MCDONNELL DOUGLAS TECHNICAL SERVICES CO.
HOUSTON ASTRONAUTICS DIVISION

SPACE SHUTTLE ENGINEERING AND OPEPATIONS SUPPORT

DESIGN NOTE NO. 1.4-4-9

RTLS ENTRY LOAD RELIEF PARAMETER OPTIMIZATION

MISSION PLANNING, MISSION ANALYSIS AND SOFTWARE FORMULATION

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1.0 SUMMARY

This note presents the results of a study of a candidate load relief control law for use during the pullup phase of Return-to-Launch-Site (RTLS) abort entries. The study investigated the control law parameters and cycle time which optimized performance of the normal load factor limiting phase (load relief phase) of an RTLS entry. The study established a set of control law gains, a smoothing parameter, and a normal force coefficient curve fit which resulted in good load relief performance considering the possible aerodynamic coefficient uncertainties defined in Reference 1. Also, the examination of various guidance cycle times revealed improved load relief performance with decreasing cycle time. A .5 second cycle provided smooth and adequate load relief in the presence of all the aerodynamic uncertainties examined.

Appendix A presents a derivation of the control law.

2.0 INTRODUCTION

The entry phase of an RTLS abort begins following separation of the Orbiter from the external tank (ET). Following the low angle of attack separation, the angle of attack is recovered to a higher value to provide high lift for the subsequent pullup. This angle of attack is maintained until the normal force on the vehicle reaches a specified limit. At this point, angle of attack is decreased to maintain the normal load at the limit through pullup.

A control law was formulated by the Flight Performance Branch (FPB) of NASA at the Johnson Space Center (JSC) to vary angle of attack to maintain normal load at the desired value during pullup (see Appendix A). The control law was examined to determine the gains and cycle time which optimized the load relief phase performance.

3.0 DISCUSSION

The load relief logic is based on the following equation:

$$(1)\quad \alpha_c = \alpha_{PRESENT} + \left[K_1 \left(\frac{n_{REF} - n}{n}\right) + K_2\left(\frac{\dot{h}}{h_s} + \frac{2\mathcal{D}}{V}\right)\Delta t\right]\left[\frac{C_{N_0} + C_{N_1}\alpha + C_{N_2}\alpha^2}{C_{N_1} + 2C_{N_2}\alpha}\right]$$

where:	α_c	commanded angle of attack (deg)
	$\alpha_{PRESENT}$	present angle of attack (deg)
	K_1, K_2	control law gains
	n_{REF}	normal load factor limit (g's)
	n	current load factor (g's)
	$\dot{h}$	altitude rate (FPS)
	h_s	density scale height (ft)
	$\mathcal{D}$	drag acceleration (FPS^2)
	V	relative velocity (FPS)
	Δt	guidance cycle time (sec)
	$C_{N_0}, C_{N_1}, C_{N_2}$	coefficients for a curve fit of normal force coefficient (C_N) $v.$ α
	α	average angle of attack over projected cycle (deg)

The derivation of this equation is presented in Appendix A and a flowchart of the load relief logic as incorporated into the Analytic Drag Control (ADC) subroutine (Subroutine CONGID) of the Space Vehicle Dynamic Simulation (SVDS) program is presented in Appendix B. The parameters examined in this study include the control law gains (K_1 and K_2), the guidance cycle time (Δt), and the coefficients for the C_N versus angle of attack curve fit ($C_{N_0}, C_{N_1}, C_{N_2}$). These parameters were optimized to provide a normal load factor profile which achieved and maintained the normal load limit without overshoot. The study utilizes a mission 3A RTLS abort which has a 2.2g normal load factor limit. Dispersed aerodynamic models were used in the optimization process to provide a load relief scheme as insensitive to aerodynamic uncertainties as possible.

3.1 Control Law Gain Selection

The control gains K_1 and K_2 were first examined using a linear curve fit for C_N versus angle of attack (C_{N_2} = 0; see Figure 3.1-1) and a guidance cycle time of 2. seconds. Initially K_1 was set to 1.0 and K_2 varied (see Figure 3.1-2 to Figure 3.1-5). A value for K_2 of 1.1 yielded the best shaped profile. K_2 was then held constant at 1.1 and K_1 varied (see Figure 3.1-6 to Figure 3.1-9). A value for K_1 of 1.3 yielded the best shaped profile, however the load relief response was not as flat as desired. To try to obtain flatter load relief response, a quadratic curve fit for C_N versus angle of attack was incorporated, resulting in the profile presented in Figure 3.1-10. This yielded the desired flat response.

