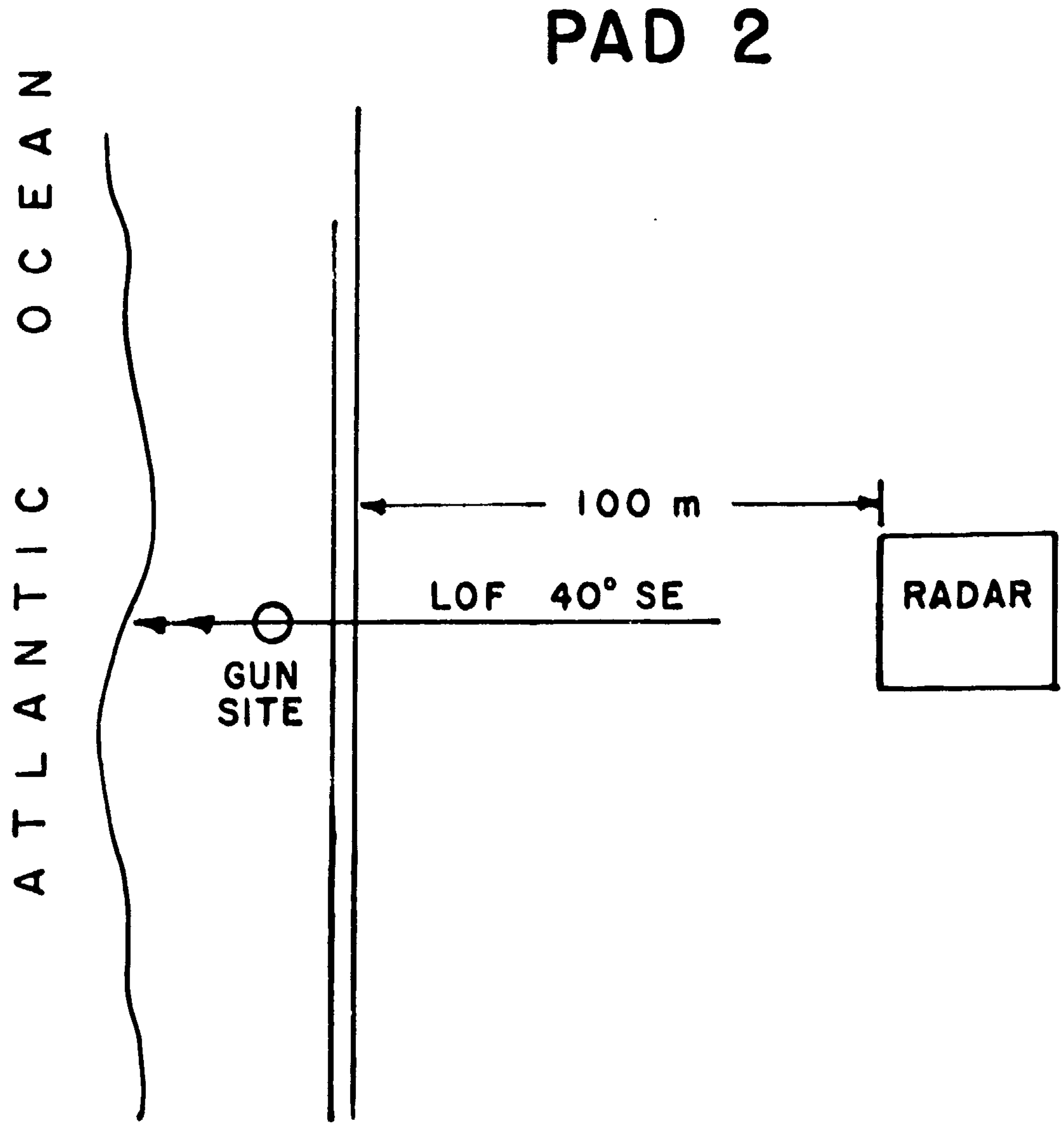

Figure 4. Launch Area At Wallops Island, Virginia

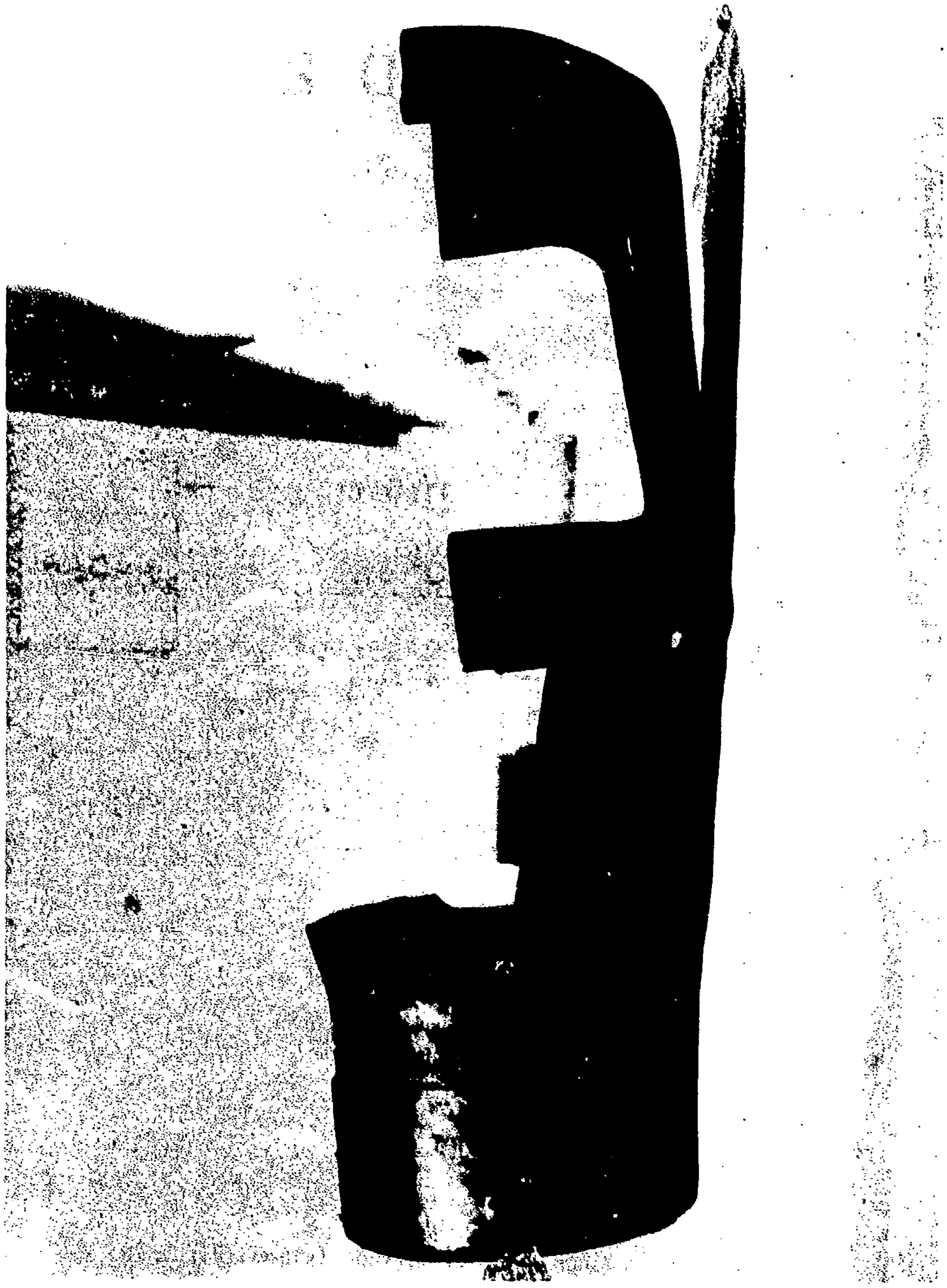

Figure 5. Yaw Inducer

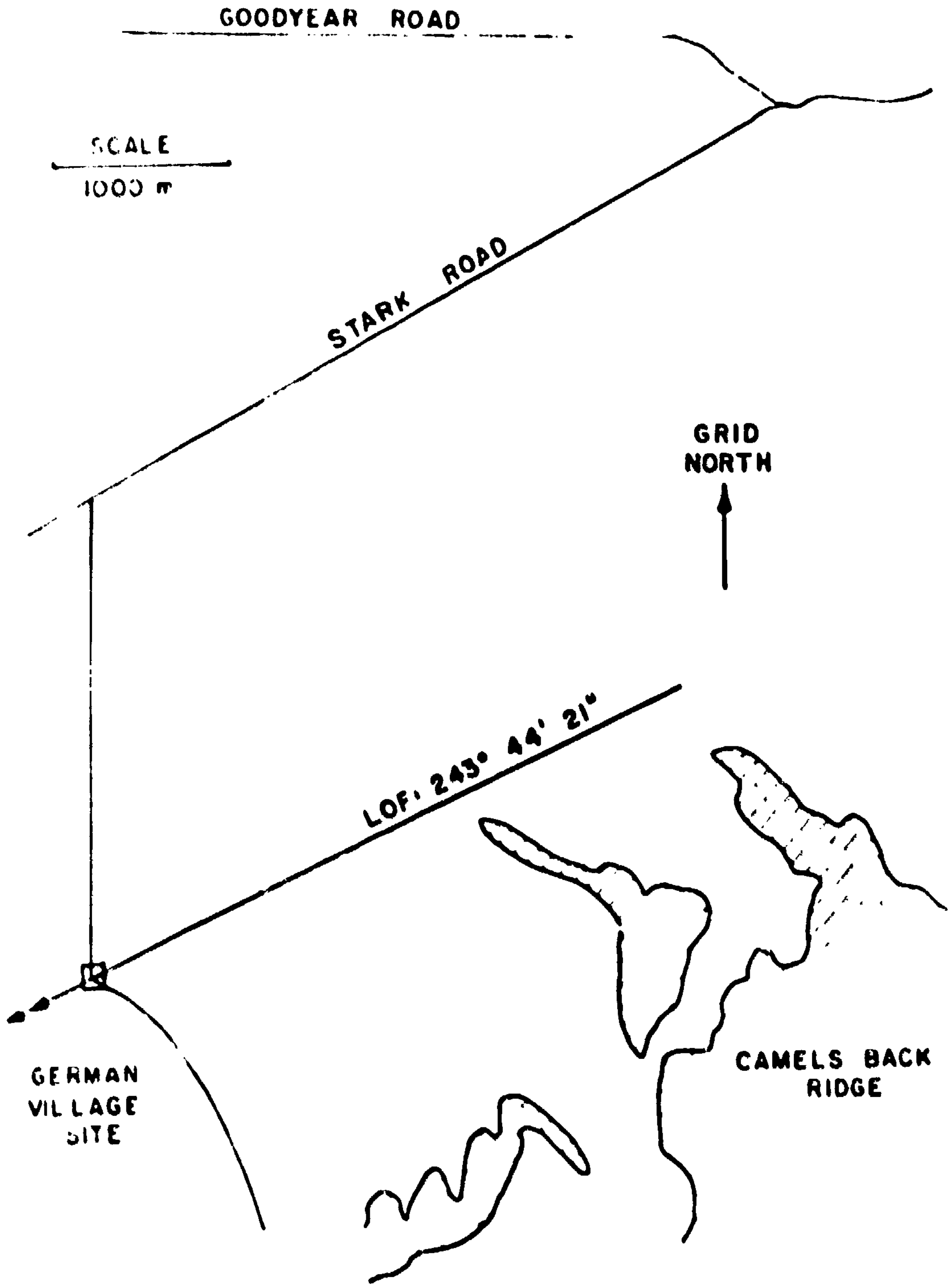

Figure 6. German Village Range

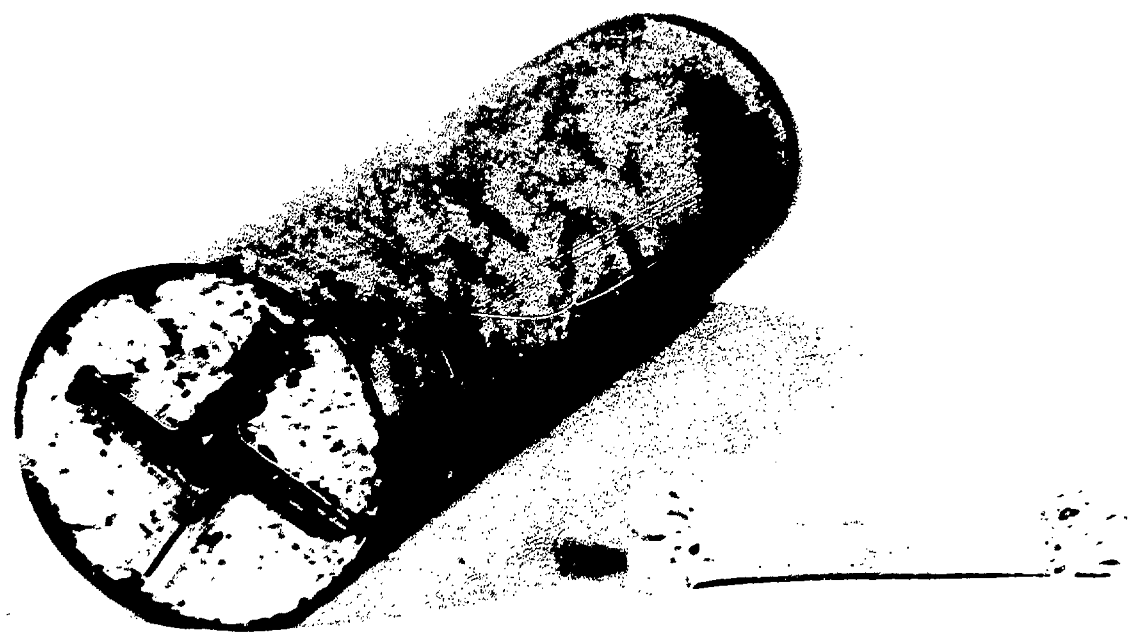

Figure 7. Detailed View of Original XM761 Canister and Wick

Full Scale

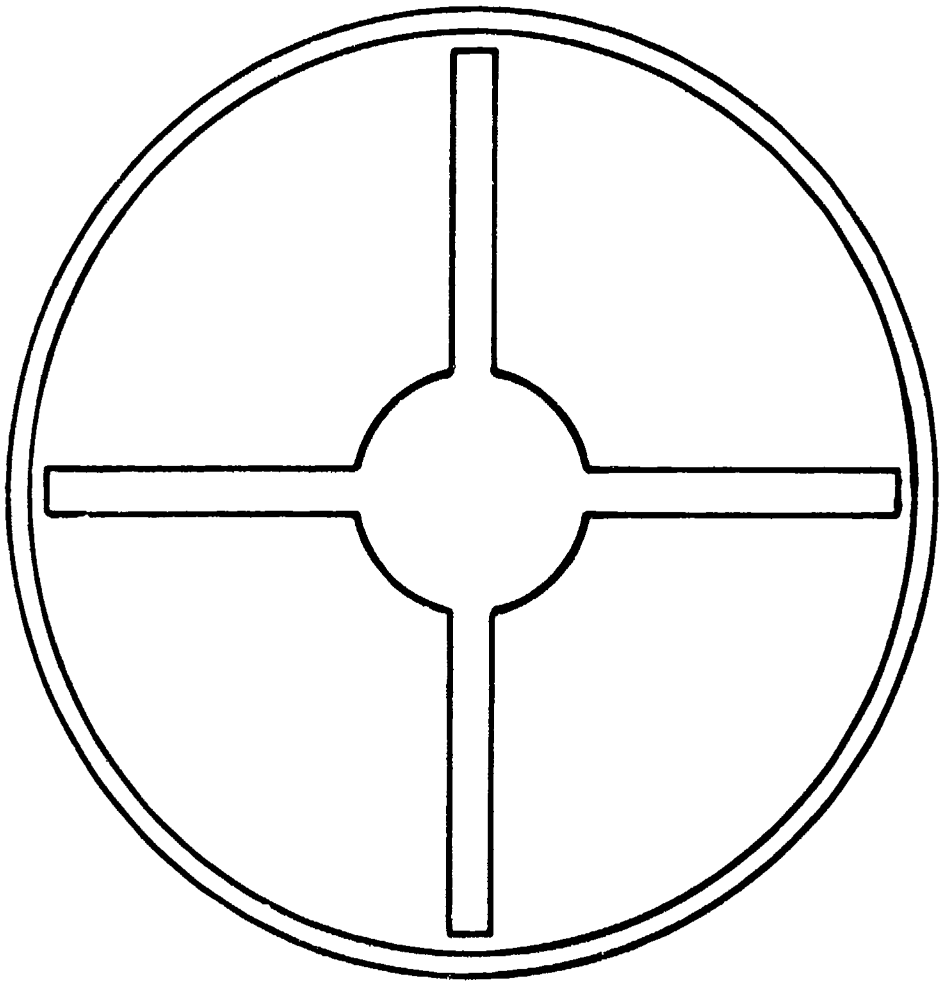

Figure 8. Solid x-rib Used in The Diagnostic Rounds

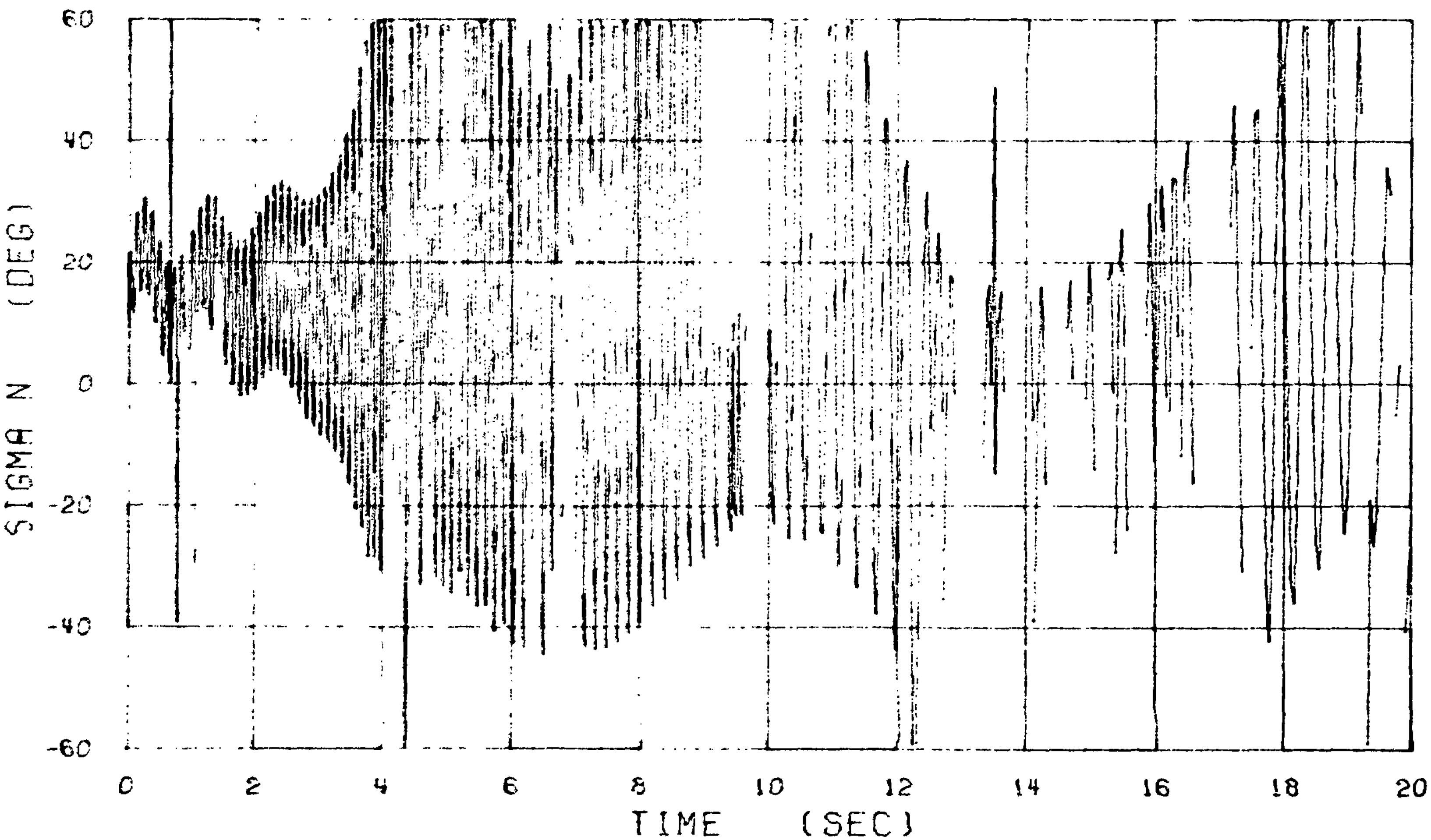

FIGURE 9. SIGMA N VS TIME ROUND E1-9183

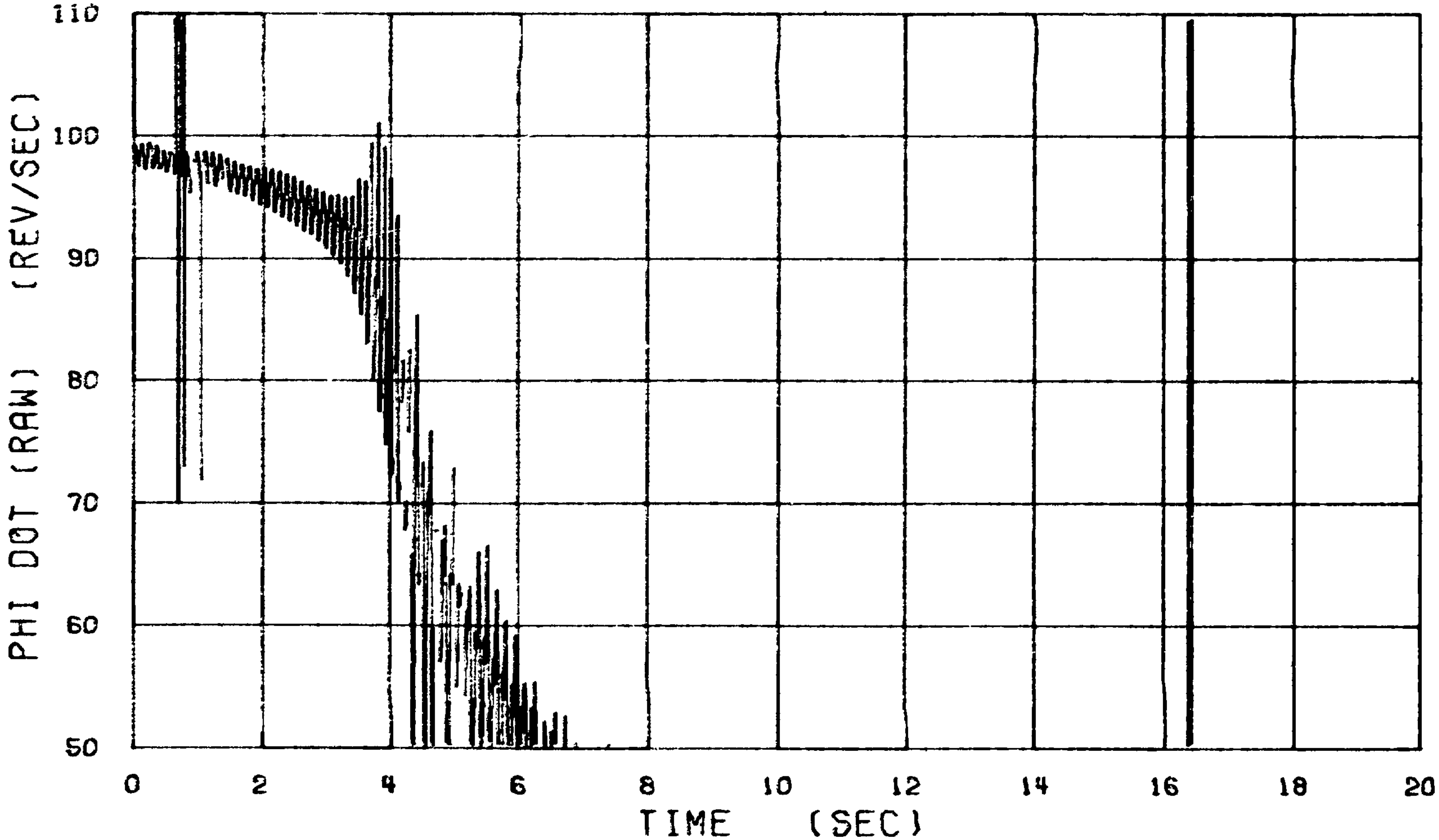

FIGURE 10. PHI DOT (RAW) VS TIME ROUND E1-9183

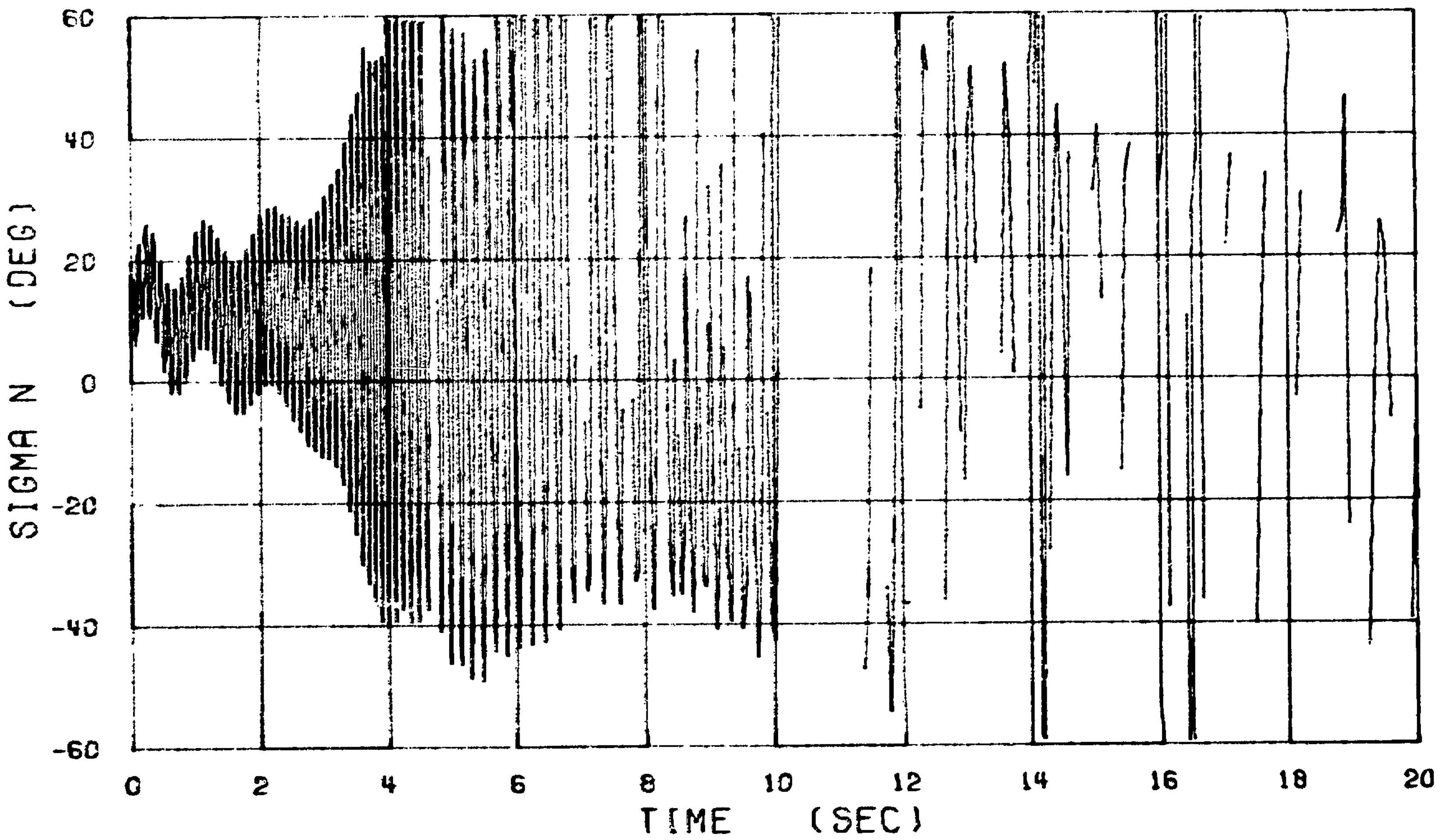

FIGURE 11. SIGMA N VS TIME ROUND E1-9184

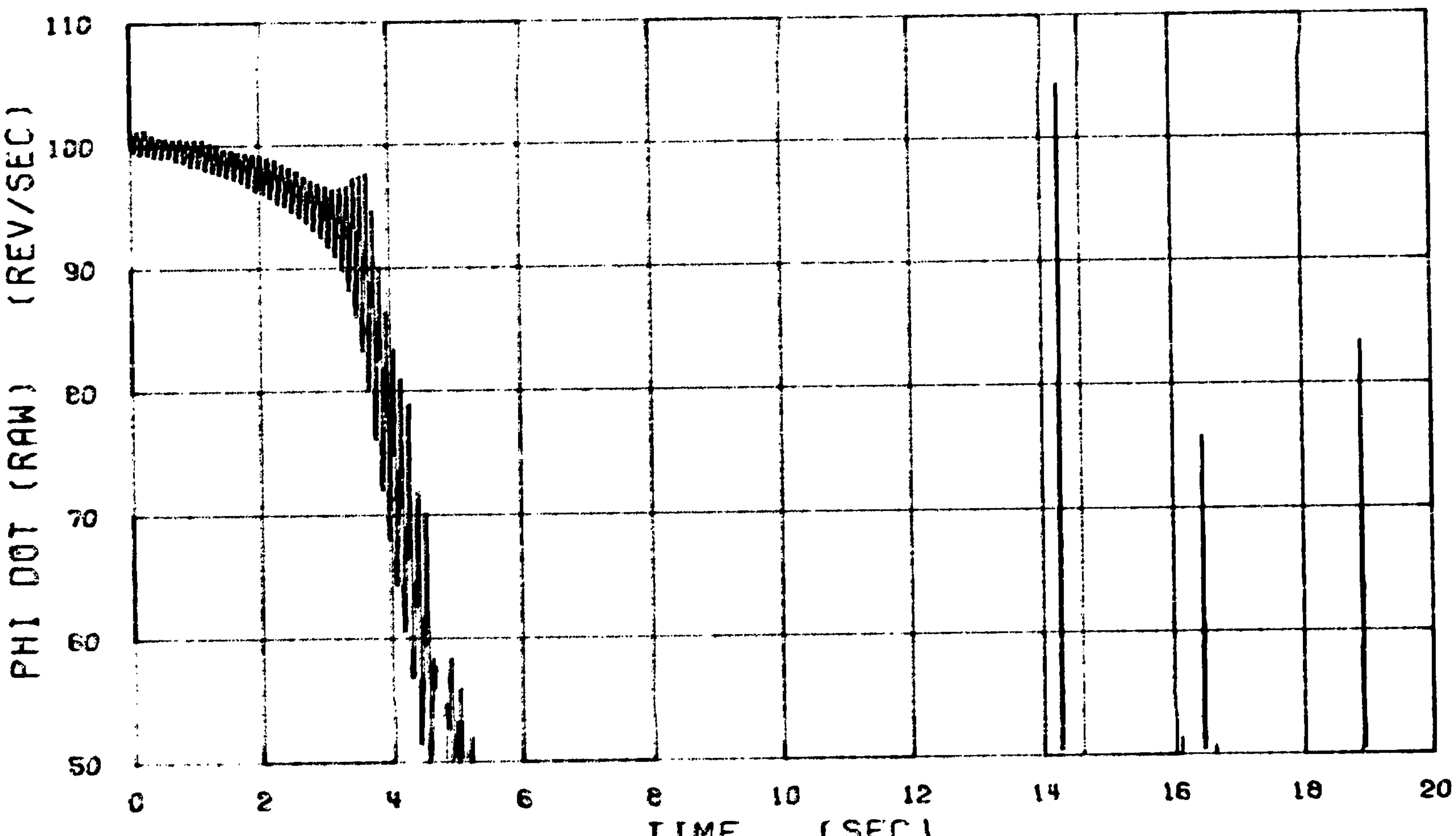

FIGURE 12 PHI DOT (RAW) VS TIME ROUND E1-9184

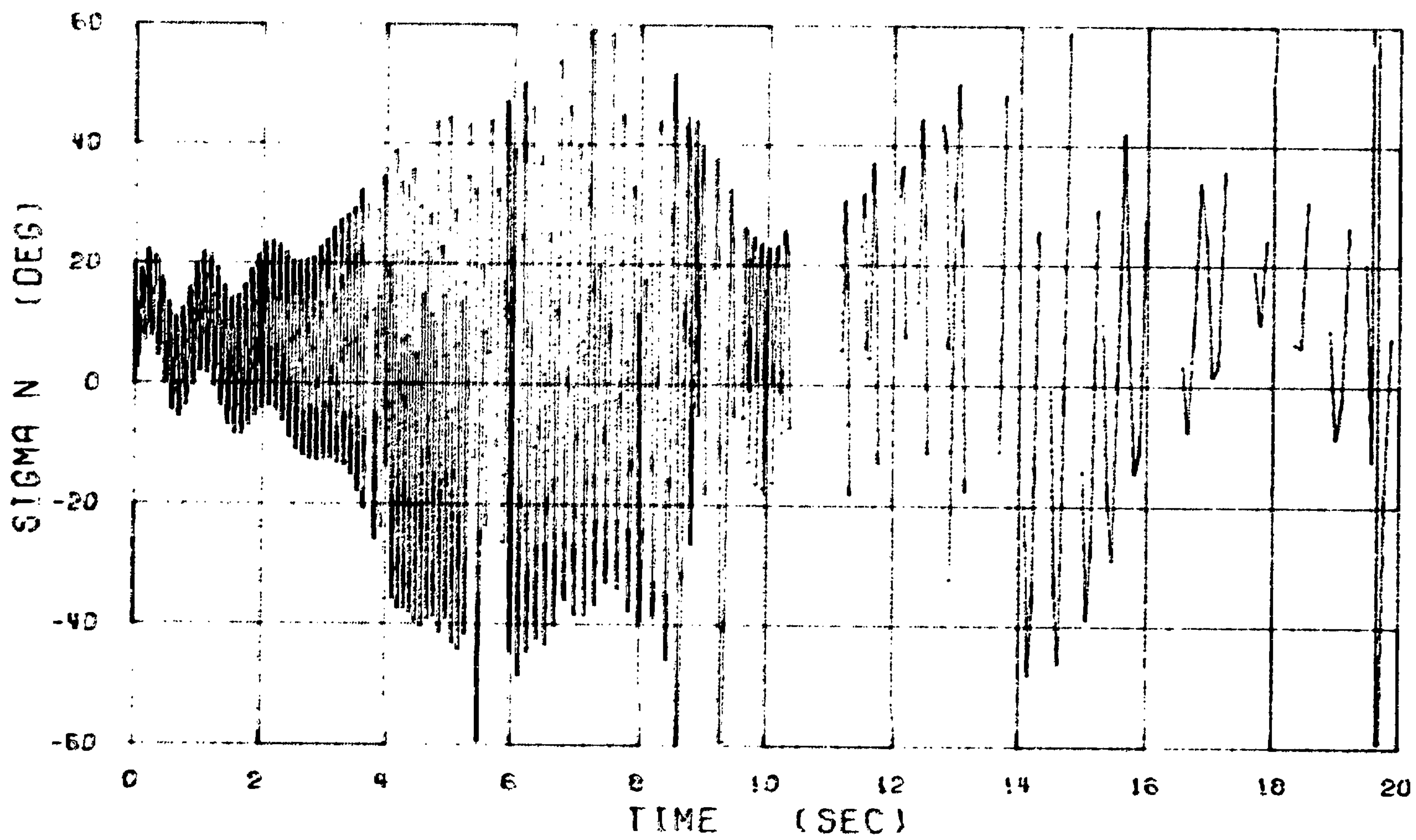

FIGURE 13. SIGMA N VS TIME ROUND E1-9185

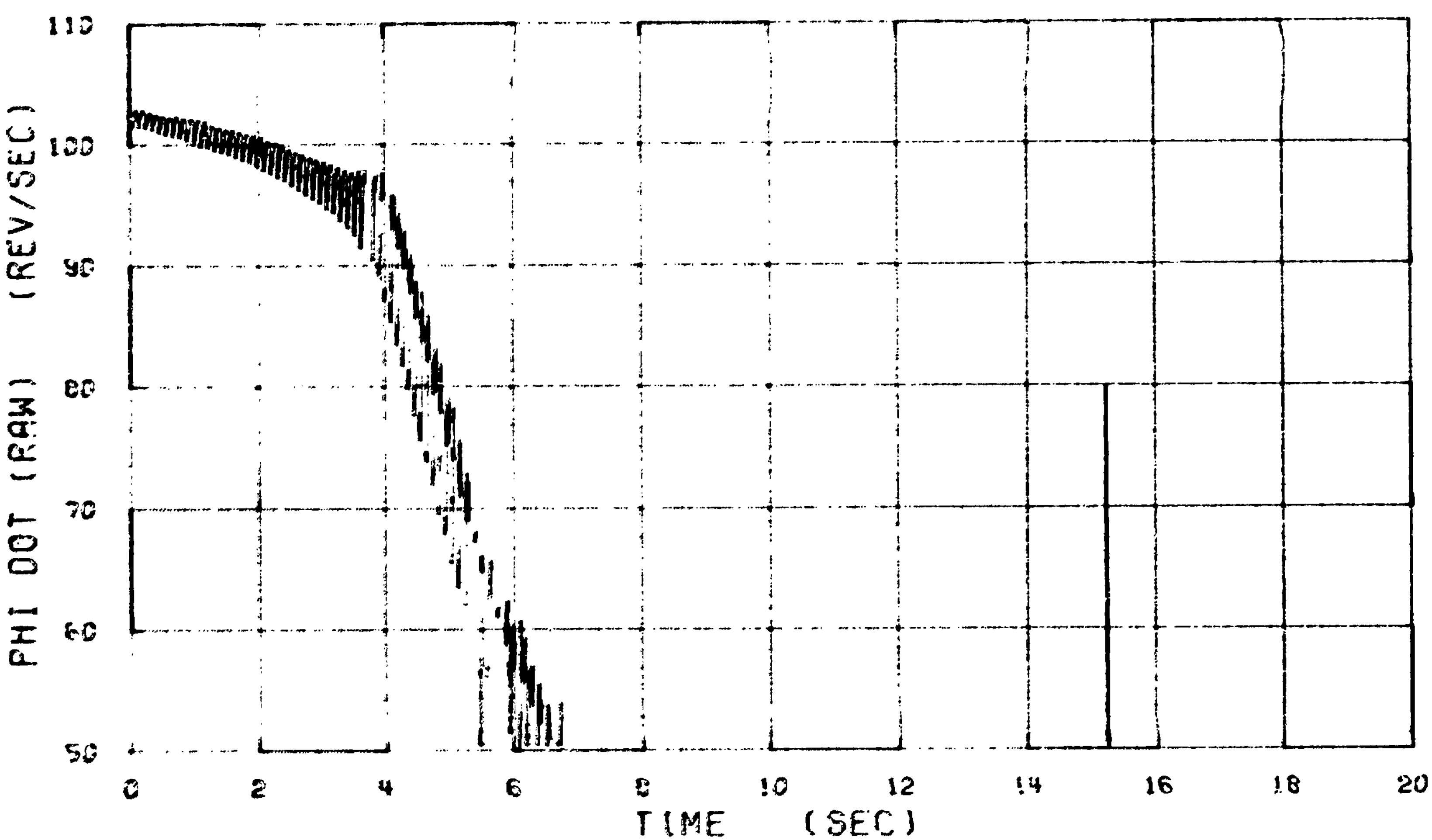

FIGURE 14 PHI DOT (RAW) VS TIME ROUND E1-9185

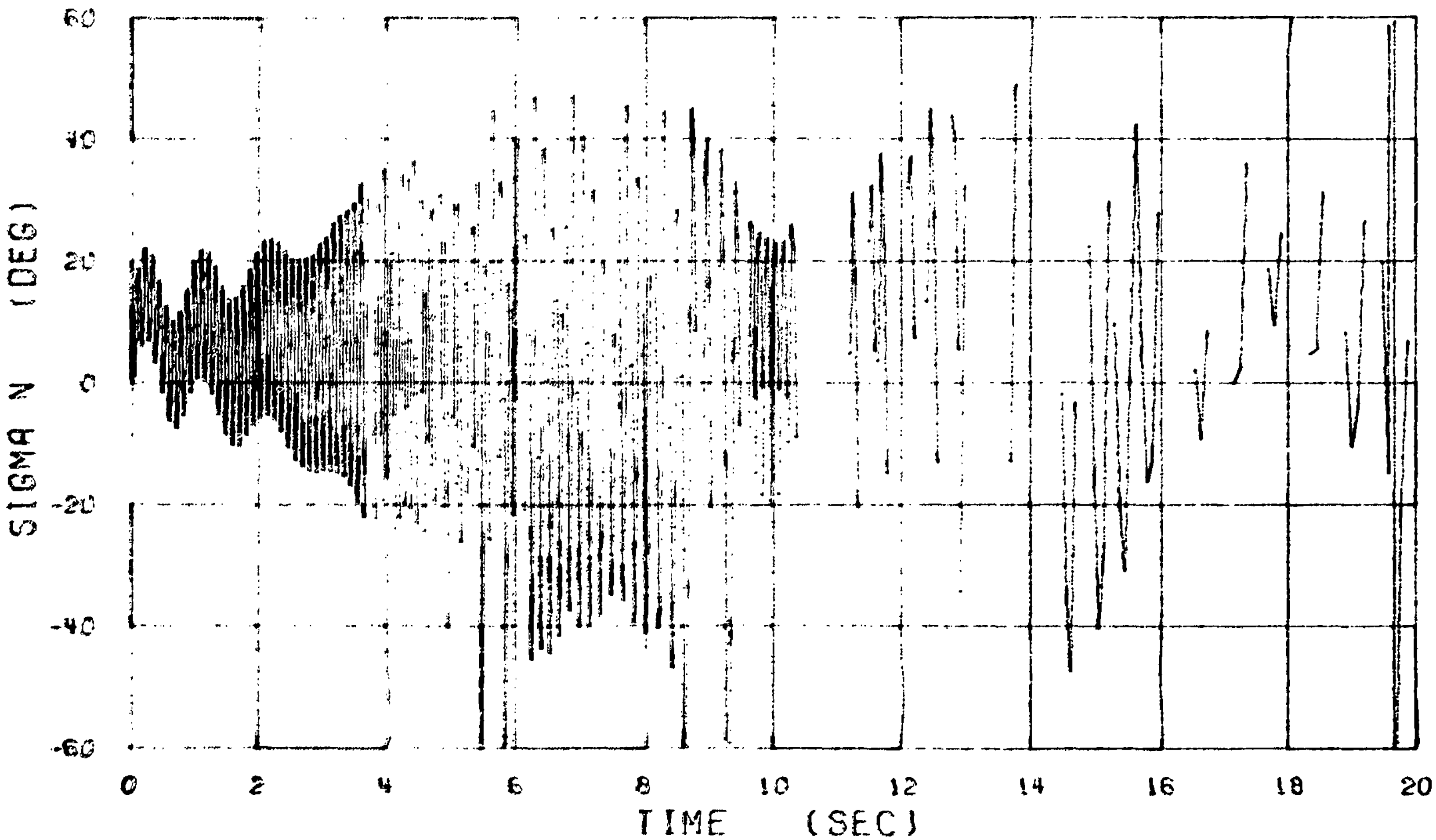

FIGURE 15. SIGMA N VS TIME ROUND E1-9186

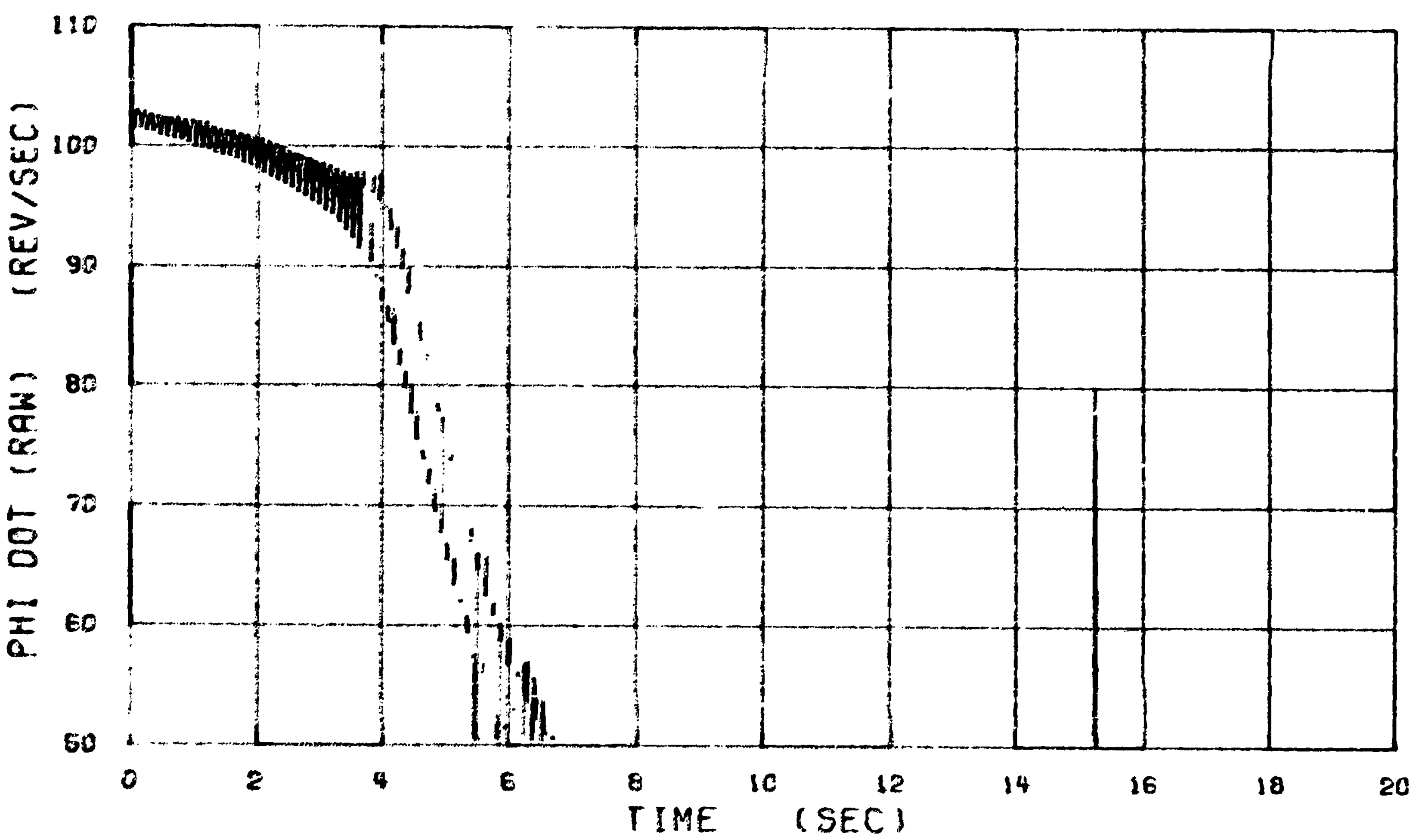

FIGURE 16. PHI DOT (RAW) VS TIME ROUND E1-9186

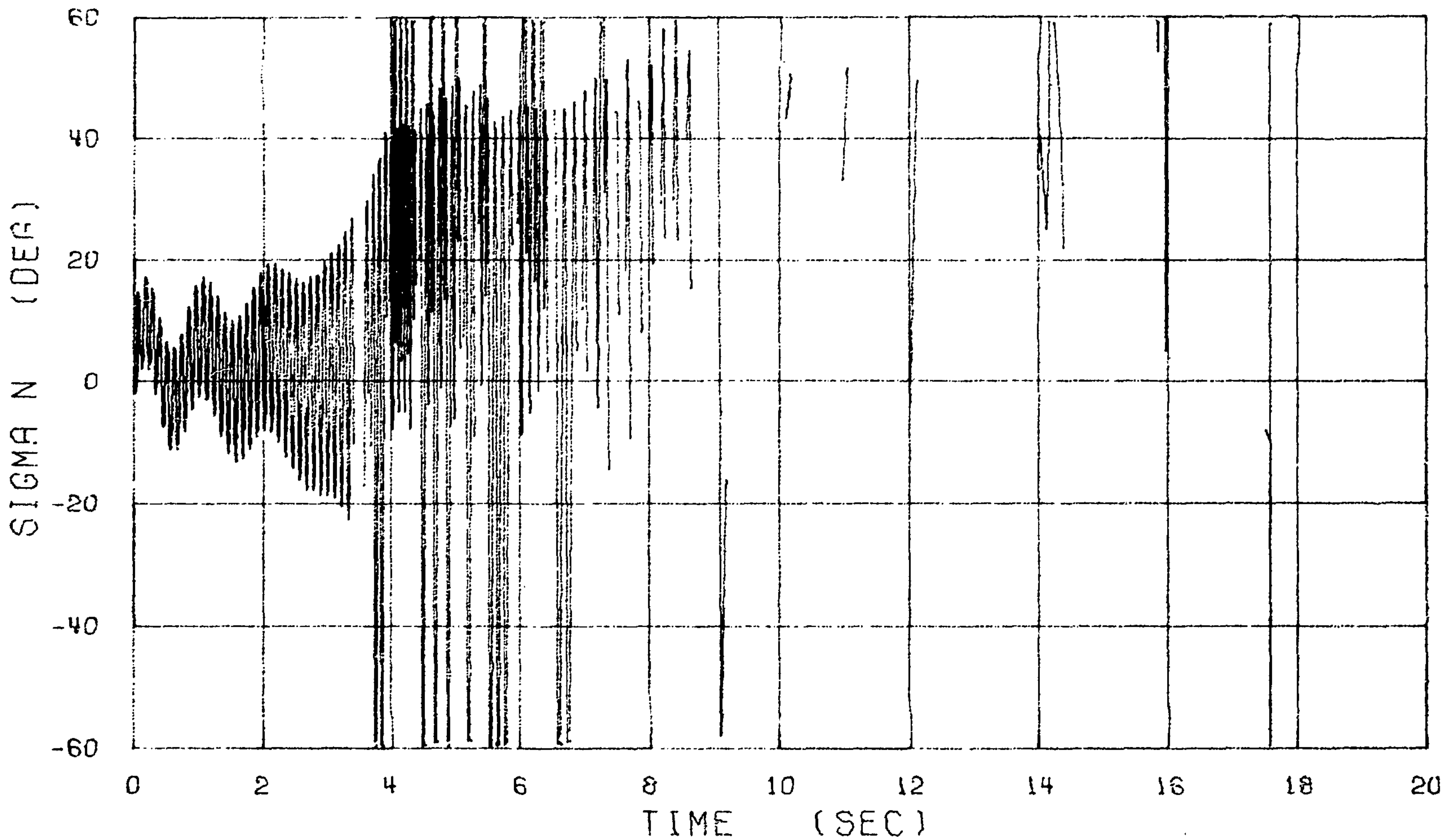

FIGURE 17. SIGMA N VS TIME ROUND E1-9187

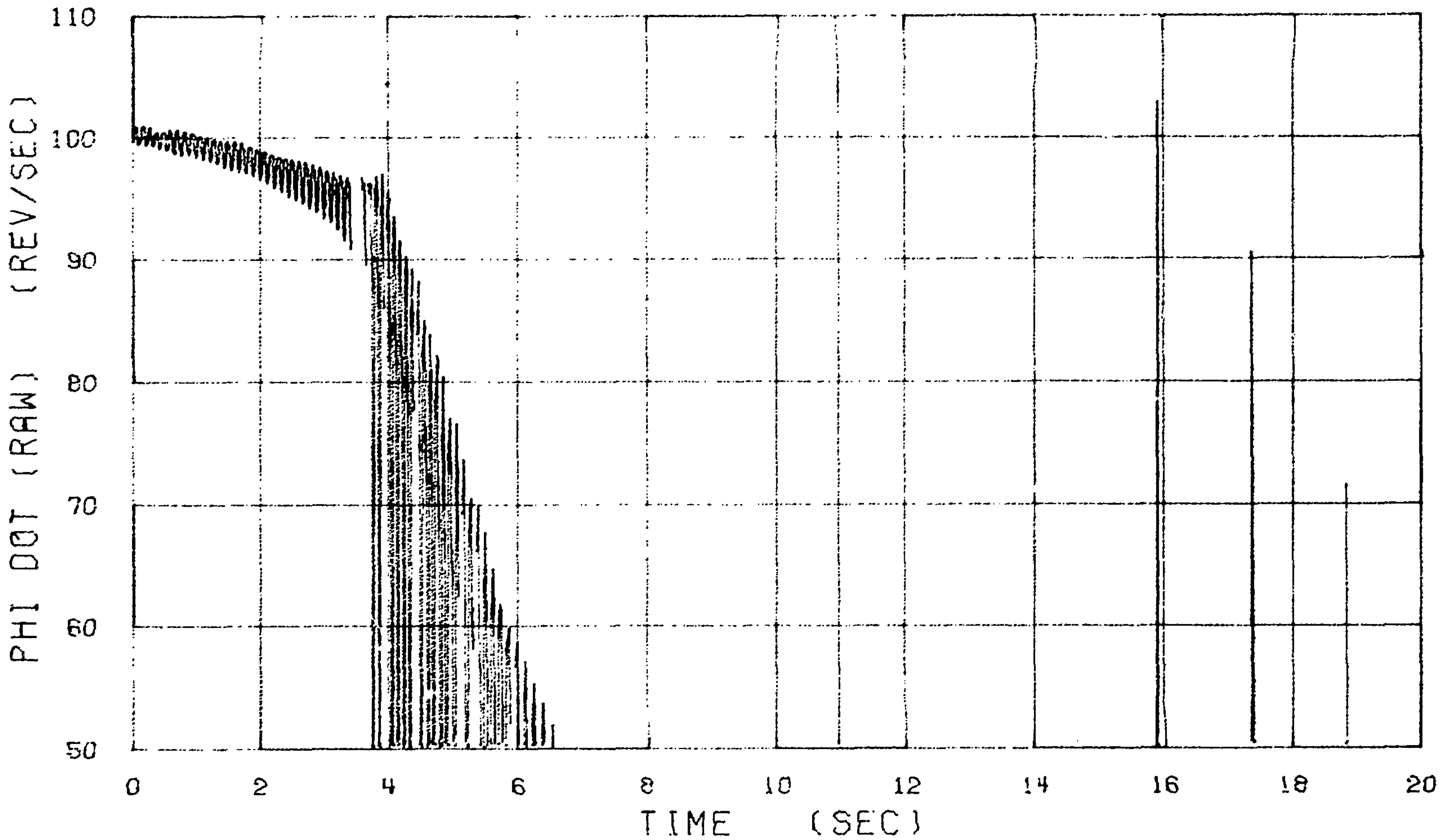

FIGURE 18. PHI DOT (RAW) VS TIME ROUND E1-9187

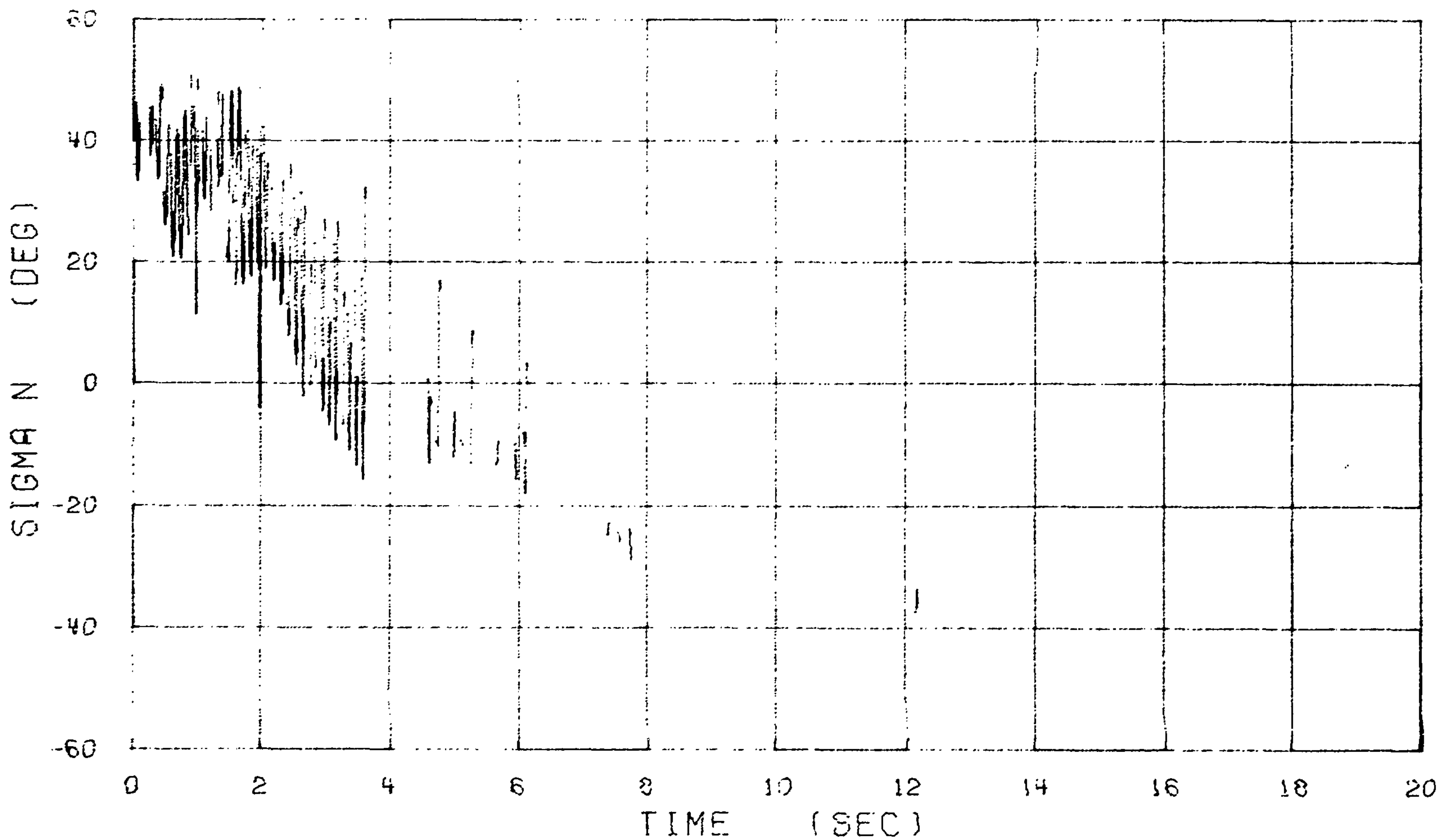