To evaluate the performance for aerodynamic coefficient uncertainties, several sets of dispersed coefficients were tested. These dispersions

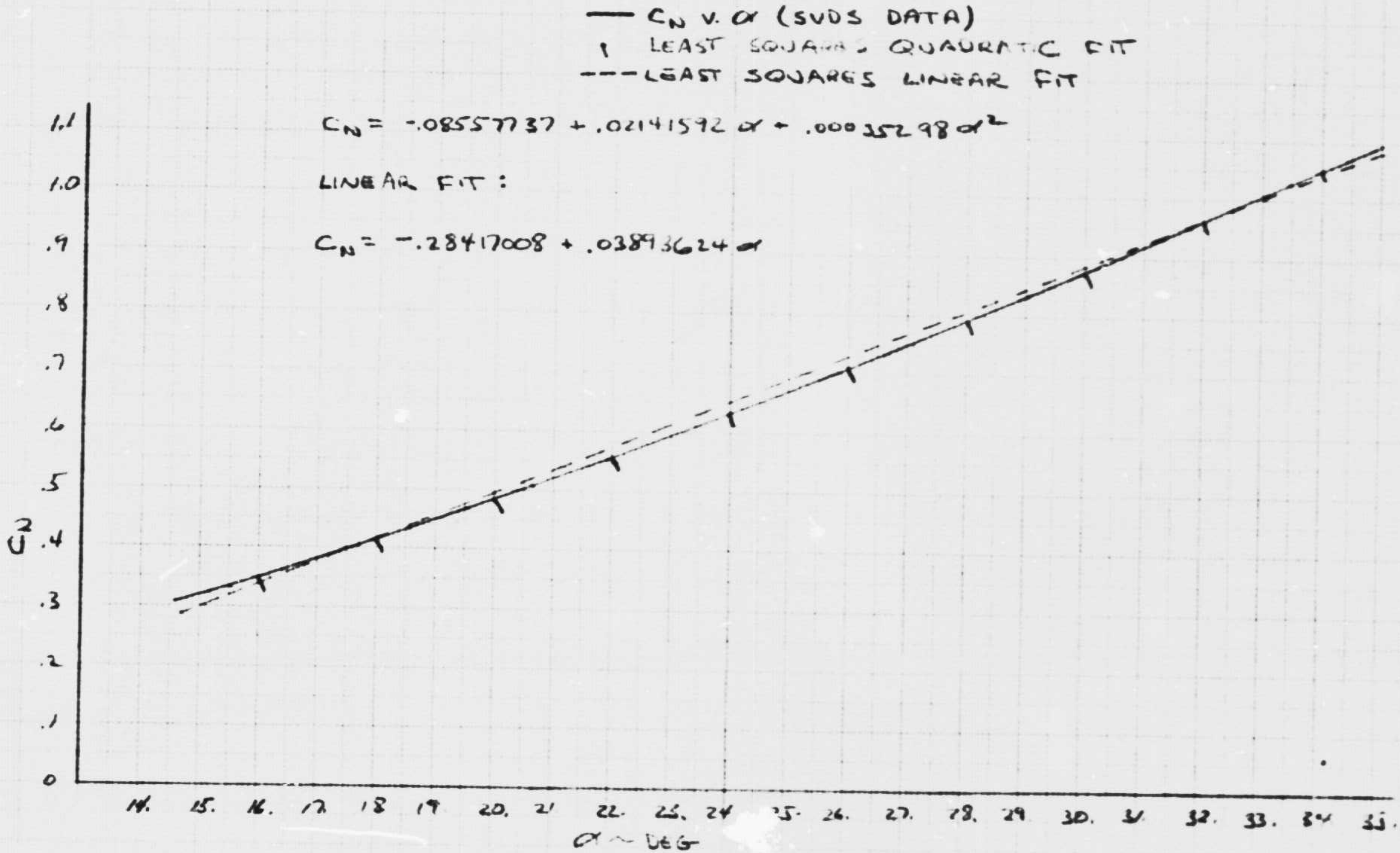


Figure 3.1-1

C_N VERSUS ANGLE OF ATTACK

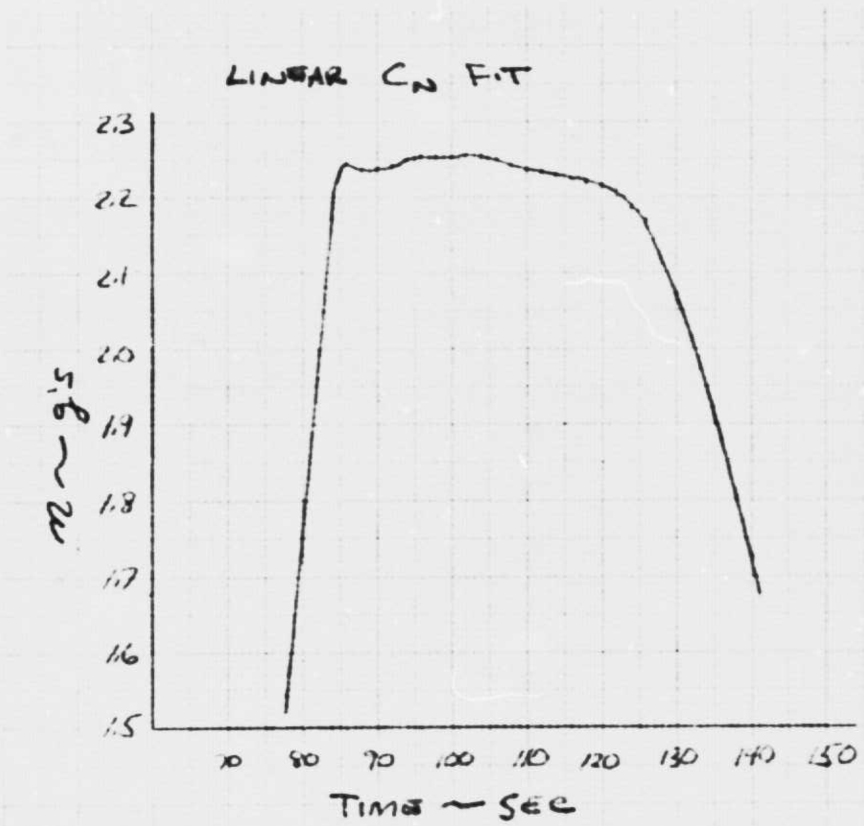


Figure 3.1-2

NORMAL LOAD FACTOR υ. TIME

K_1 = 1. K_2 = .9

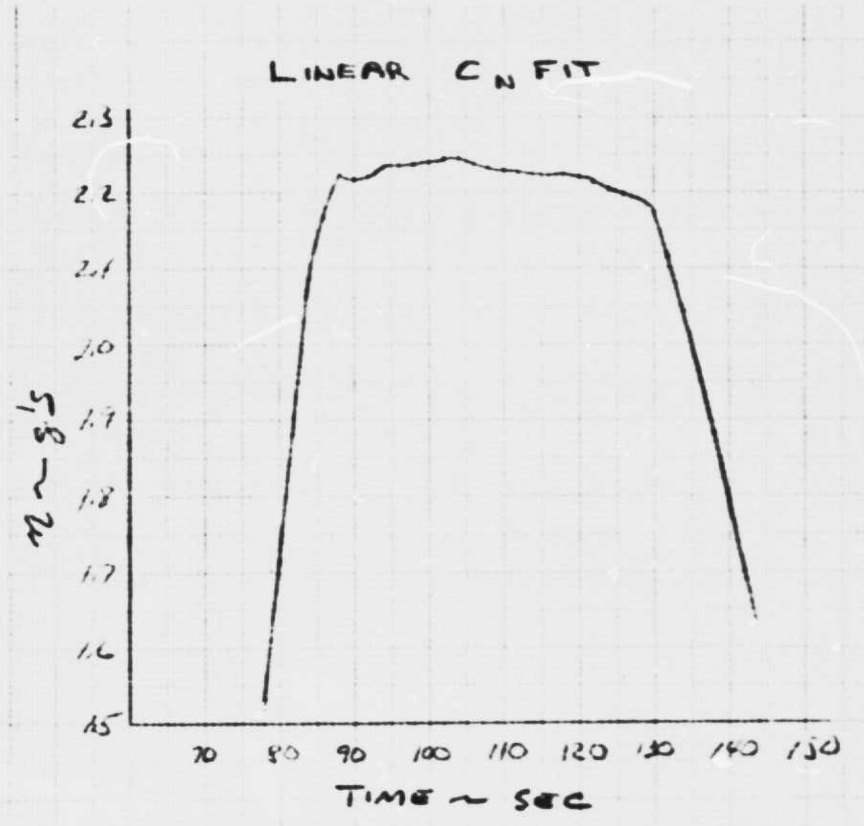


Figure 3.1-3

NORMAL LOAD FACTOR υ. TIME

K_1 = 1. K_2 = 1.