FIGURE 19. SIGMA N VS TIME ROUND E1-9180

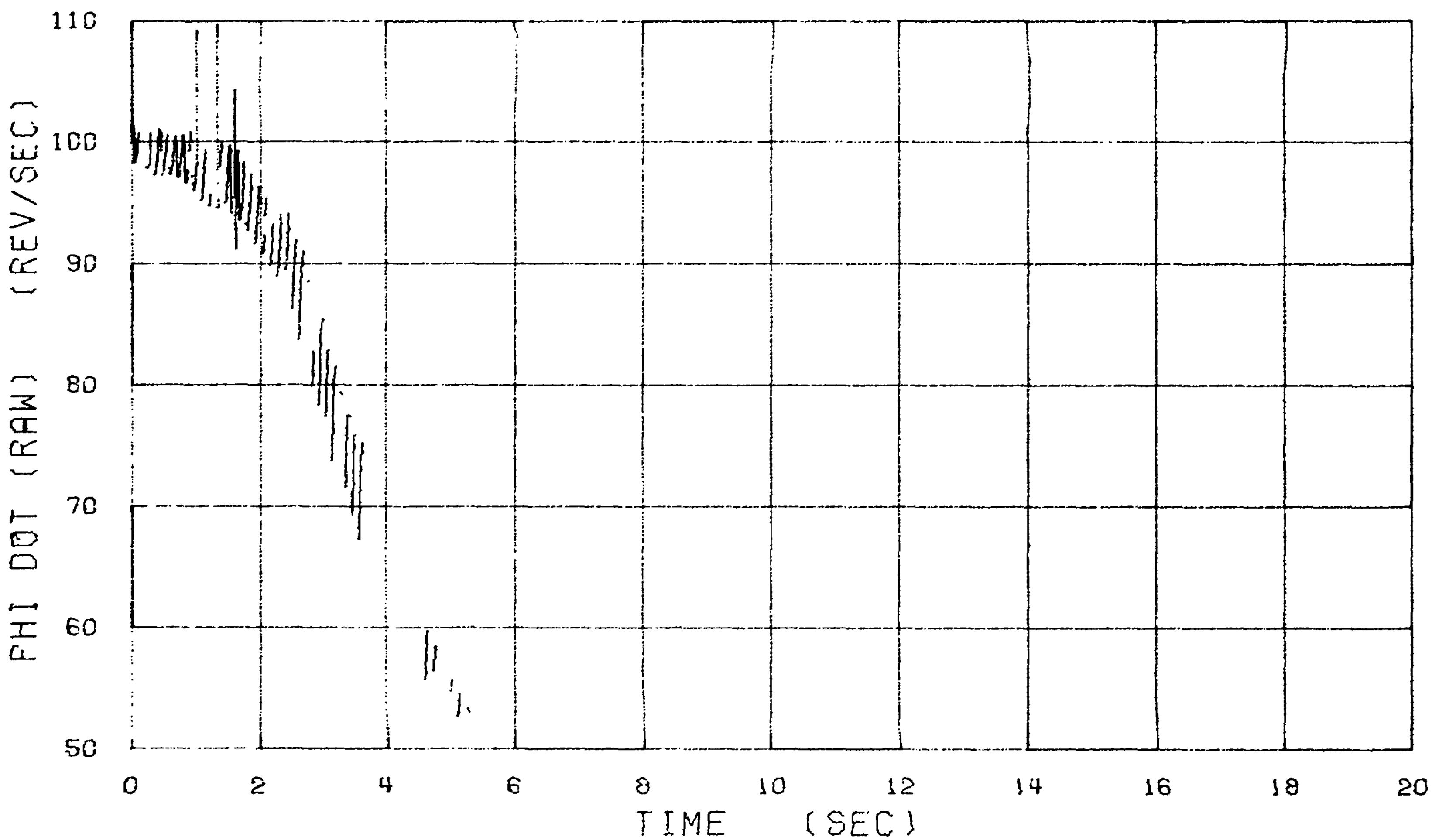

FIGURE 20. PHI DOT (RAW) VS TIME ROUND E1-9180

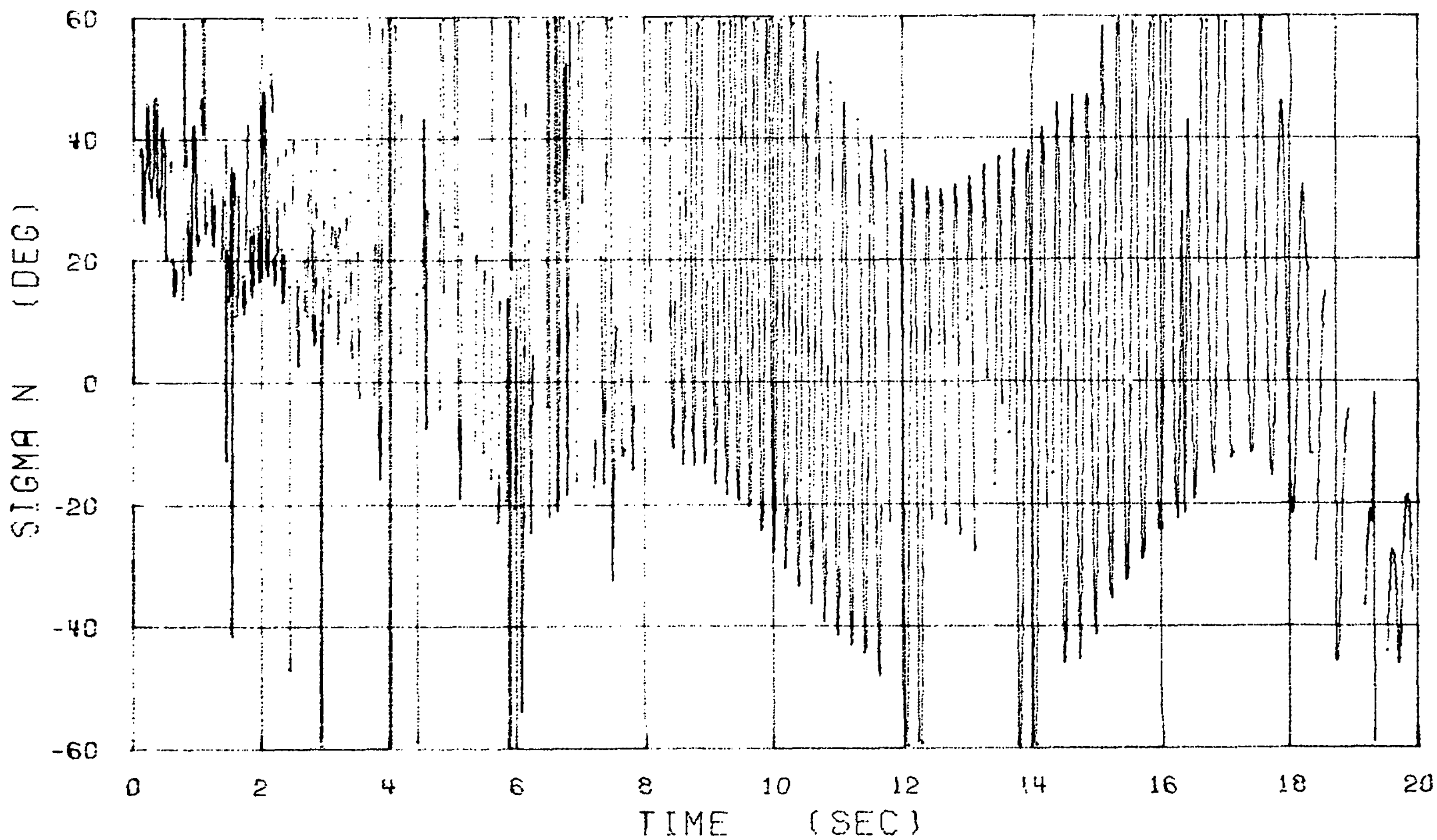

FIGURE 21. SIGMA N VS TIME ROUND E1-9181

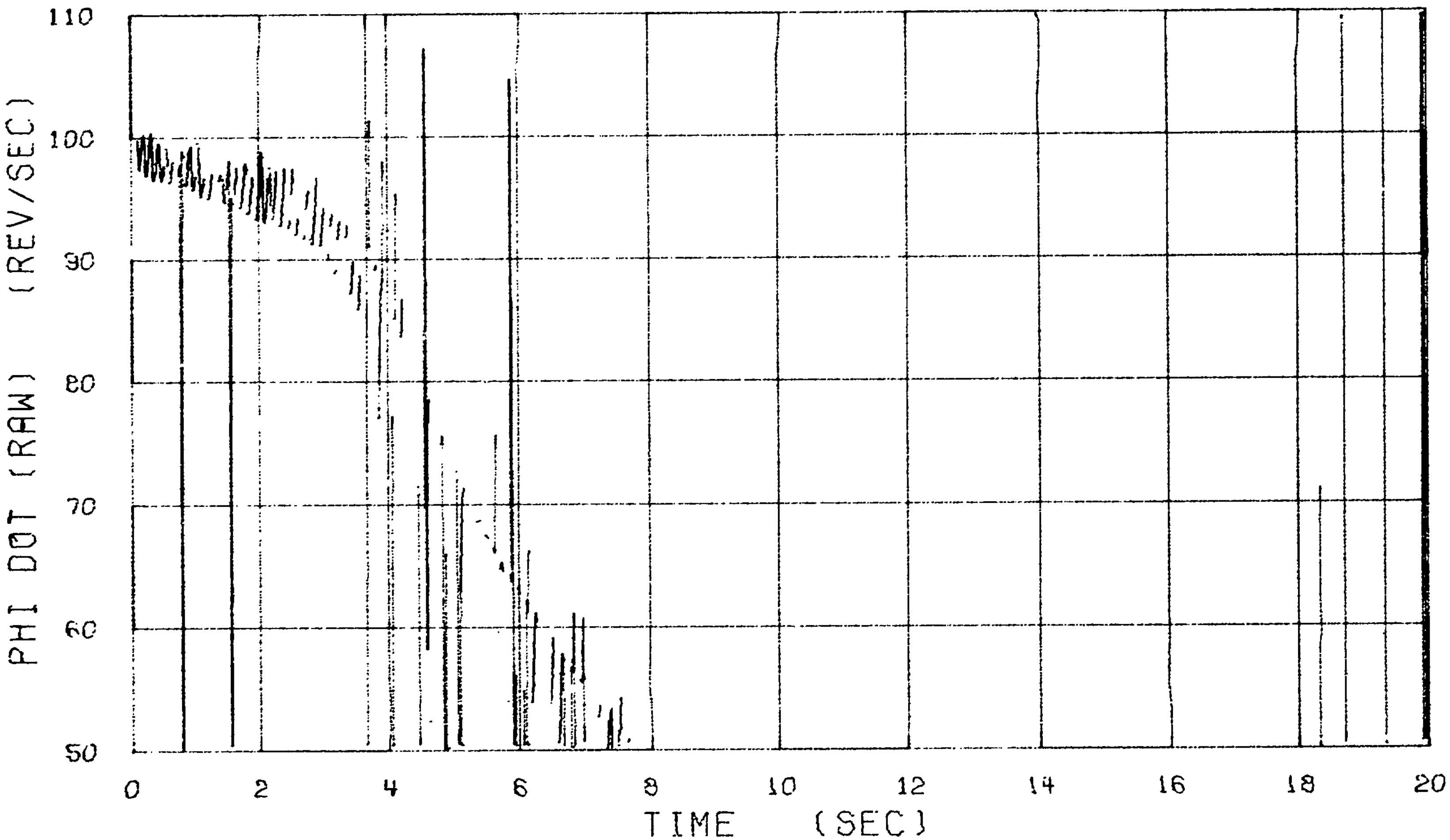

FIGURE 22. PHI DOT (RAW) VS TIME ROUND E1-9181

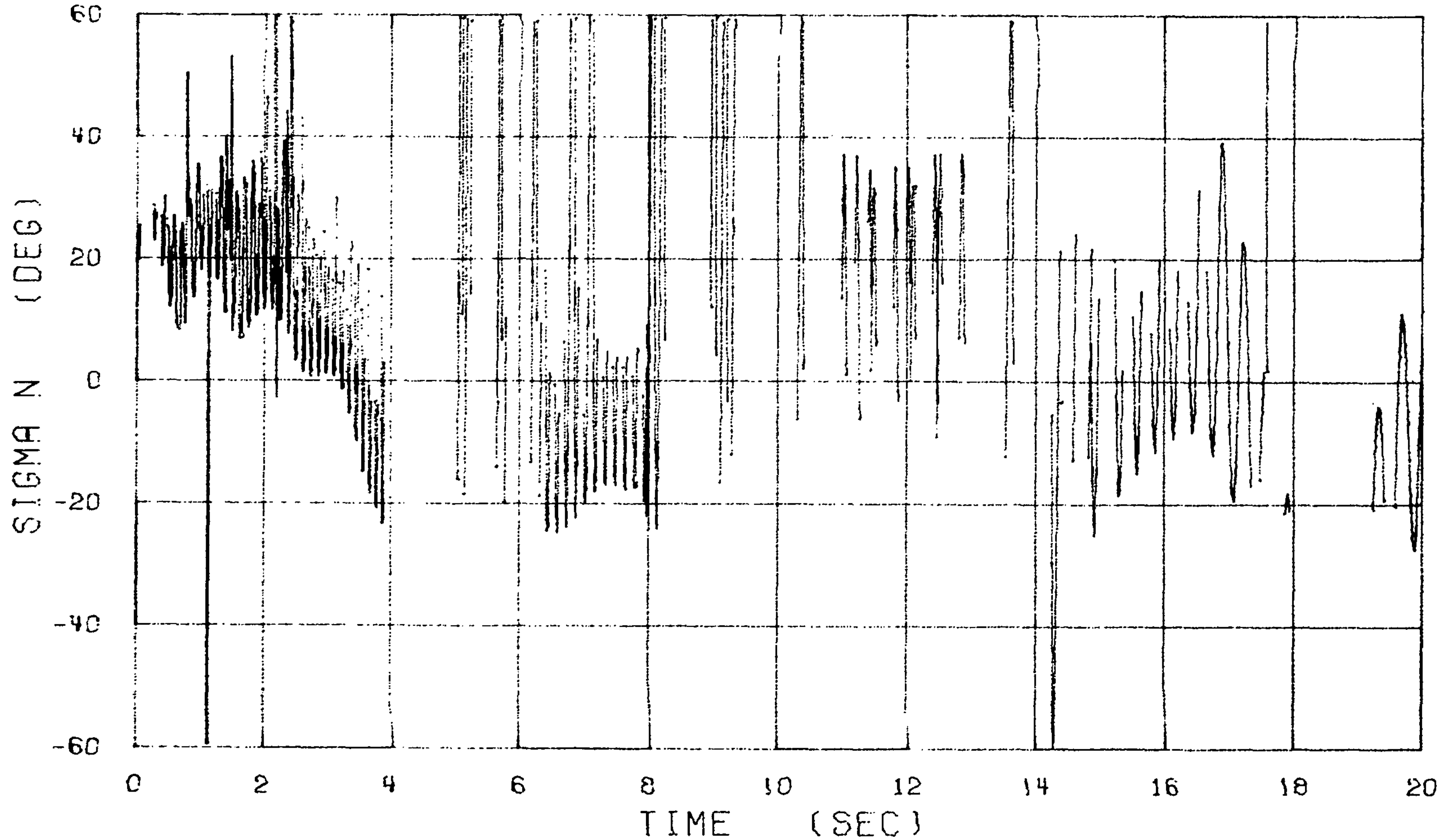

FIGURE 23. SIGMA N VS TIME ROUND E1-9182

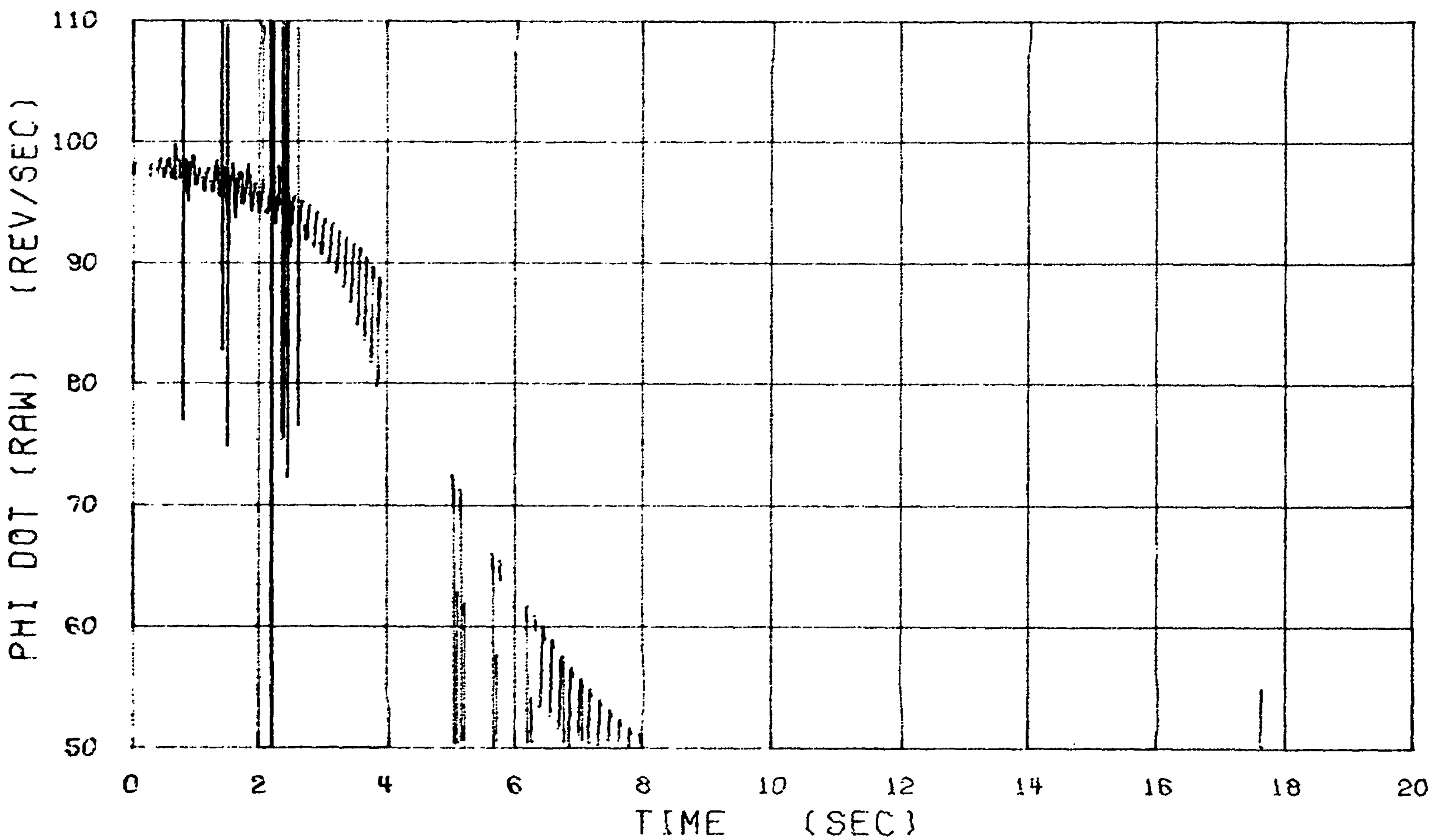

FIGURE **24.** PHI DOT (RAW) VS TIME ROUND E1-9182

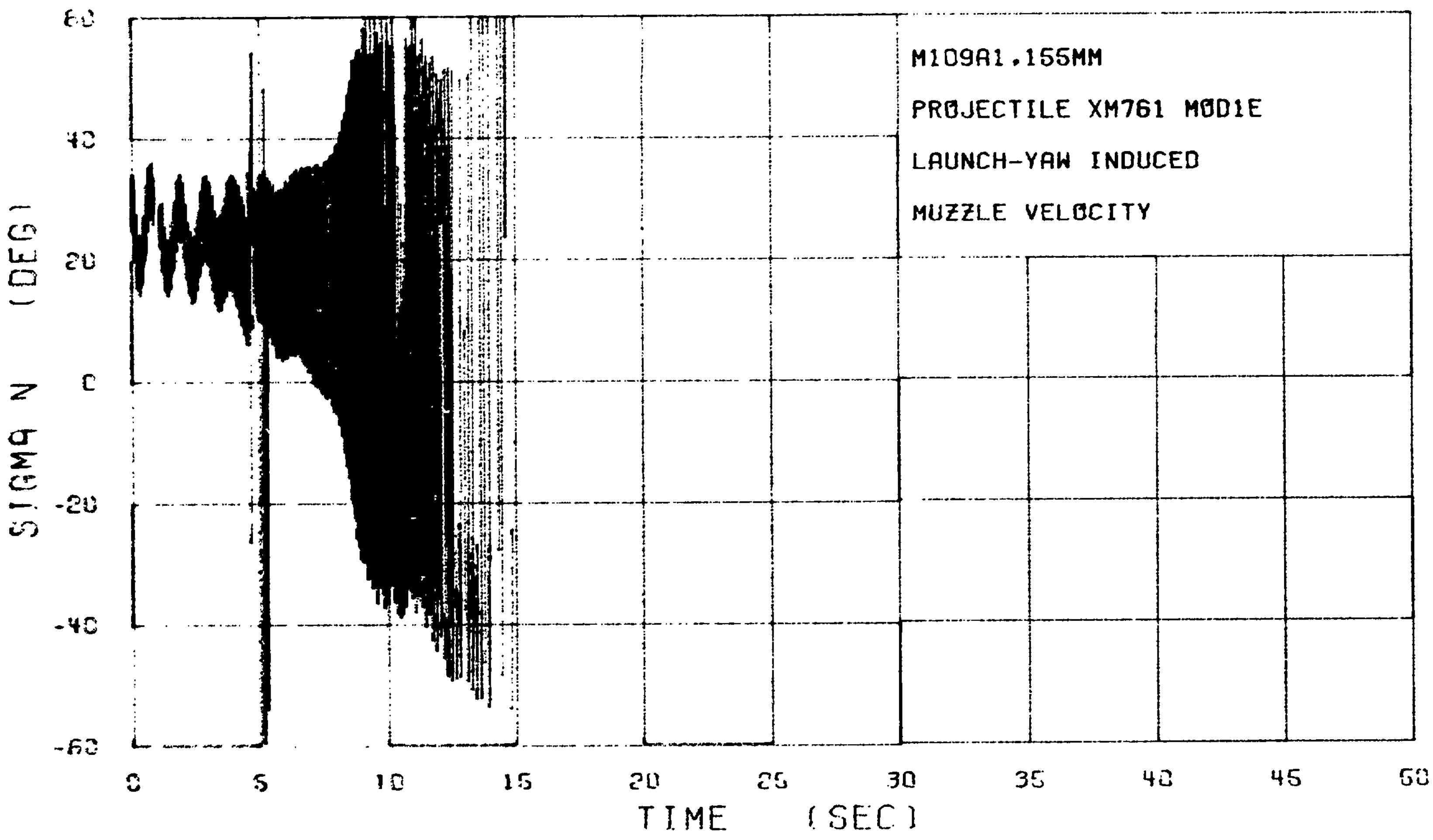

FIGURE 25. SIGMA N VS TIME ROUND DPG 2

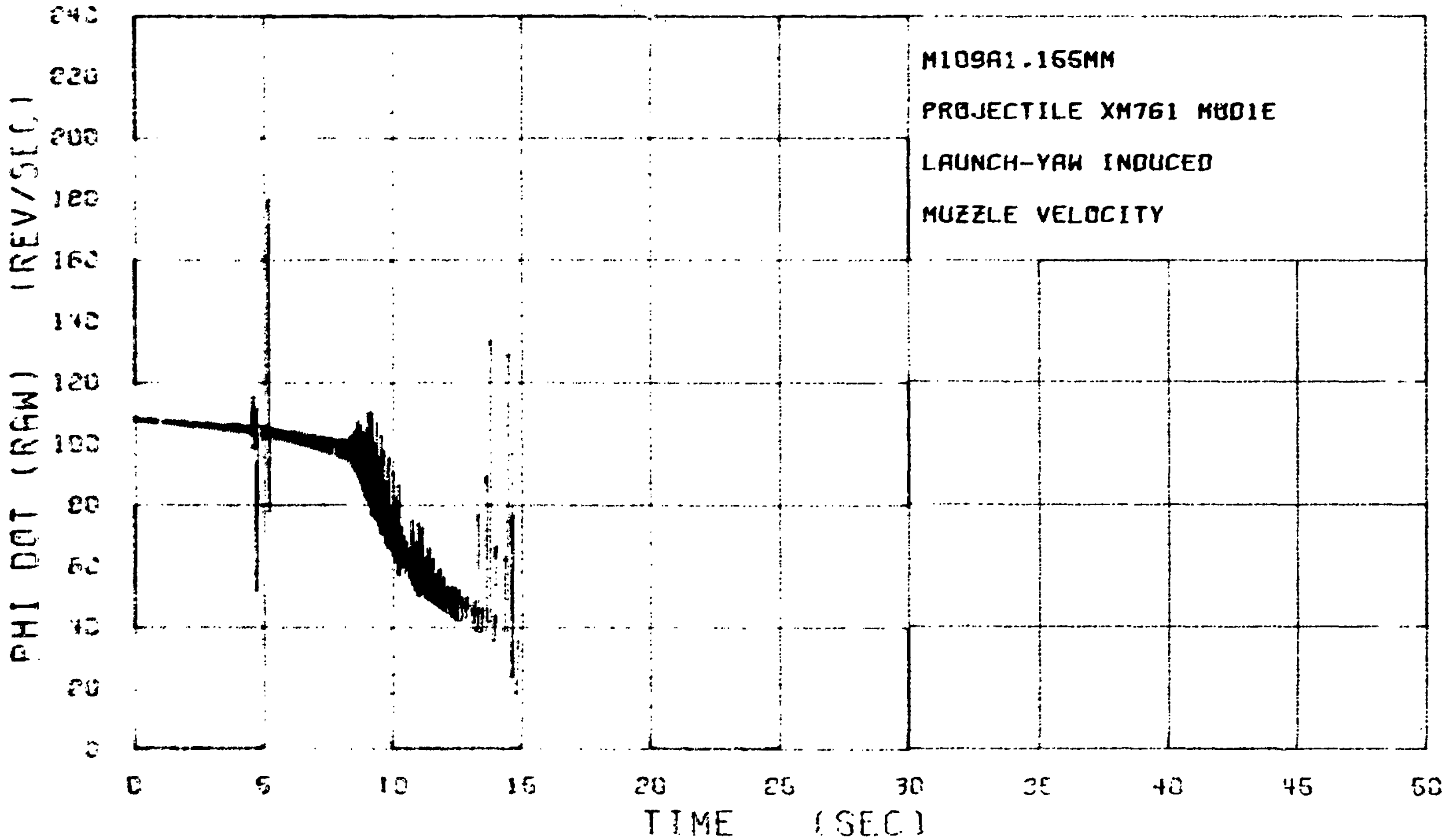

FIGURE 26. PHI DOT (RAW) VS TIME ROUND DPG 2

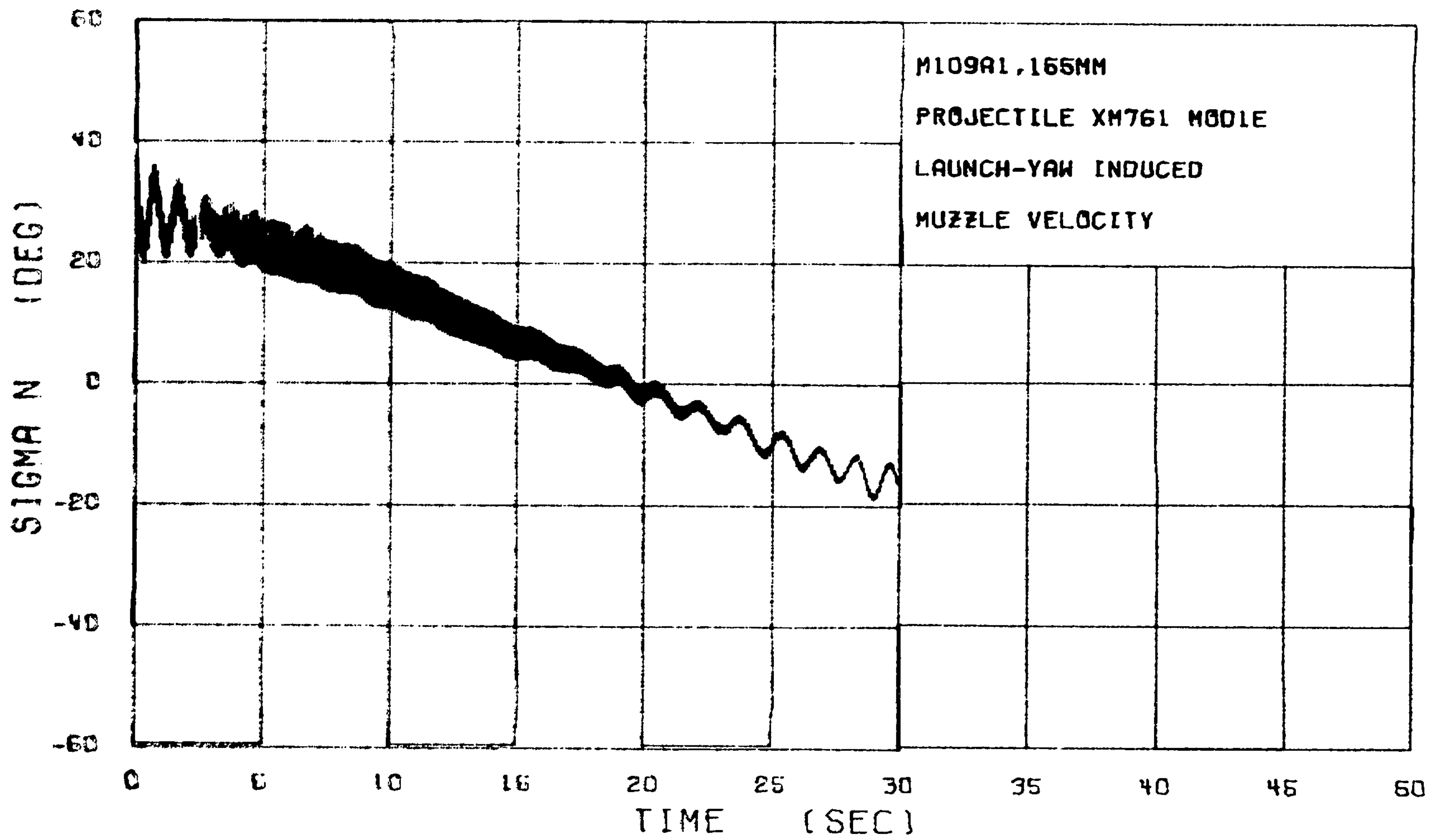

FIGURE 27. SIGMA N VS TIME ROUND DPG 3

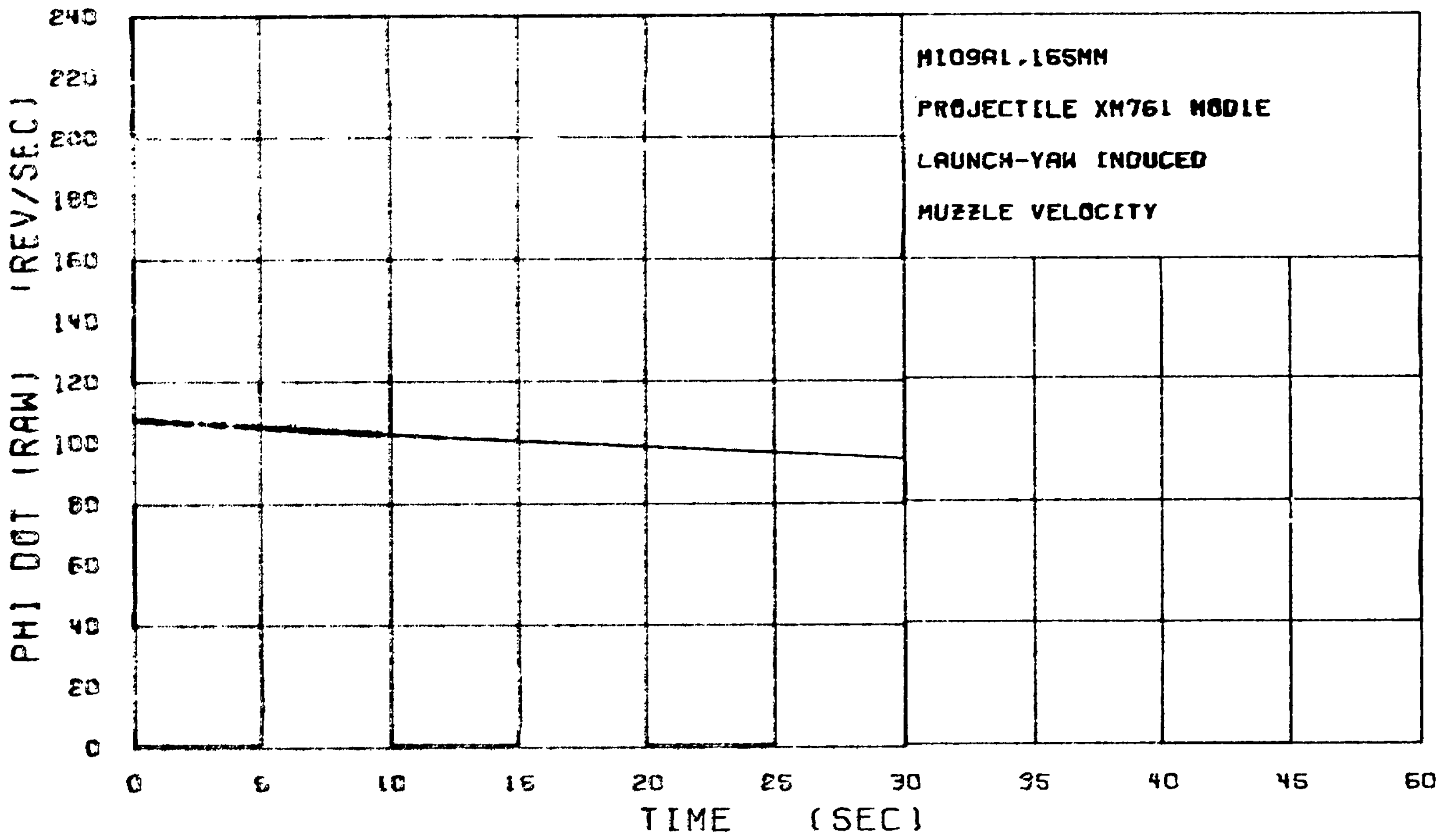

FIGURE 28. PHI DOT (RAW) VS TIME ROUND DPG 3

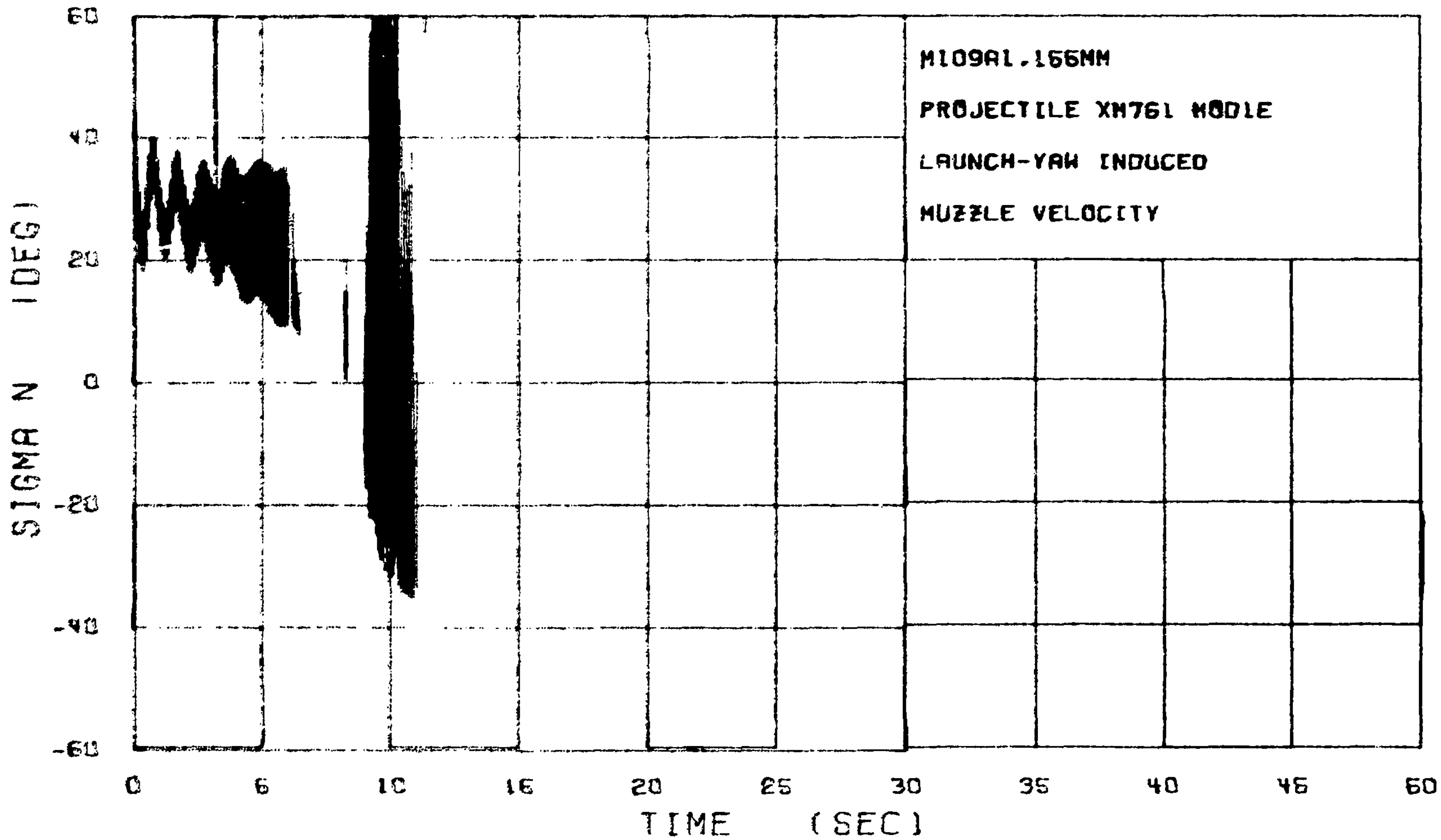

FIGURE 29. SIGMA N VS TIME ROUND DPG 4

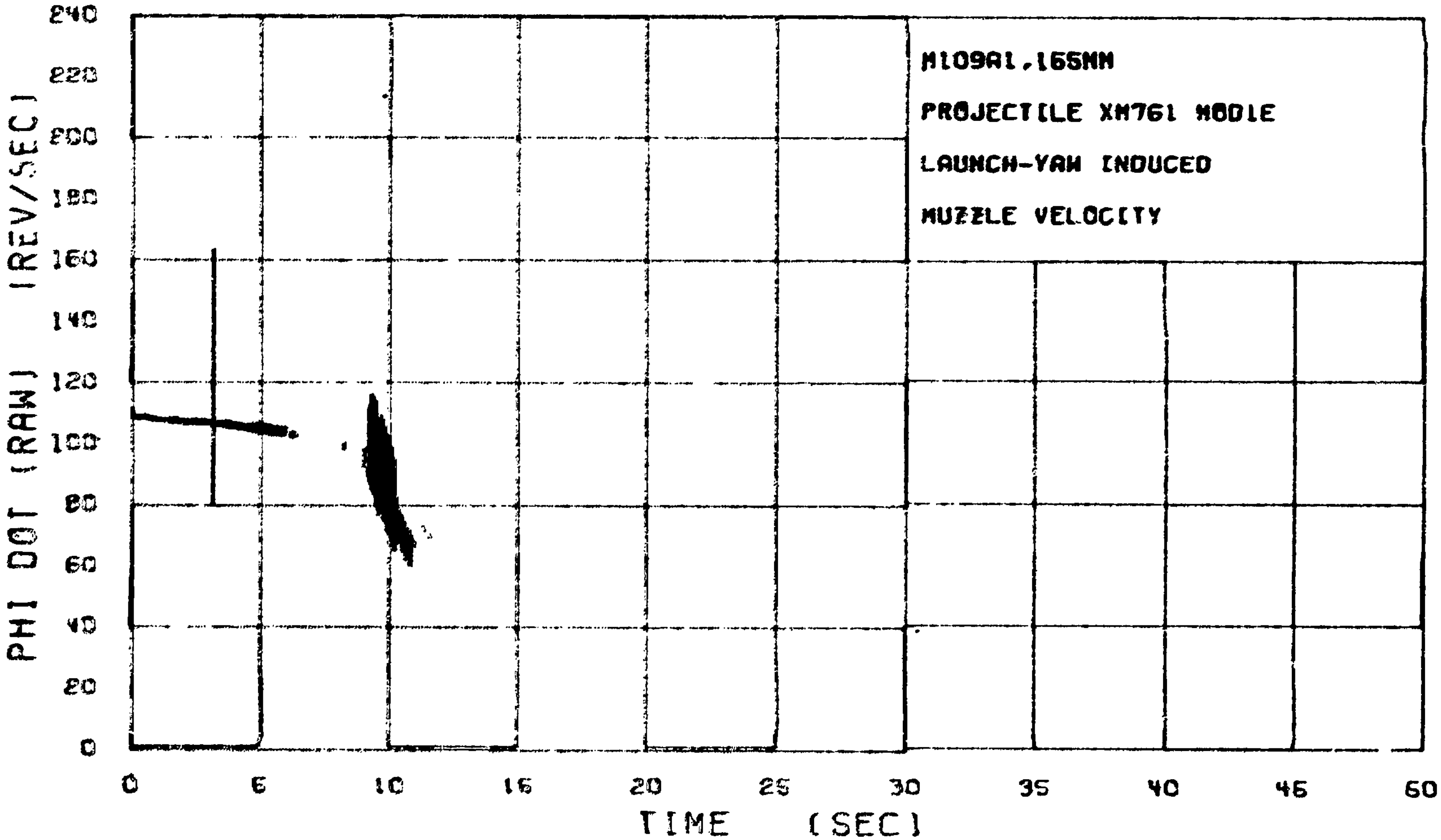

FIGURE 30. PHI DOT (RAW) VS TIME ROUND DPG 4

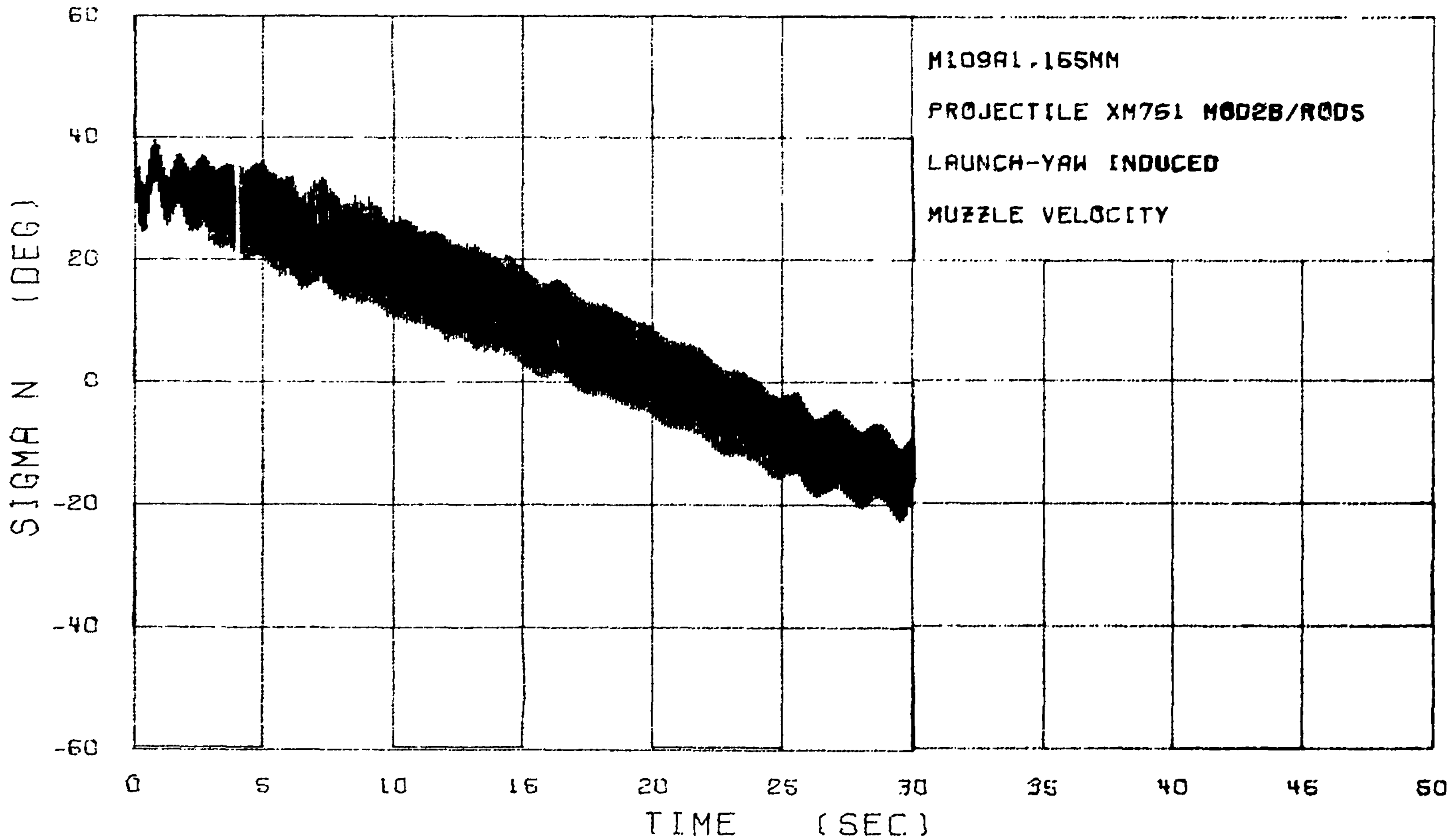

FIGURE 31. SIGMA N VS TIME ROUND DPG 8

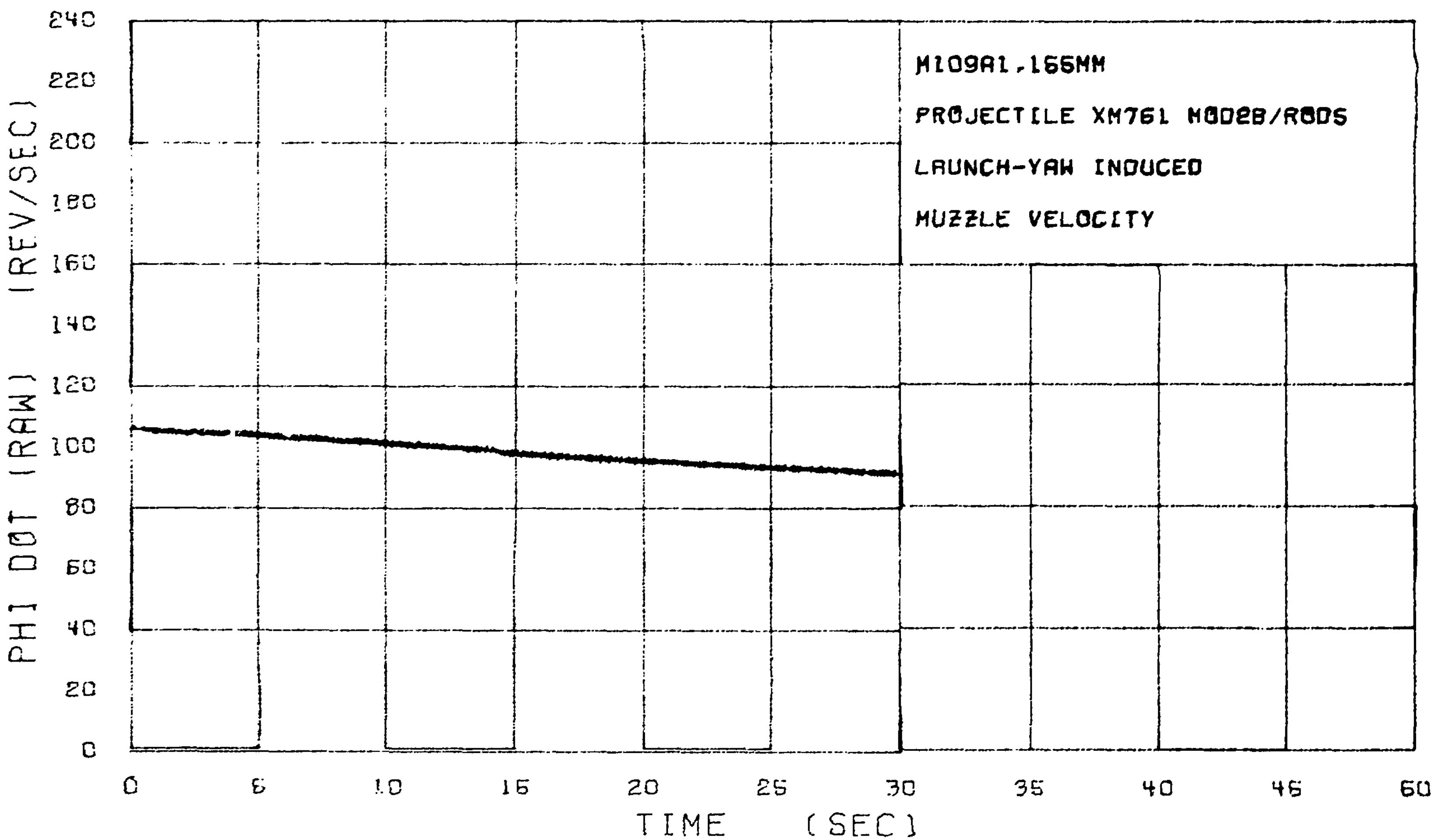

FIGURE 32. PHI DOT (RAW) VS TIME ROUND DPG 8

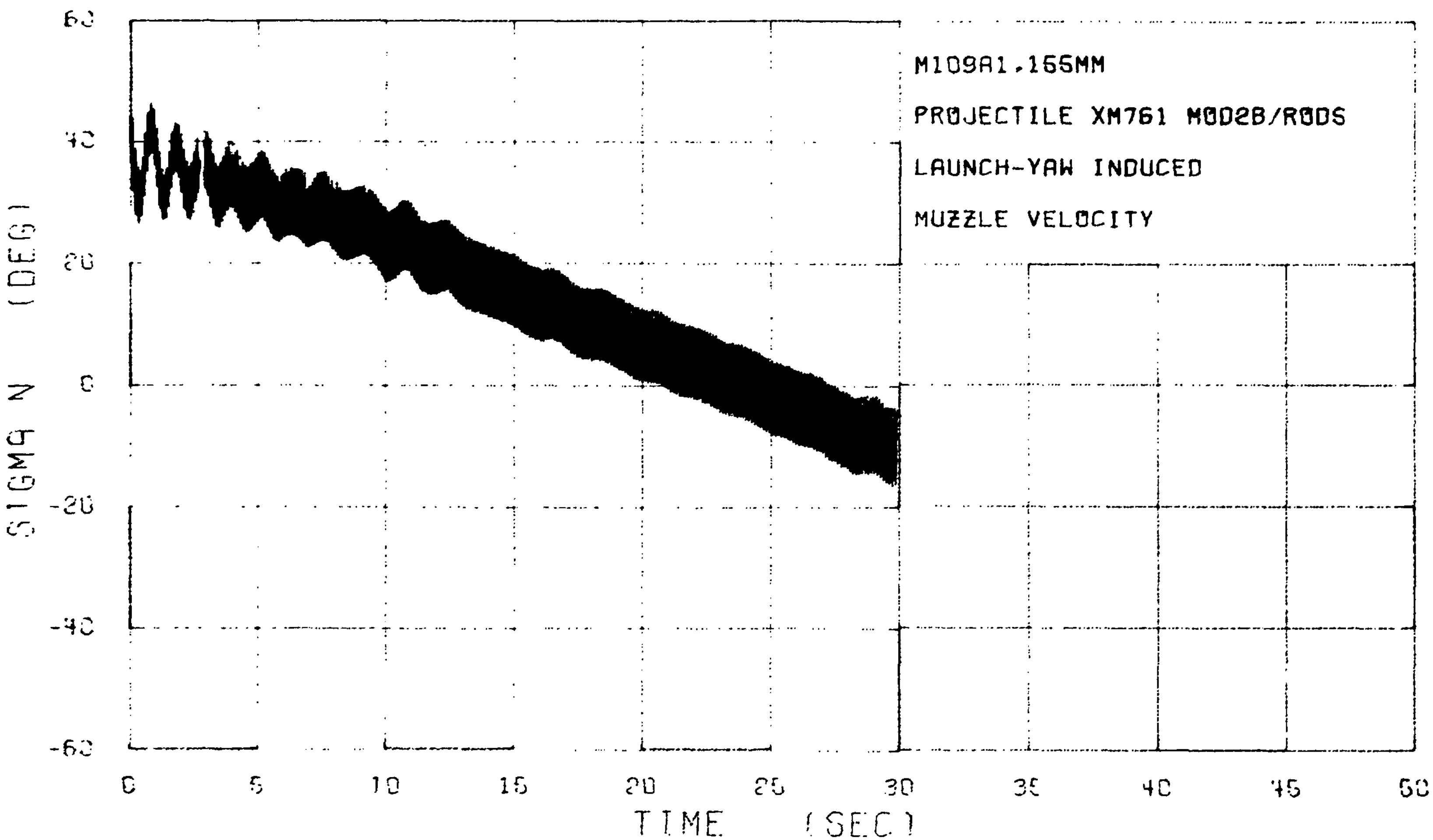

FIGURE 33. SIGMA N VS TIME ROUND DPG 11

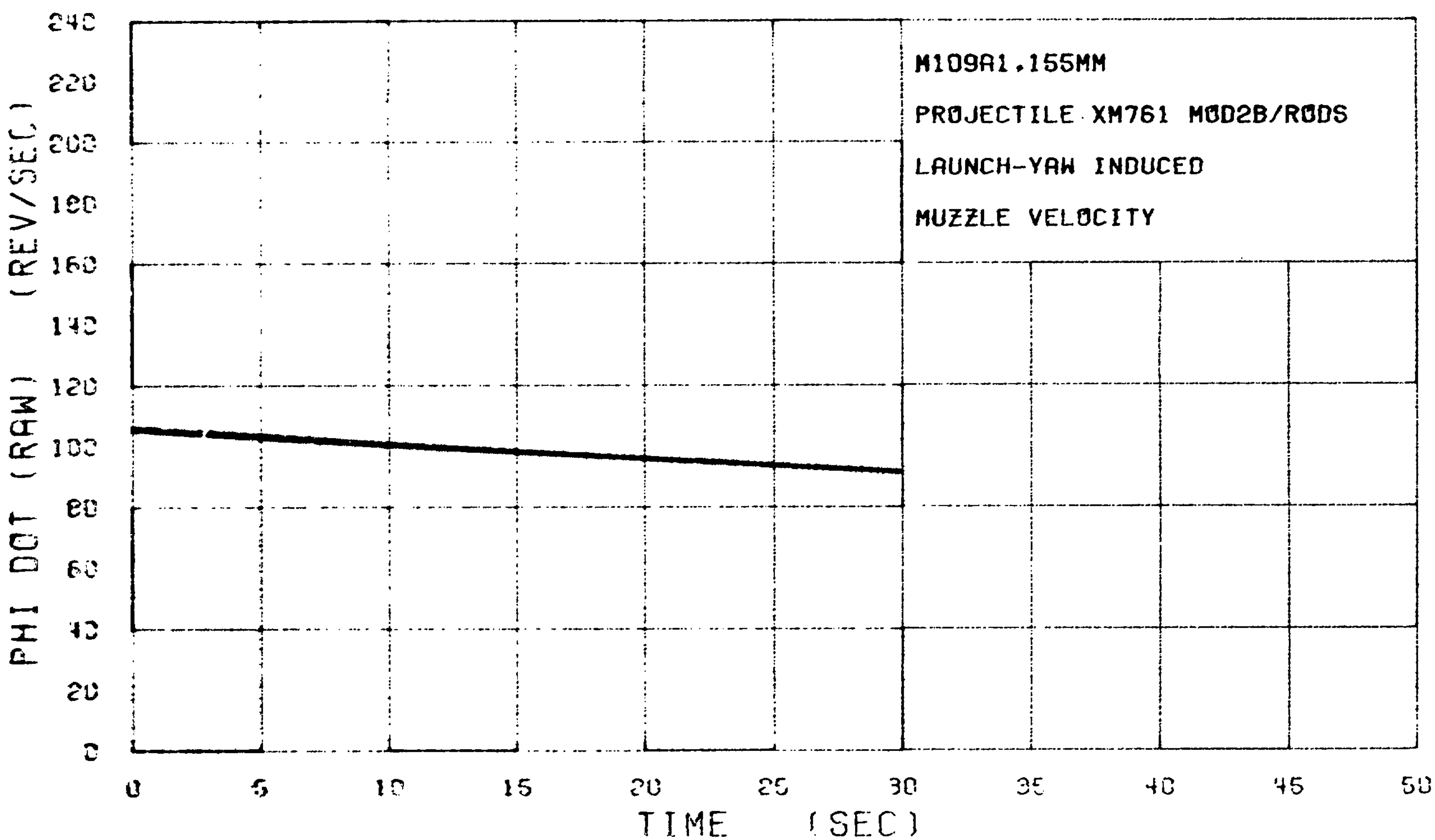

FIGURE 34. PHI DOT (RAW) VS TIME ROUND DPG 11

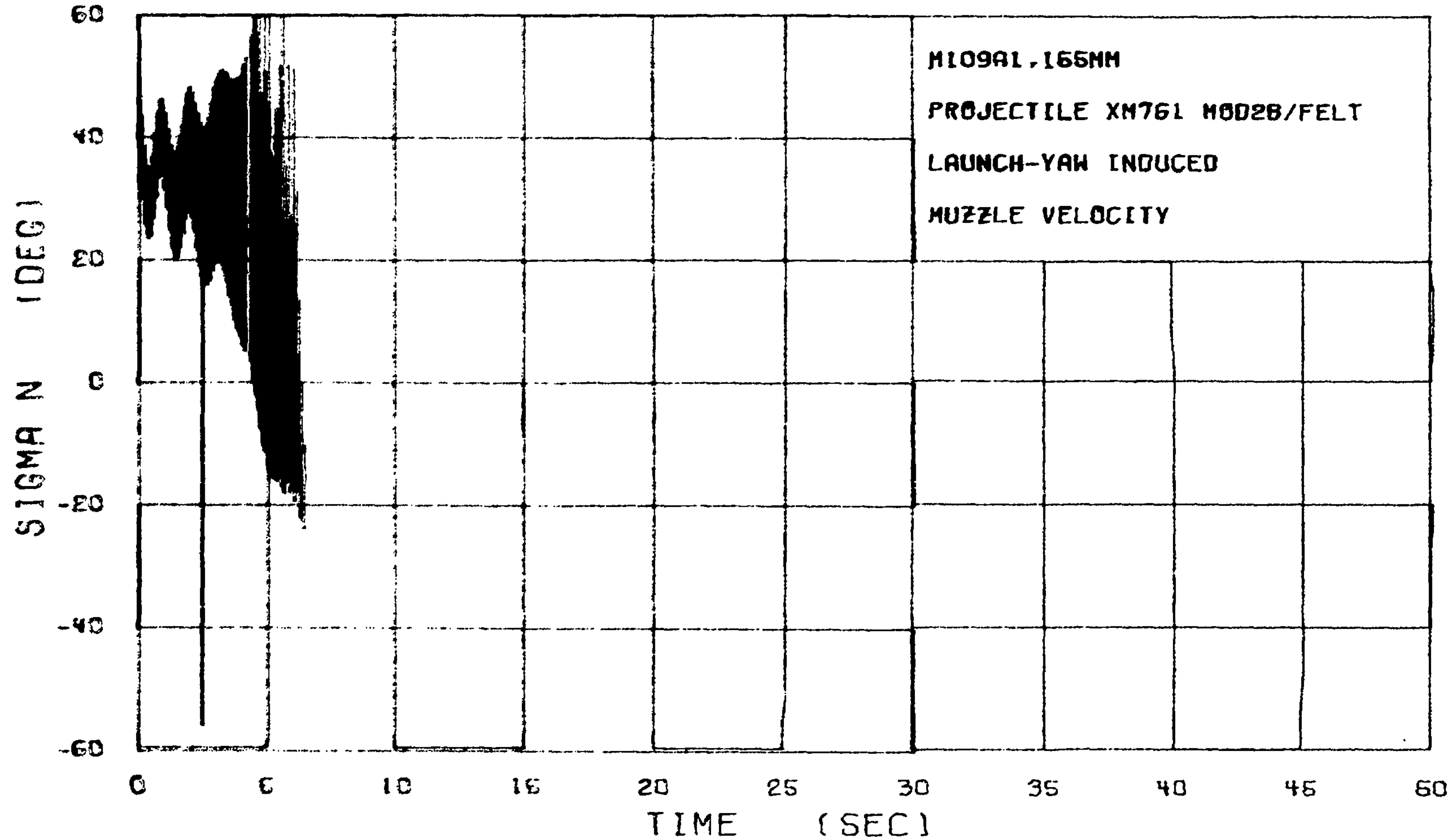

FIGURE 35. SIGMA N VS TIME ROUND DPG 9

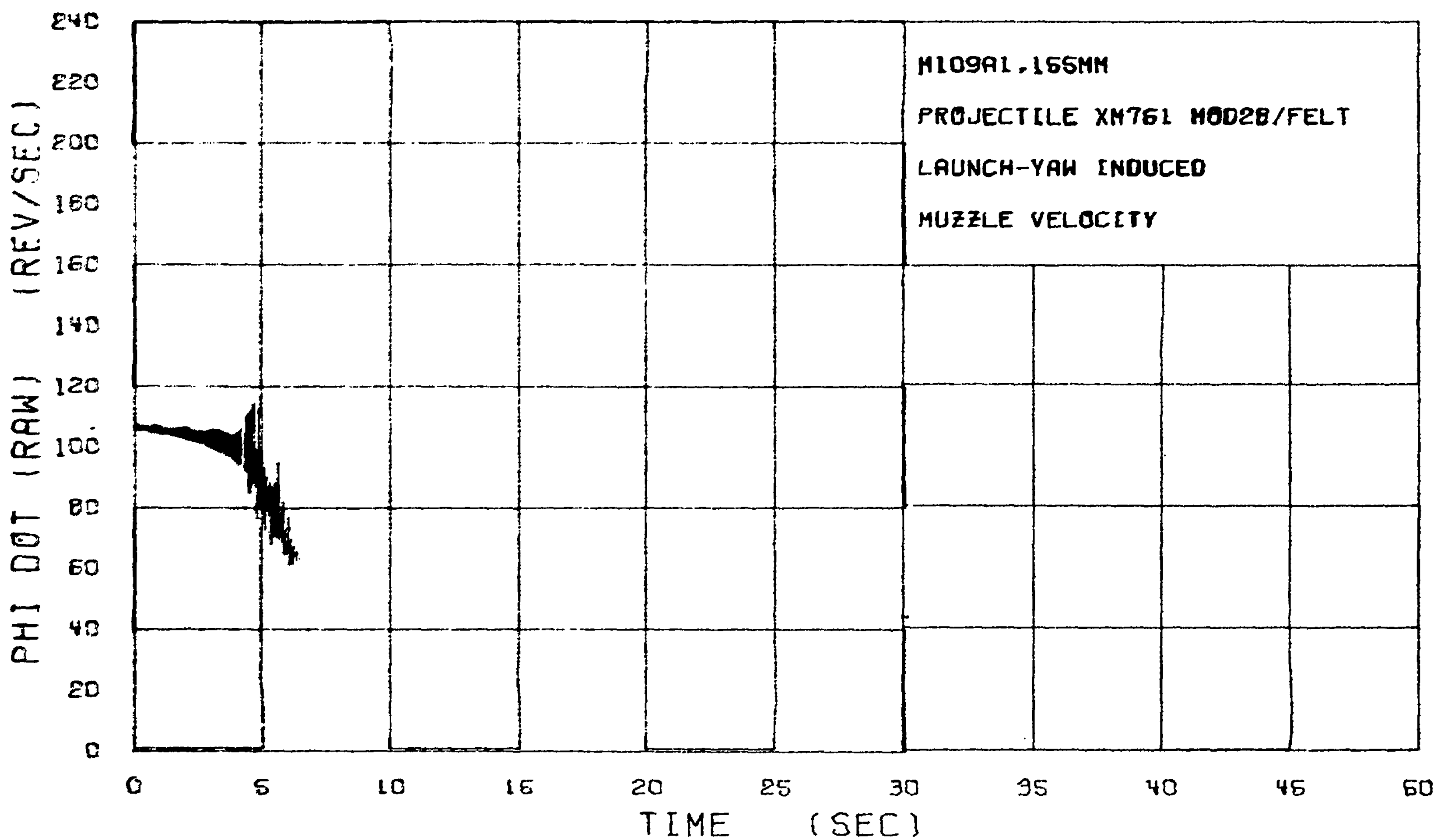

FIGURE 36. PHI DOT (RAW) VS TIME ROUND DPG 9

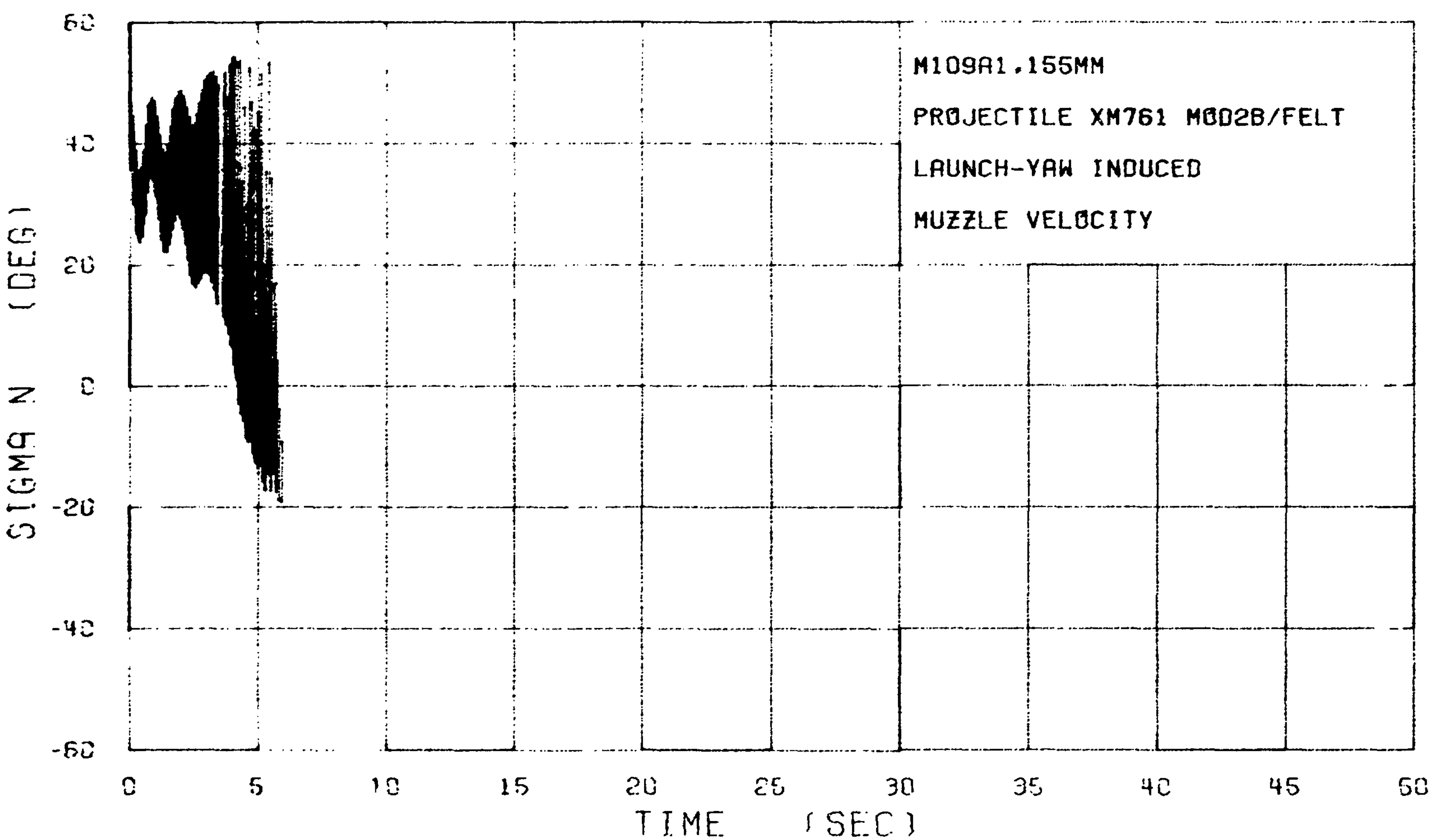

FIGURE 37. SIGMA N VS TIME ROUND DPG 10

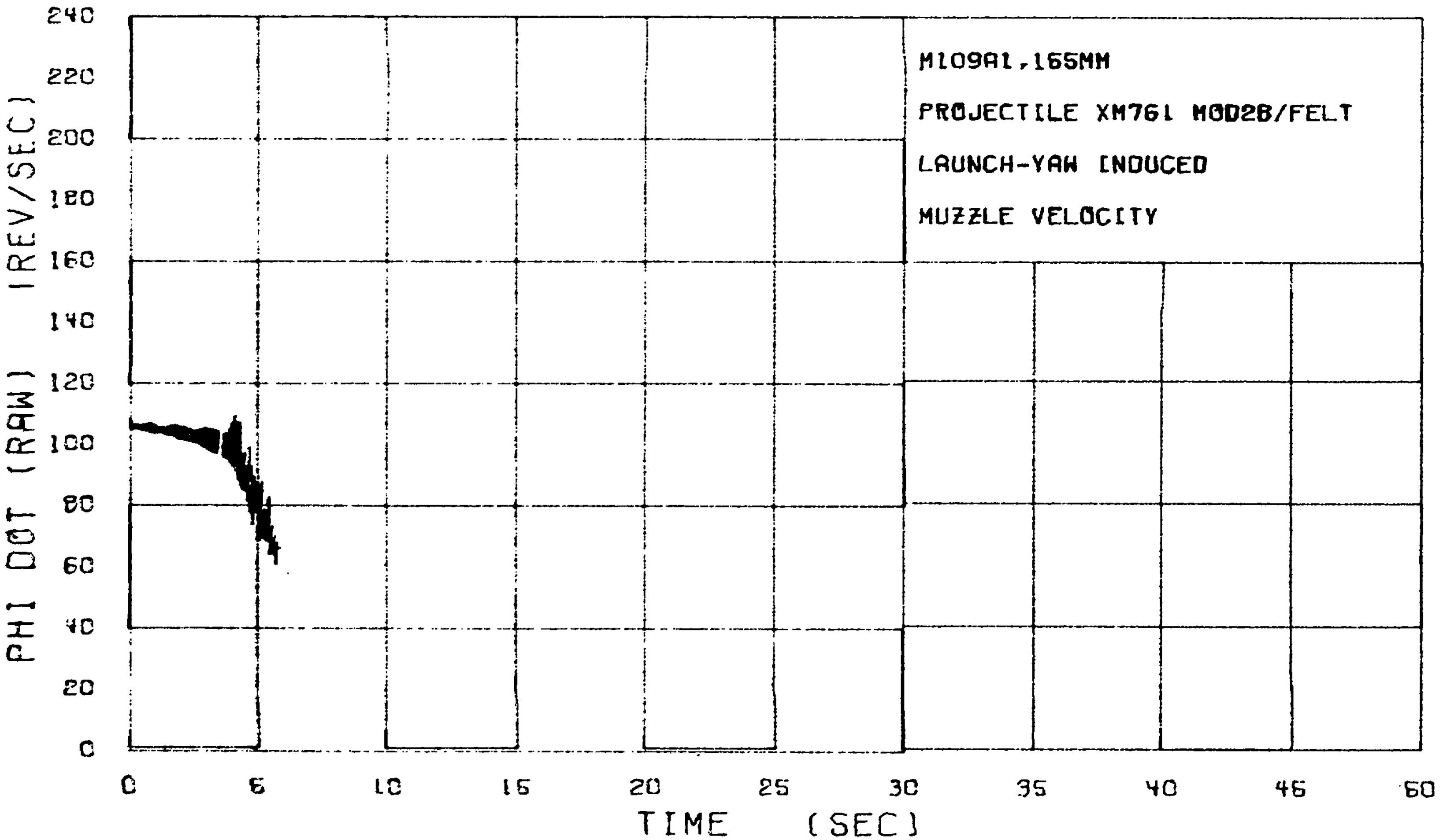

FIGURE 38. PHI DOT (RAW) VS TIME ROUND DPG 10

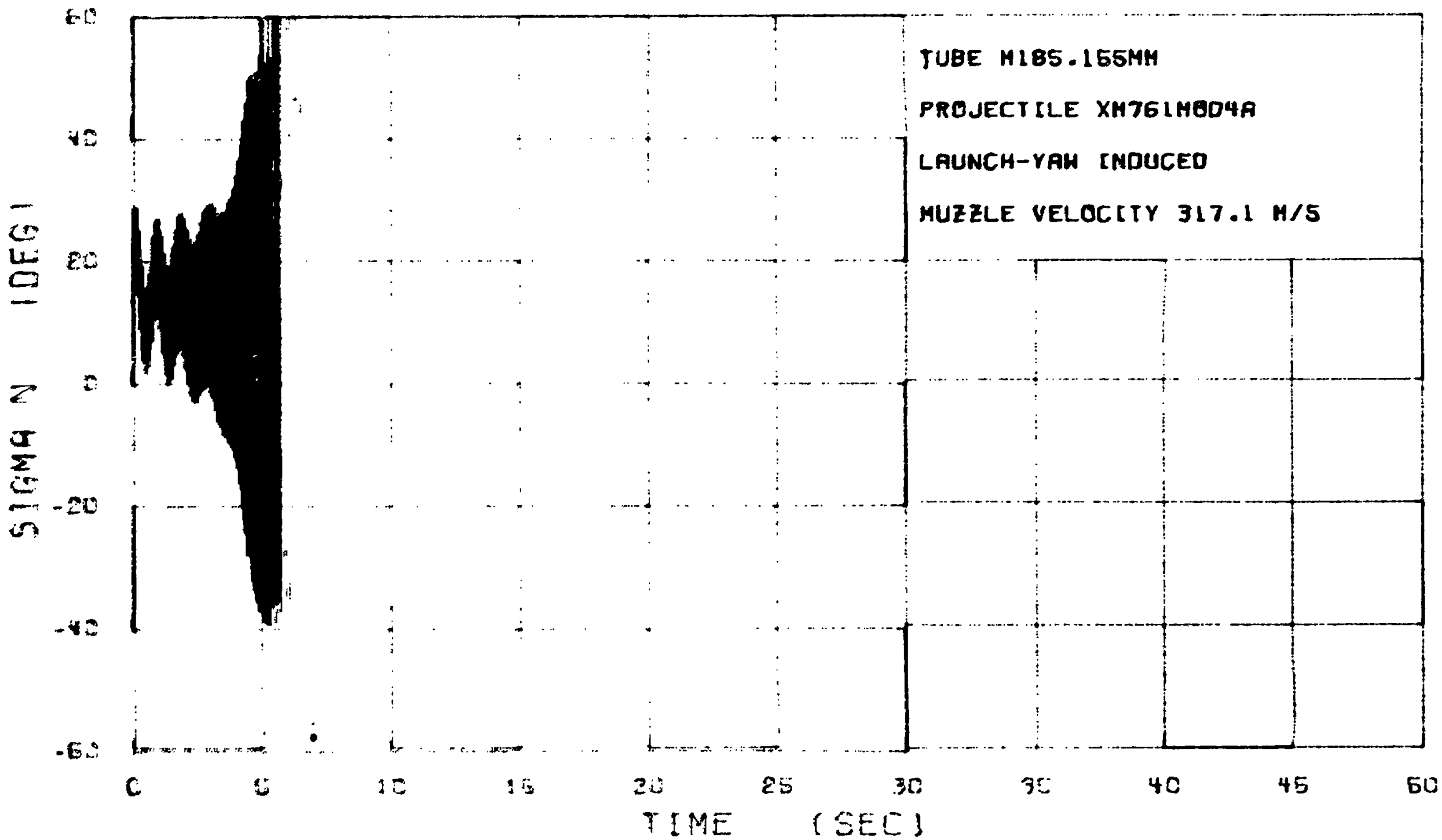

FIGURE 39. SIGMA N VS TIME ROUND E1-9391

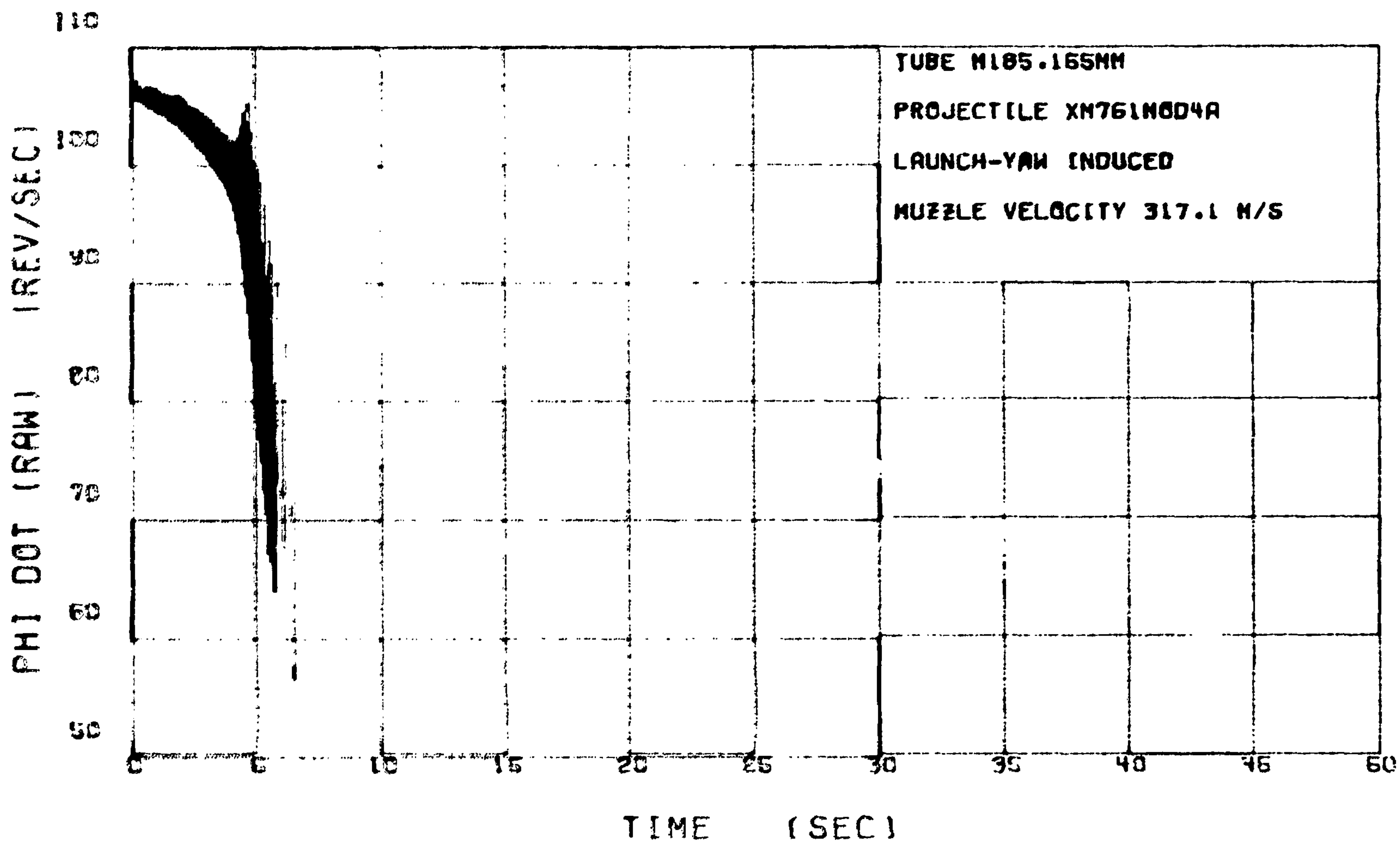

FIGURE 40. PHI DOT (RAW) VS TIME ROUND E1-9391

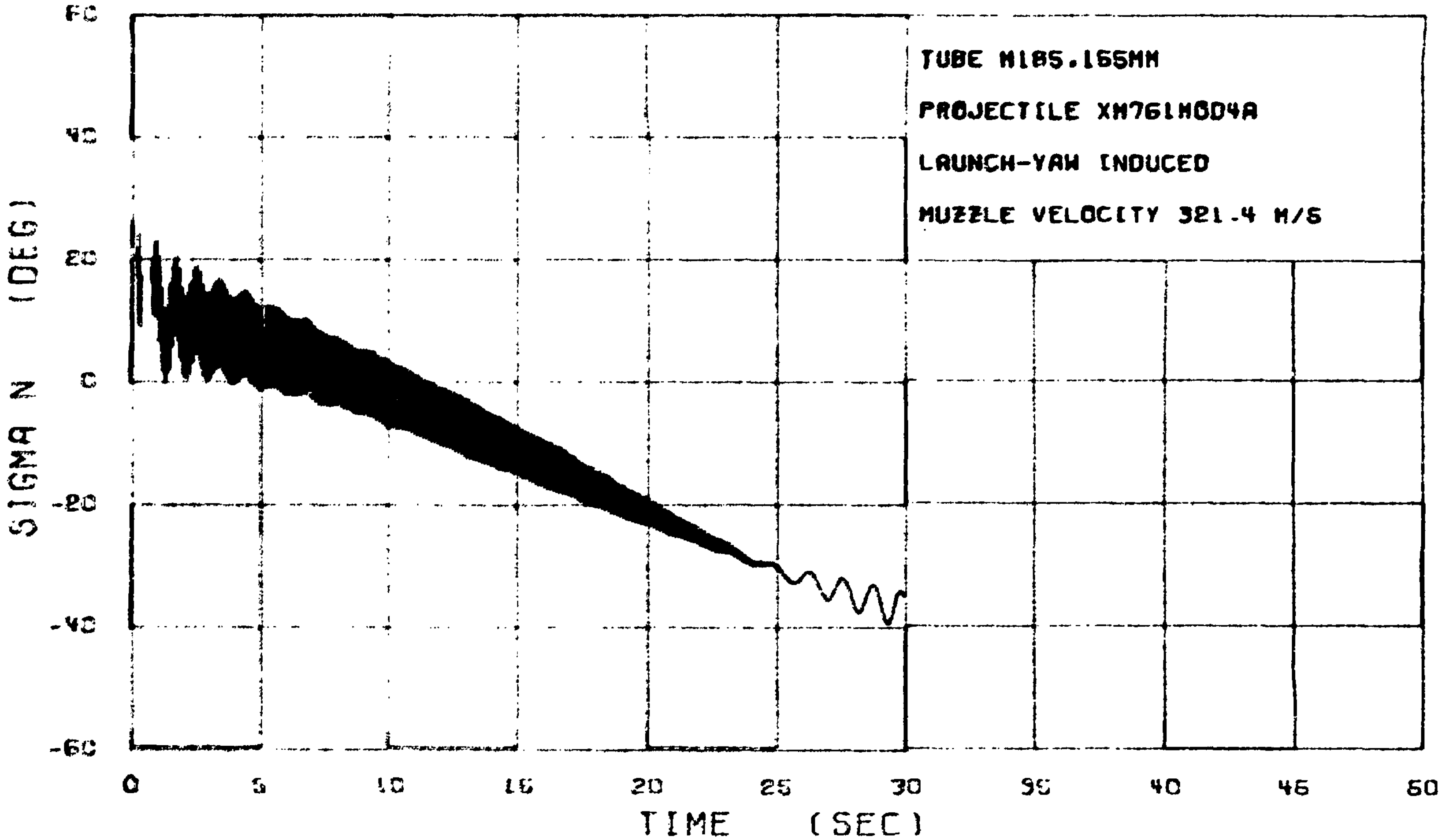

FIGURE 41. SIGMA N VS TIME ROUND E1-9392

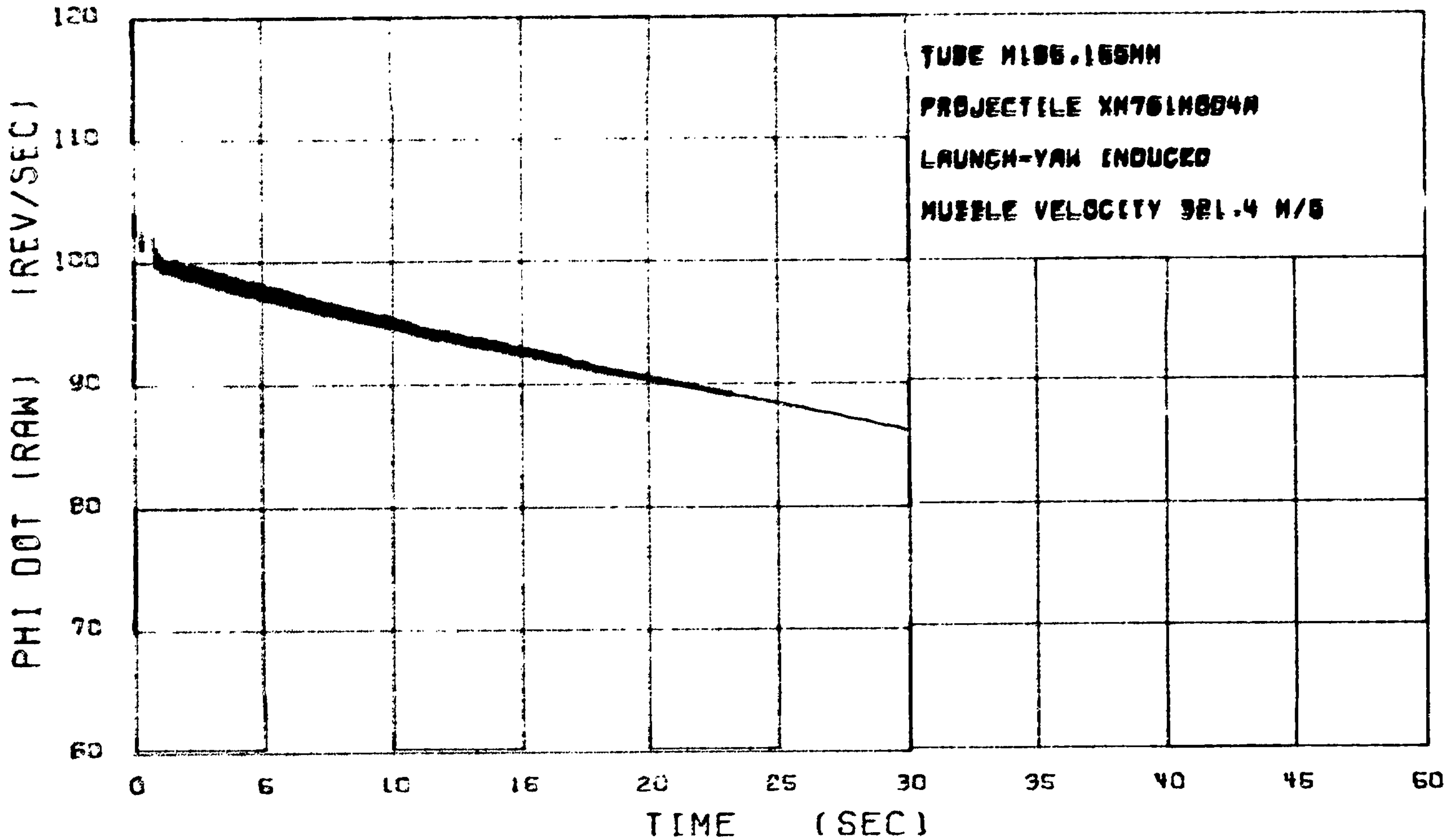

FIGURE 42. PHI DOT (RAW) VS TIME ROUND E1-9392

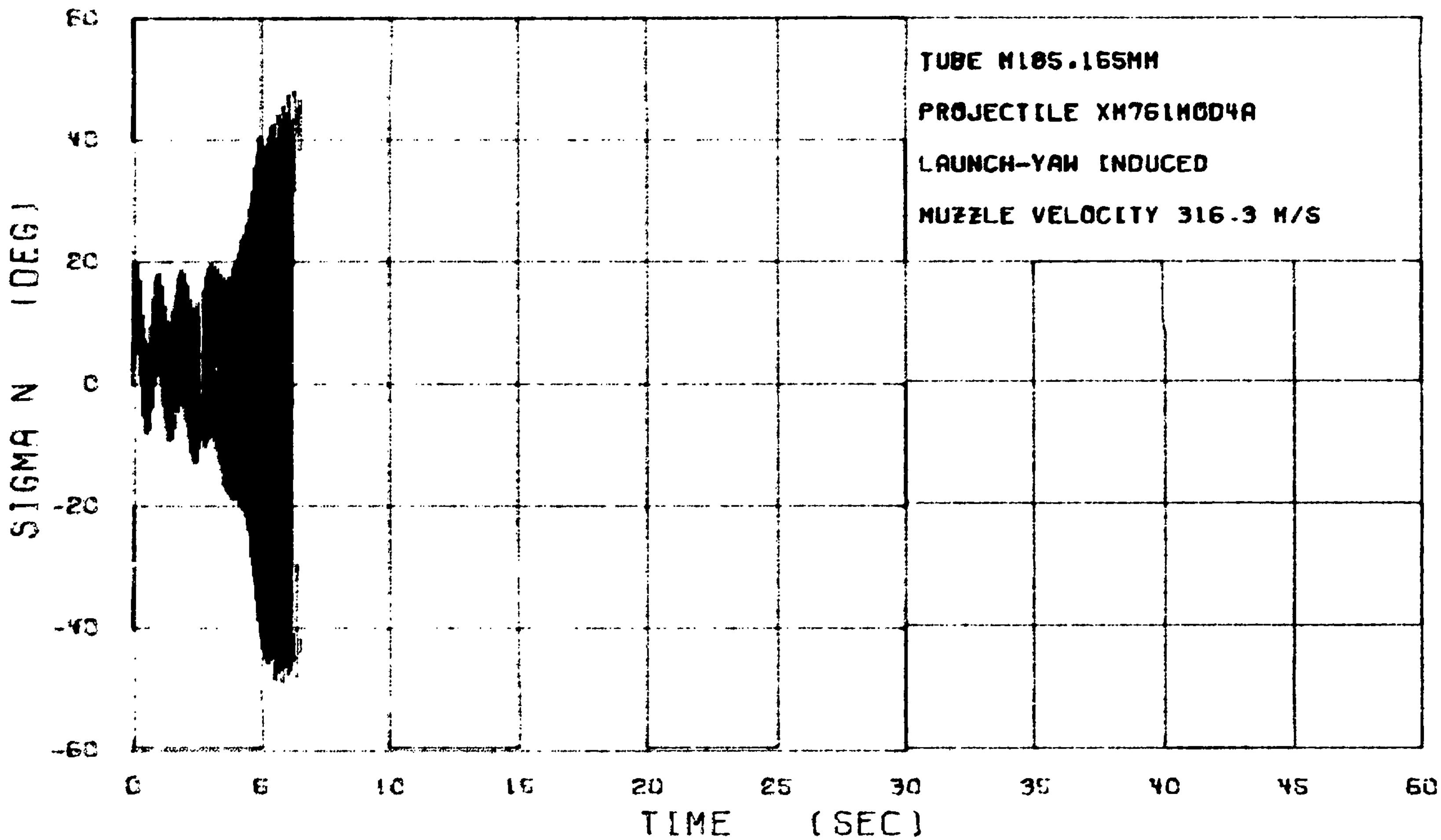

FIGURE 43. SIGMA N VS TIME ROUND E1-9394

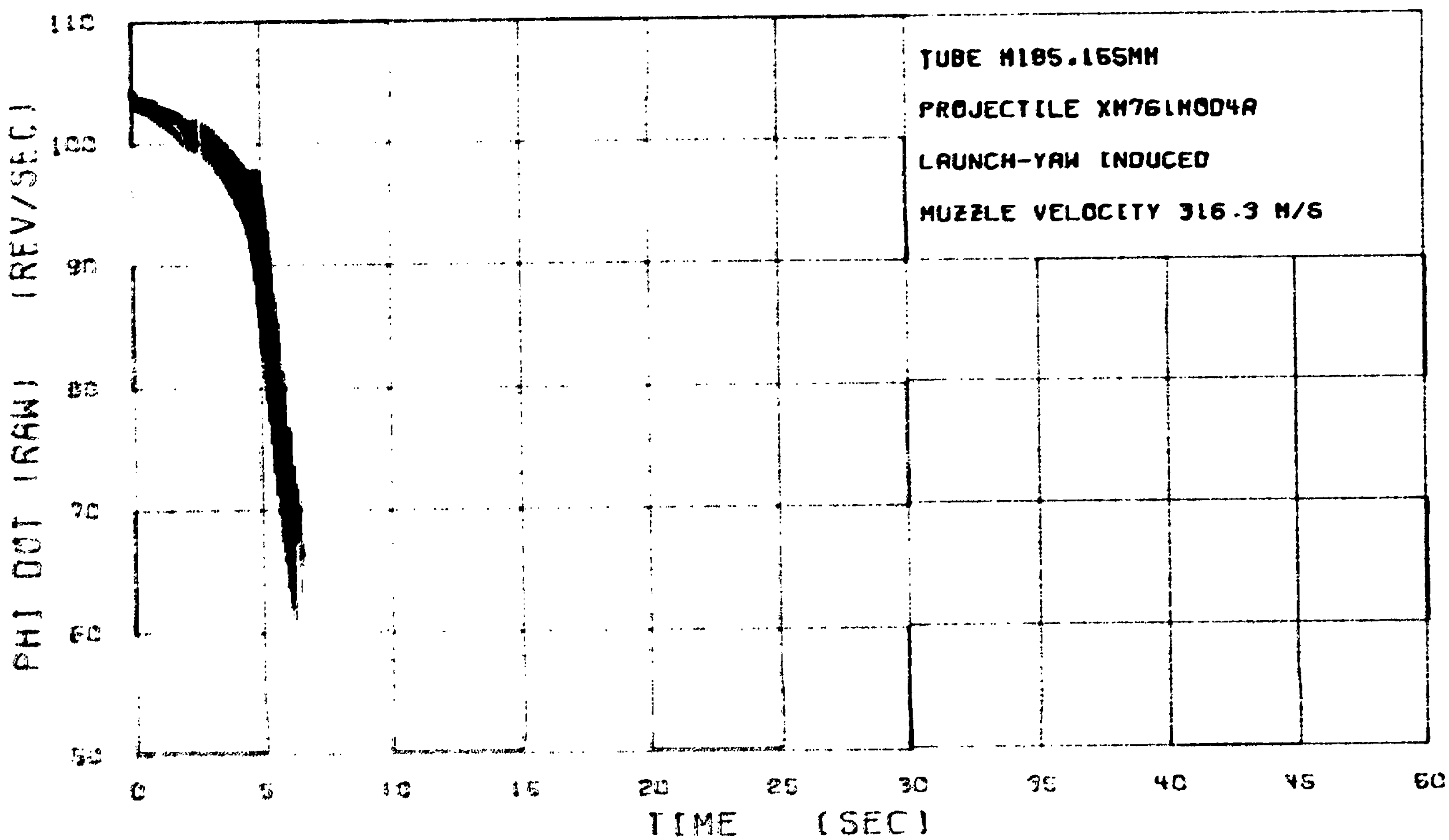

FIGURE 44. PHI DOT (RAW) VS TIME ROUND E1-9394

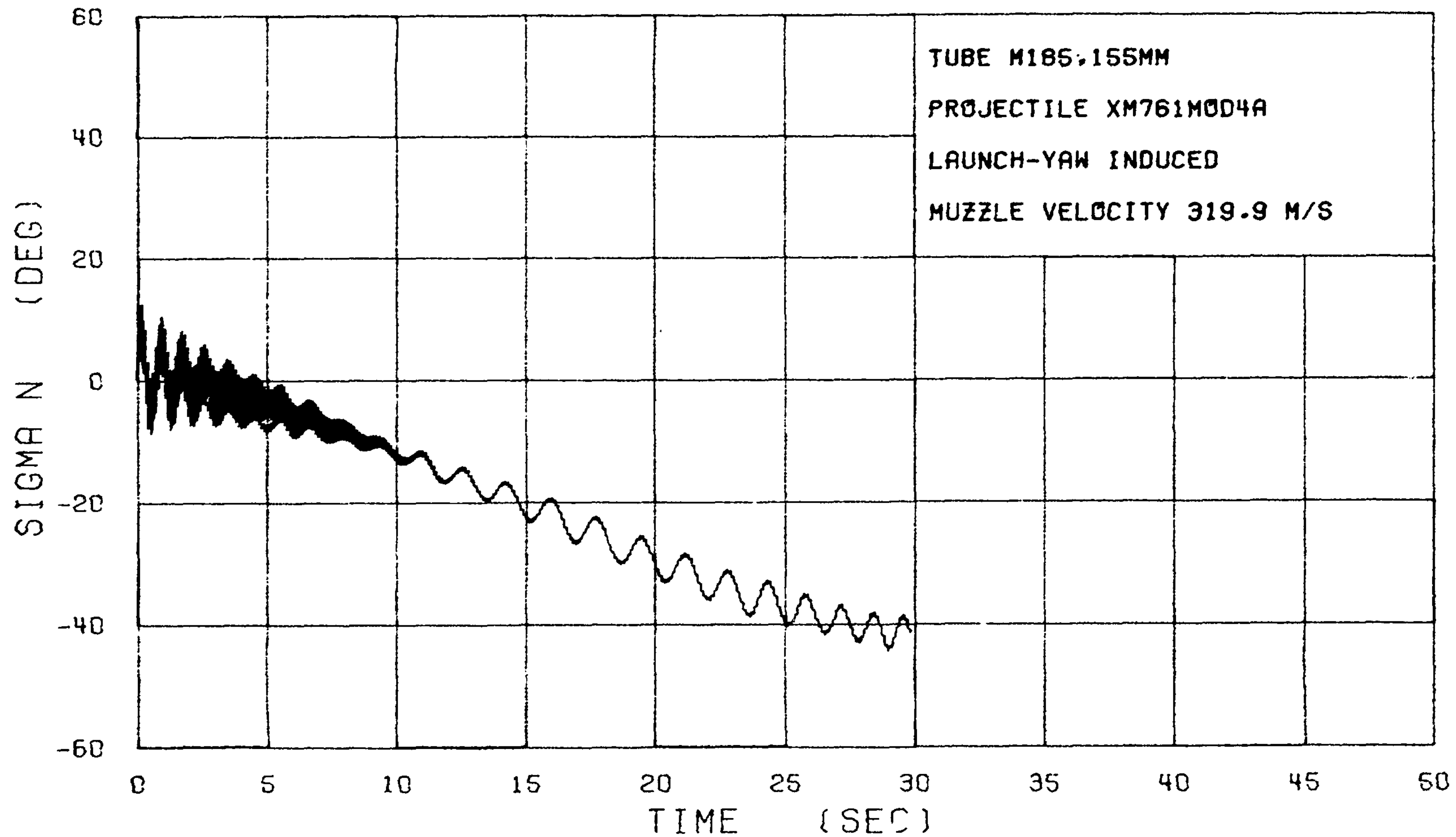

FIGURE 45. SIGMA N VS TIME ROUND E1-9395

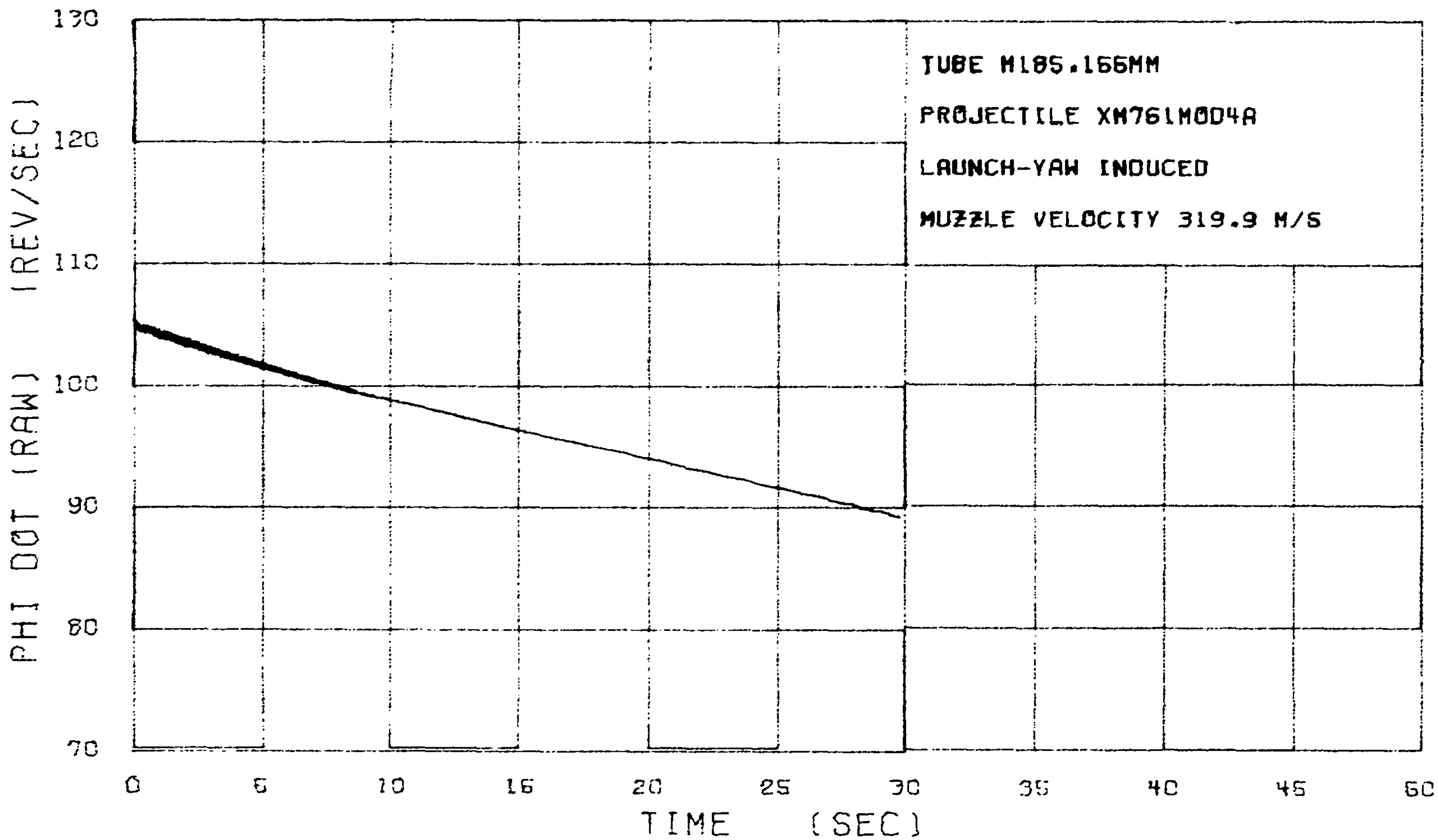

FIGURE 46. PHI DOT (RAW) VS TIME ROUND E1-9395

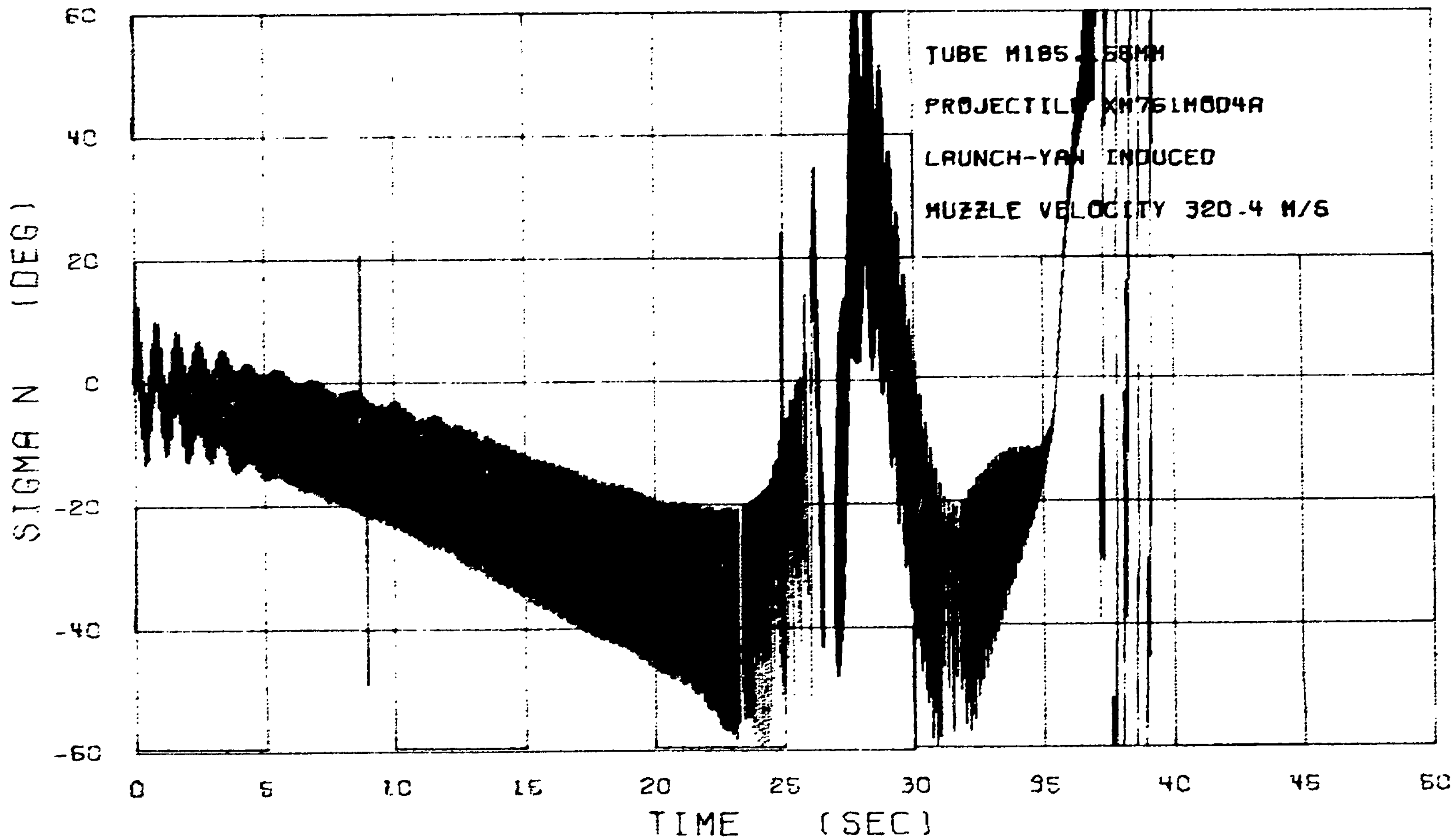

FIGURE **47.** SIGMA N VS TIME ROUND E1-9396

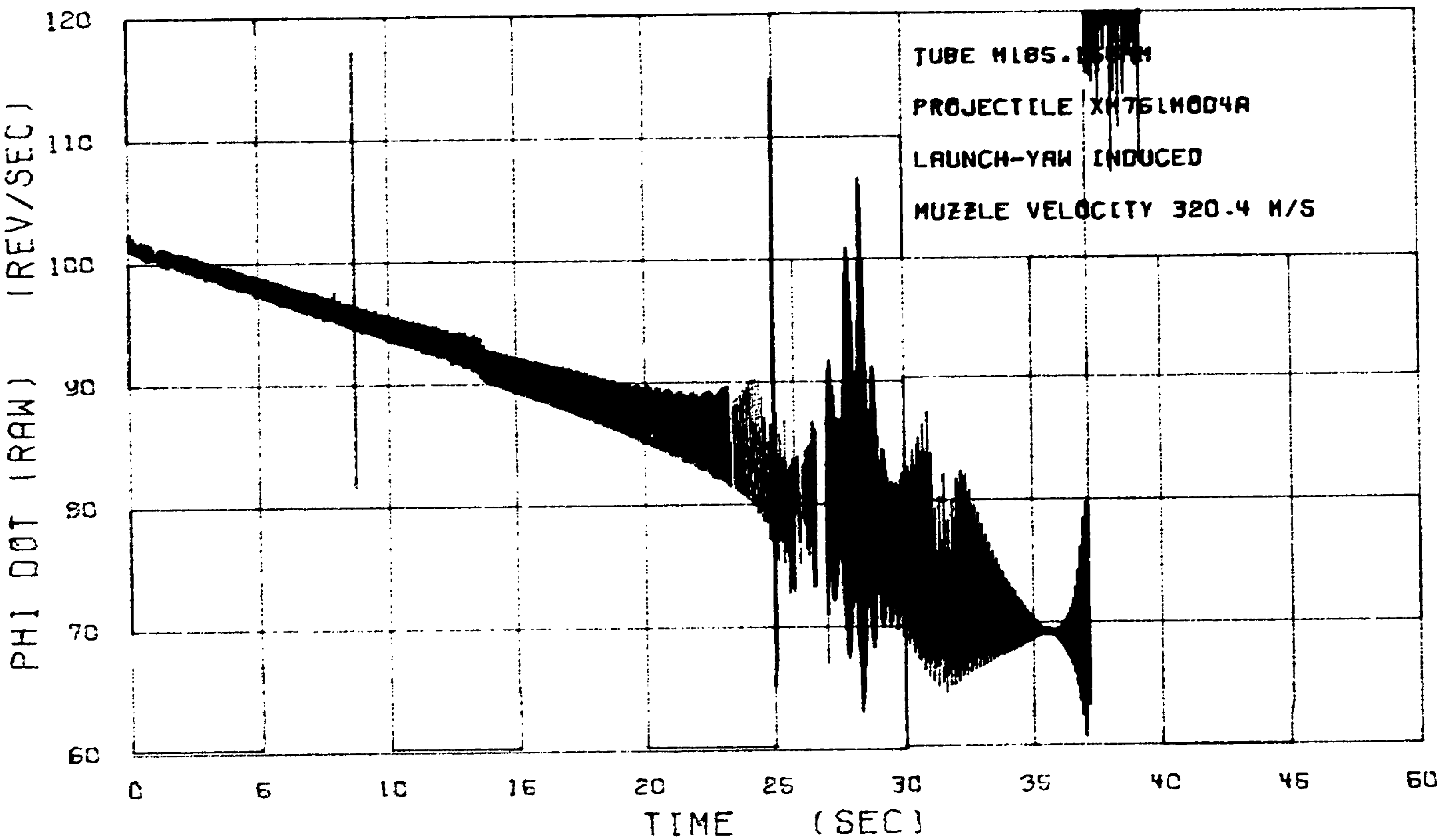

FIGURE 48. PHI DOT (RAW) VS TIME ROUND E1-9396

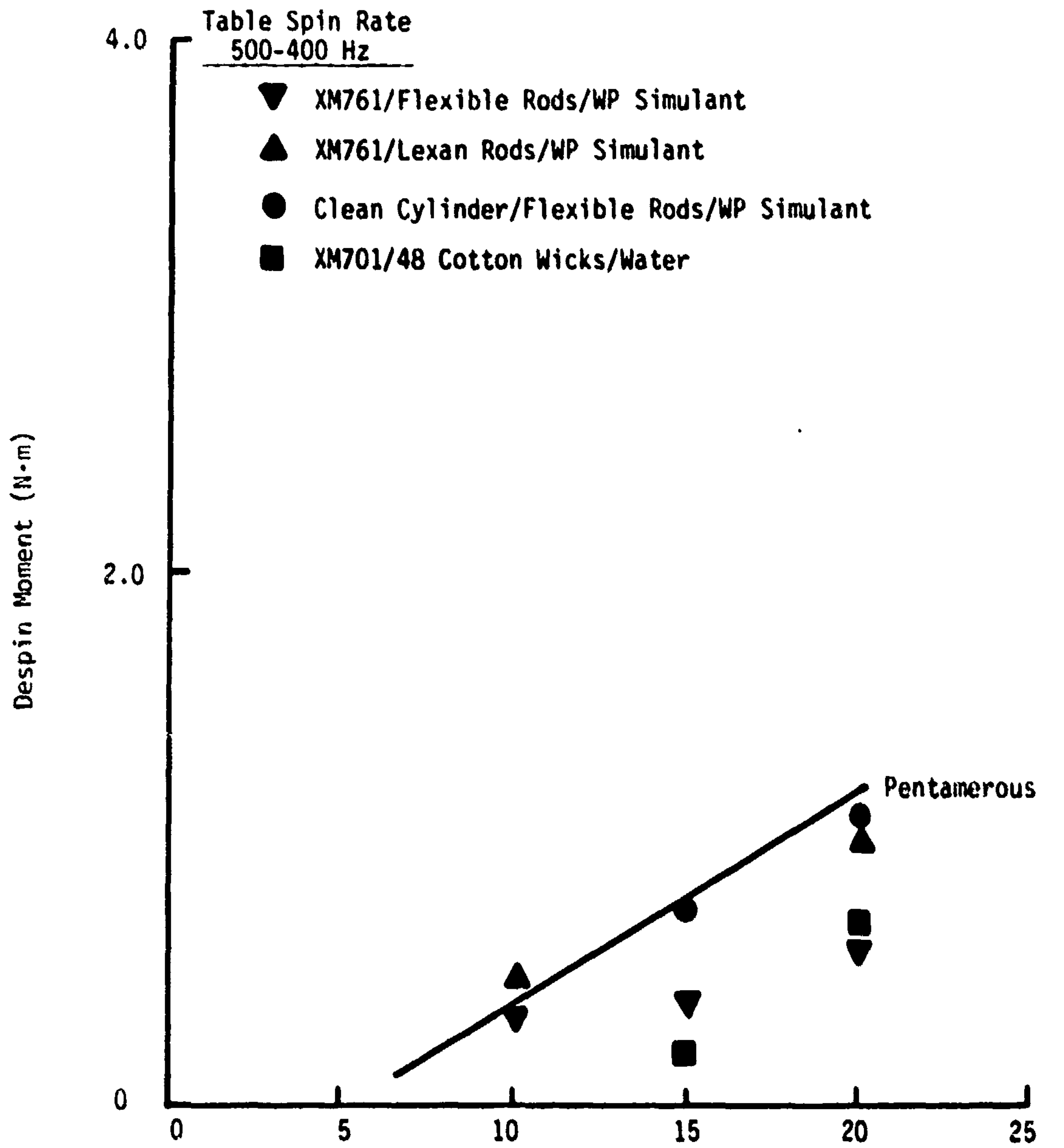

Figure 49. WSCT Spin Fixture Data Applicable to Phase II