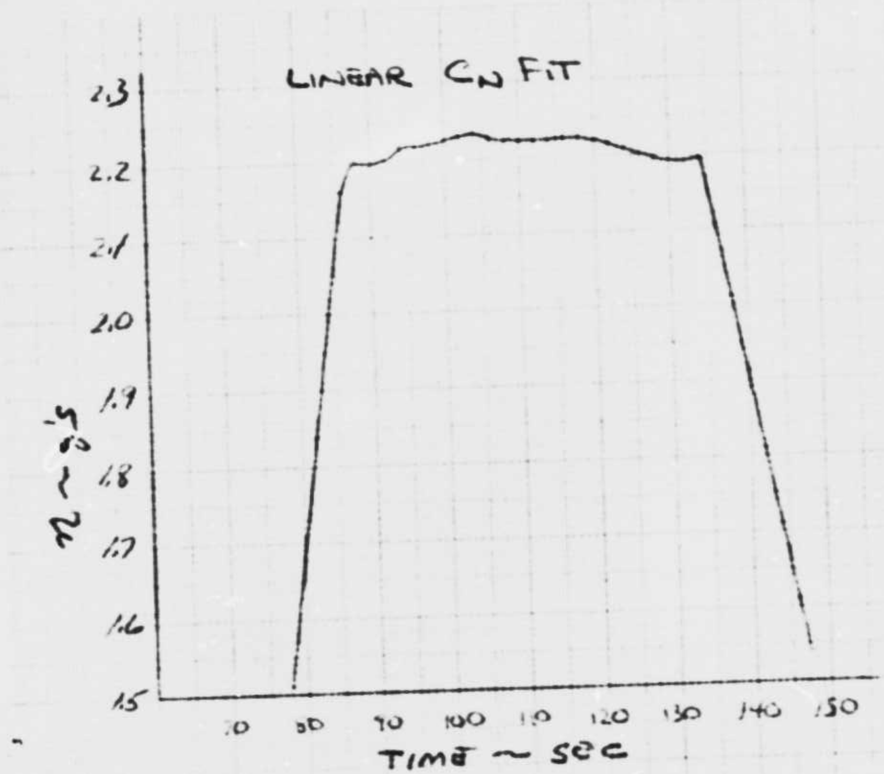


Figure 3.1-4

<u>NORMAL LOAD FACTOR υ. TIME</u>

$K_1 = 1. \quad K_2 = 1.1$

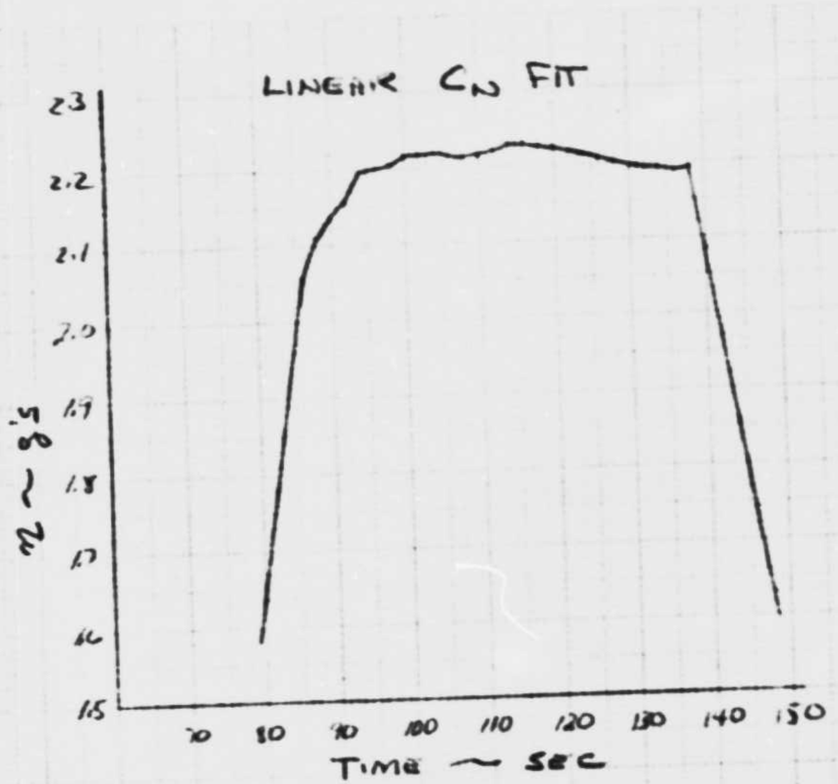


Figure 3.1-5

<u>NORMAL LOAD FACTOR υ. TIME</u>

$K_1 = 1. \quad K_2 = 1.2$

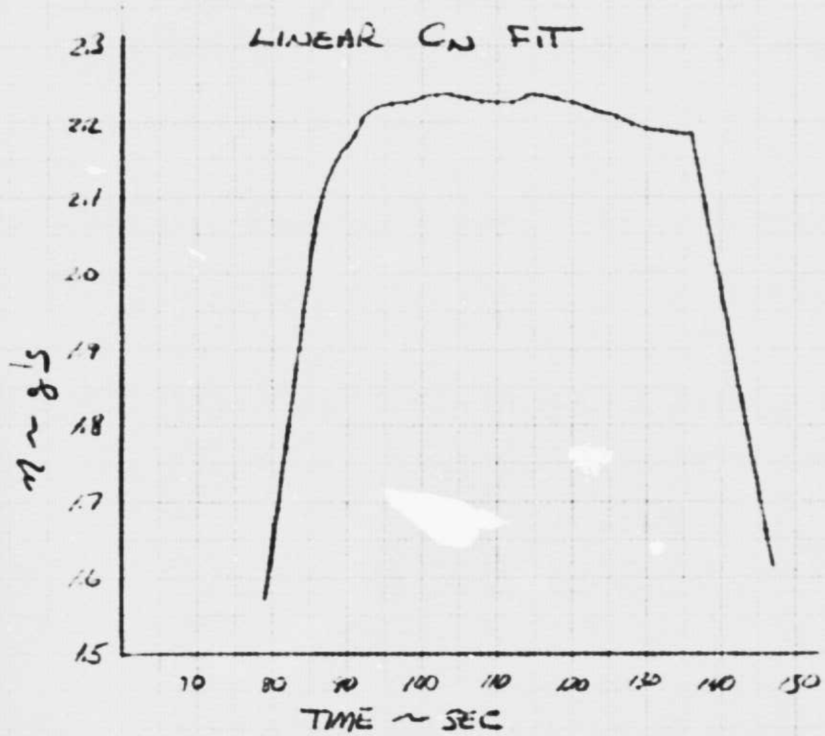


Figure 3.1-6

NORMAL LOAD FACTOR v. TIME

K_1 = .9 K_2 = 1.1

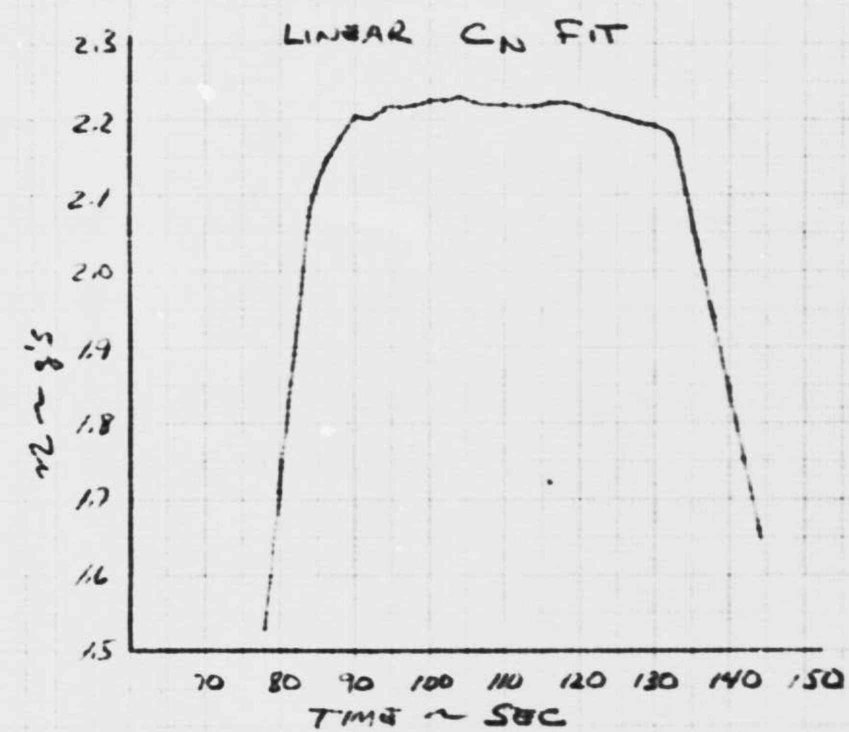


Figure 3.1-7

NORMAL LOAD FACTOR v. TIME

K_1 = 1.1 K_2 = 1.1

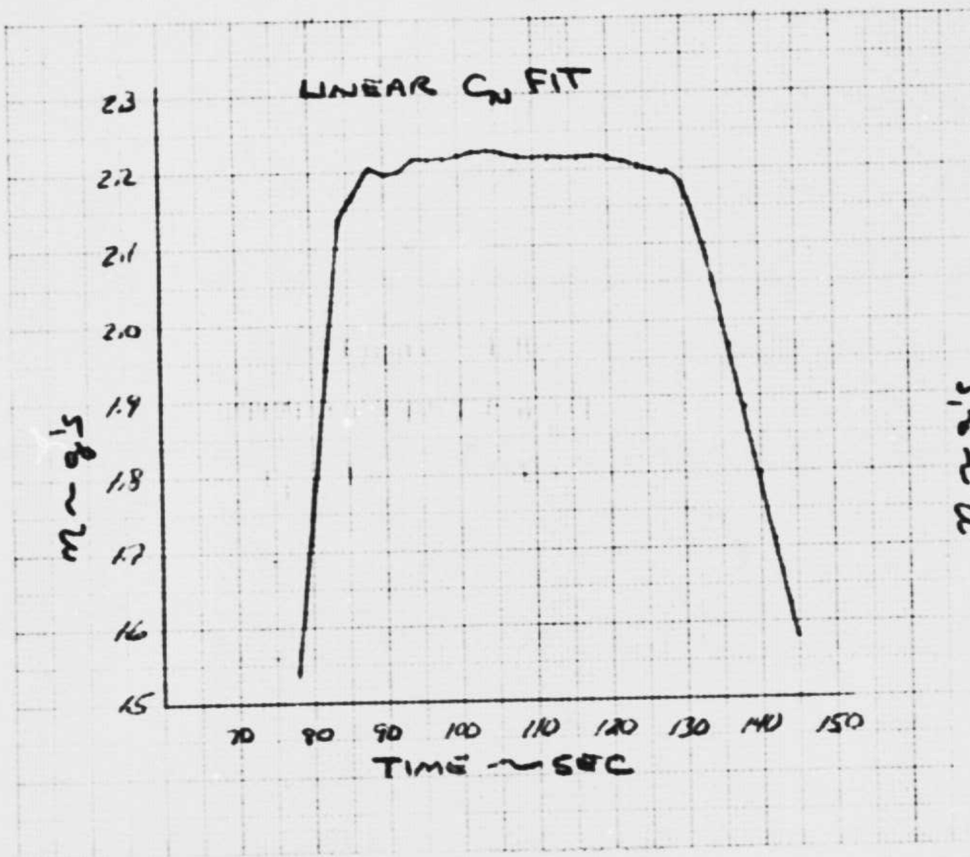


Figure 3.1-8

<u>NORMAL LOAD FACTOR υ. TIME</u>

$K_1 = 1.2 \quad K_2 = 1.1$