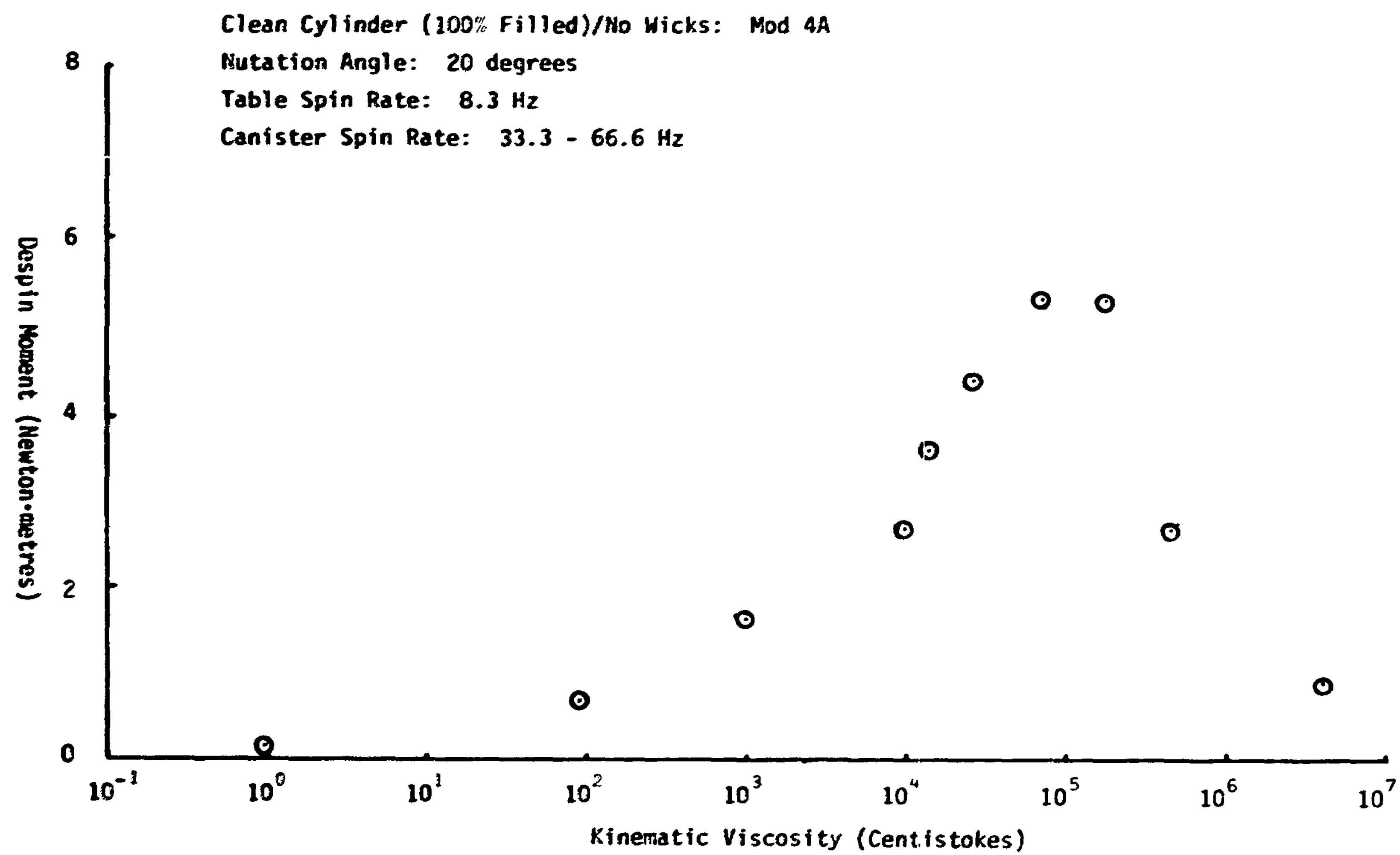

Figure 50. WSCT Spin Fixture Data Pertinent to BRL Phase III, Courtesy Mr. Miles Miller

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APPENDIX A

APPENDIX A. WEAPONS SYSTEMS CONCEPTS TEAM SPIN FIXTURE*

A laboratory test fixture has been designed, fabricated and tested which will cause a full scale canister and inclosed payload assembly from a 155mm artillery shell to undergo the basic rotational flight motions of an actual projectile. The canister will simultaneously experience the spin rate, nutation rate, and nutation yaw angle. The fixture measures the decrease in spin resulting from the motion of the non-rigid payload elements relative to the canister. The presence and magnitude of the despin moment is used to assess the flight stability of a projectile that may carry such a payload.

An initial series of tests were conducted on the fixture using an actual wick/WP (48 wicks, x-rib) canister assembly with calcium nitrate as the WP simulant. The canister was evaluated with the WP simulant in both a solid (cool) and a liquid (hot) state. No canister despin moment due to payload motion was experienced during any tests with the calcium nitrate in the solid condition. However, tests with the calcium nitrate in a liquid state produced a large despin moment. The data indicated that the despin moment experienced by this configuration was proportional to the square of table spin rate (nutation frequency) and the square of the canister angle (nutation angle). The moment was not a function of canister spin rate, provided that a sufficient canister spin rate was present (>15 rps). Since only rotational motions are modeled by the spin fixture, it was realized that large despin moments do not require set-back (longitudinal acceleration) nor yaw disturbance (yaw acceleration).

A "reusable" canister which included a removable end cap was fabricated to allow various payload configurations to be evaluated in the test fixture. Tests conducted with the reusable canister configured for the XM761 but used a blended freon simulant and produced despin moments similar to those obtained with the same canister and calcium nitrate.

A series of tests was conducted on the fixture with slight variations from the XM761 canister. In all cases, blended Freon was used as a WP simulant. Canister fill levels of 75, 85, and 100 percent were evaluated and resulted in the same despin moment characteristics. Thus, the reduction or elimination of a void should not improve projectile stability. Removal of the x-rib made the despin moment larger. Removal of the wicks from the XM761 canister greatly reduced the despin moment, but still resulted in a small, but measurable, moment at canister angles above 10 degrees. Tests with the canister devoid of liquid but with dry wicks, did not produce any despin moment.

An M687 binary canister was also tested in the spin fixture. Two actual sub-canisters were welded together to form a single structural unit with a large circular hole cut in the separating diaphram to simulate the rupturing effect which occurs at launch. These tests resulted in a small, but measurable, despin moment at canister angles greater than 10 degrees.

**This summary was extracted from material provided by Mr. Miles Miller.*

APPENDIX B

APPENDIX B. WHITE PHOSPHOROUS (WP) FLIGHT SIMULANTS*

Because of the incendiary properties of WP, an inert simulant is sometimes used. The commonly used simulant for WP is calcium nitrate which matches the density and melting temperature of WP. The overall properties for WP and calcium nitrate (both in a liquid phase T=60°C) are listed below:

Substance	Melting Temperature (°C)	Density (gm/cm^3)	Viscosity (centipoise)	Kinematic Viscosity (centistokes)	Surface Tension (dynes/cm)
WP* (P)	44.1	1.73	2.60	1.50	43.1
Calcium Nitrate (CNO_3)	42.7	1.71	.55	.32	(--)

*Saturated with water