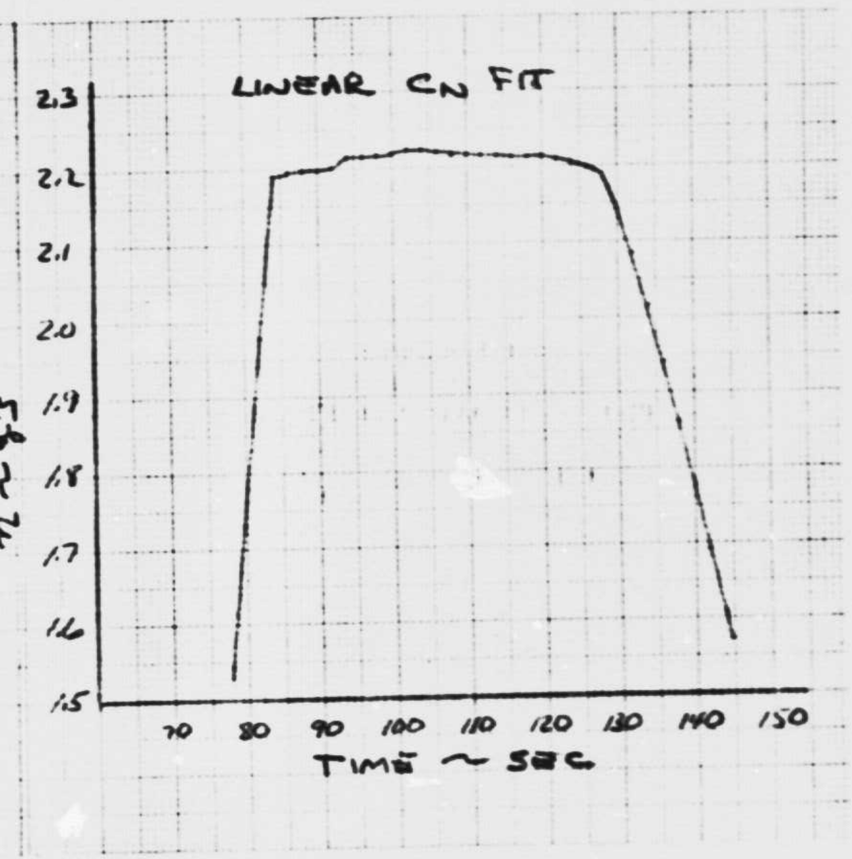


Figure 3.1-9

<u>NORMAL LOAD FACTOR υ. TIME</u>

$K_1 = 1.3 \quad K_2 = 1.1$

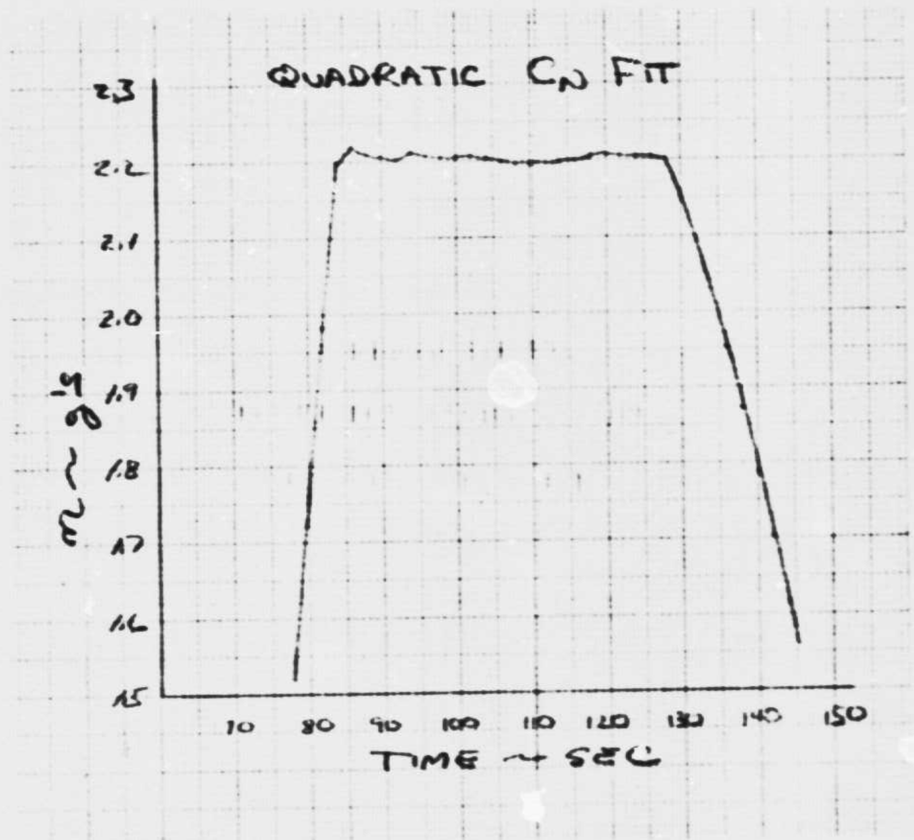


Figure 3.1-10

NORMAL LOAD FACTOR υ. TIME

K_1 = 1.3 K_2 = 1.1

were obtained from Reference 1 and are presented in Figure 3.1-11. Six test points were selected around the border of the uncertainty envelope to represent possible aerodynamic dispersions. Figures 3.1-12 to 3.1-17 present the profiles for these dispersed cases. For all cases, undesirable initial overshoots were obtained. To compensate for these initial overshoots, two areas were investigated: adjusting a constant to modify the smoothing logic as the load factor approaches the load limit and a larger K_2 gain. The smoothing logic was modified by lowering the point at which transition from the load buildup phase to the constant load factor phase is initiated (see Appendix B, page 1, smoothing constant SC). Figure 3.1-18 presents the improved profile for one dispersion point. Improvement in initial overshoot was also obtained by increasing the K_2 gain. Figures 3.1-19 to Figure 3.1-21 presents profiles for a K_2 gain of 1.2 and various K_1 gains. These profiles showed improved initial response, but a slight degradation later along the profile. Based on this, a K_2 gain schedule was established (see Figure 3.1-22). Using the K_2 gain schedule, a K_1 gain of 1.2, and the improved smoothing constant, the nominal and dispersed aerodynamic cases were investigated (see Figure 3.1-23 to Figure 3.1-29). Good performance was obtained for all cases, establishing this combination of gains, a quadratic C_N versus angle of attack curve fit, and the modified smoothing constant as the baseline for the control law.