Note that the viscosity of the calcium nitrate is almost an order of magnitude less than that of the WP. Thus, although the calcium nitrate avoids the dangerous characteristics of WP, it still must be heated to be in a liquid phase and does not match all of the physical properties of WP. Also, the surface tension of calcium nitrate is not known.

For these reasons, it is desirable that an alternate simulant for liquid WP be evolved. This simulant should have the following general characteristics:

1. Liquid at room temperature (10°C to 40°C).
2. Not dangerous to handle.
3. Closely matches the general physical properties of WP including density, viscosity, and surface tension.

Three possible choices were established.

1. Aqueous system containing silver nitrate ($AgNO_3$) to provide the required density, plus gelatin protein to thicken it to the required viscosity.
2. Carbon tetrachloride-based system using chlorinated rubber to provide the appropriate viscosity.
3. A binary system of blended E-series Freons from the E.I. Du Pont de Nemours Co.

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*This work was accomplished by the CSL Chemistry Branch.

The aqueous system has an excellent property match, is composed of readily available materials and is easily prepared. It is light-sensitive, and while stable in glass in subdued light for in excess of 72 hours, light and heat will contribute to the aging of the system and an increase in its viscosity. It is moderately expensive, and probably subject to nonlinear flow properties under stress.

The CCl_4 system offers a good property match. It is inexpensive and easy to prepare. It should be stable for long periods of time, if not indefinitely. CCl_4 will swell and attack many gaskets or fittings. CCl_4 can also cause liver damage. Most metals are unattacked by CCl_4, except for mild steel and 18-8-type stainless steels which are attacked if the CCl_4 contains moisture. This system may also be subject to nonlinear flow properties.

The E-series Freons should give an excellent property match. They are non-toxic, non-flammable, and totally inert. They are expensive, but the system would be stable indefinitely. Two of these Freons would have to be obtained and the appropriate mixture confirmed by in-house laboratory experiments. This system should not experience nonlinear flow properties.

Properties of Liquid WP and Candidate Simulant Systems

System	Density (g/ml)	Viscosity (cs)	Material Cost Per Litre
Molten WP	1.73	1.5 (62.2°C)	-
Water (1 litre) $AgNO_3$ (1.195 kg) Gelatin (16.22 g)	1.71	1.48 (21°C)	$60
CCl_4 (1 litre) Parlon S-300 (21g)	1.6	1.5 (21°C)	$2 to 3
Freon E-3 (1 part) Freon E-4 (0.21 part)	1.73	1.5 (21°C)	$76
Molten $Ca(NO_3)_2$	1.71	0.32 (62.2°C)	-

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