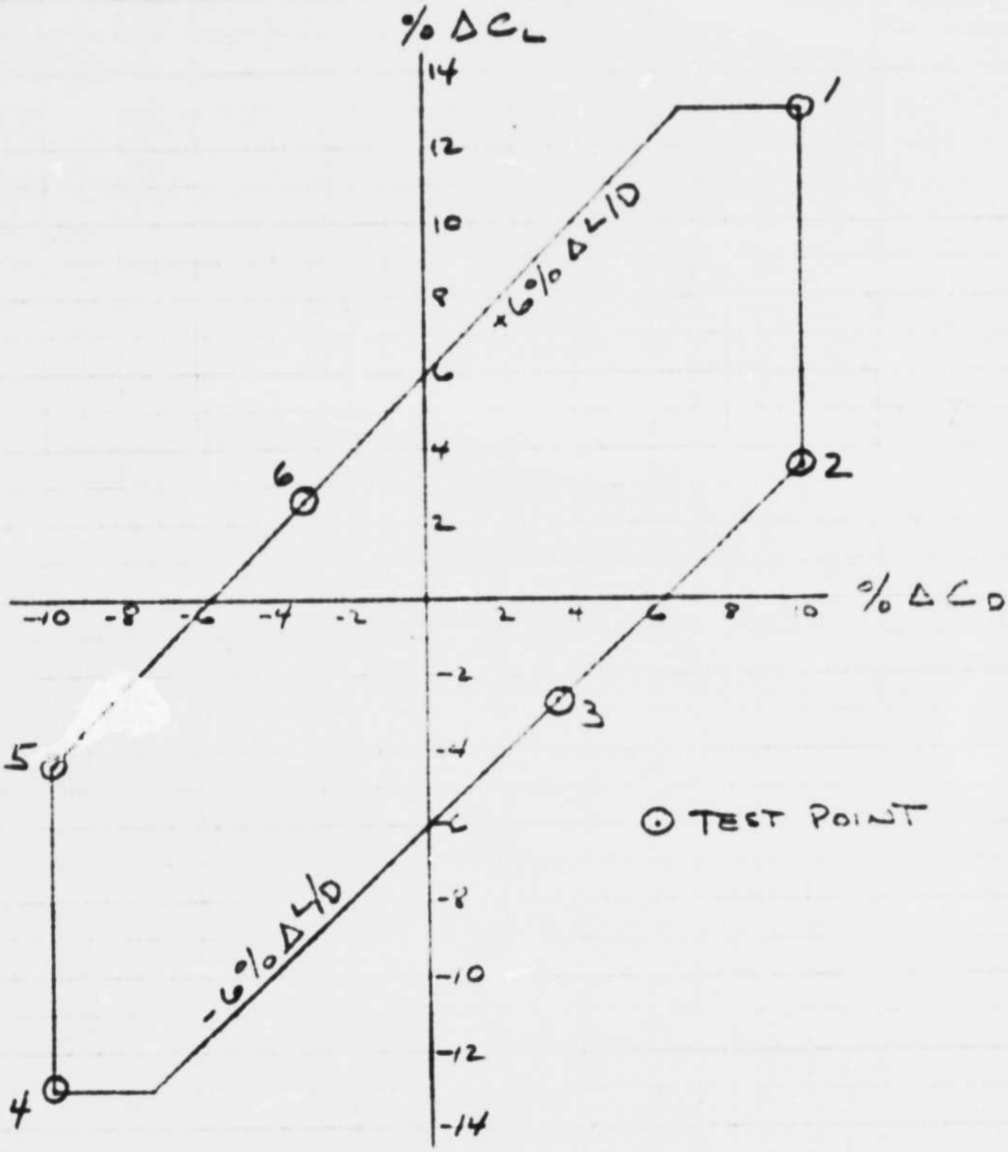


Figure 3.1-11

POSSIBLE C_L AND C_D UNCERTAINTY ENVELOPE

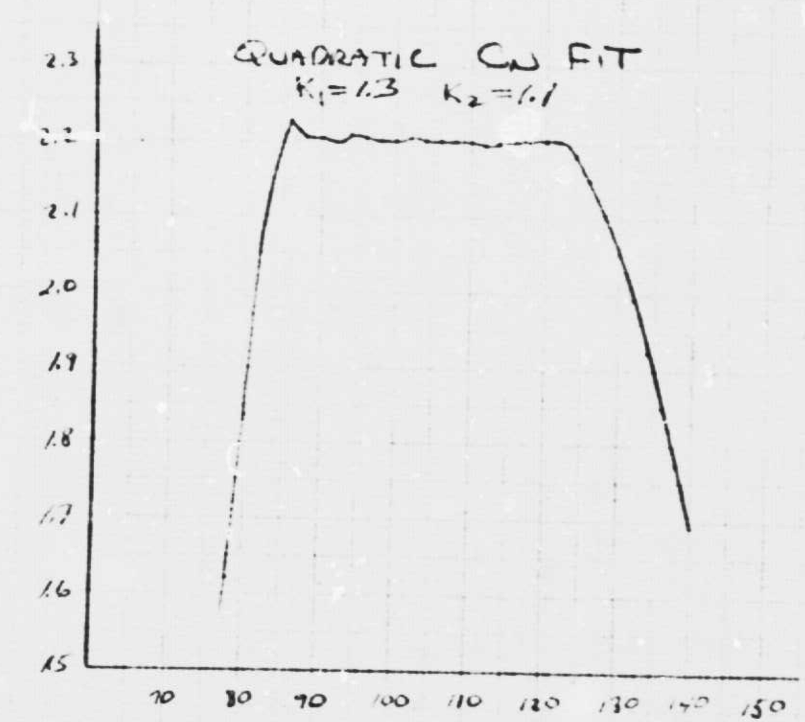


Figure 3.1-12
NORMAL LOAD FACTOR v. TIME
DISPERSION POINT 1

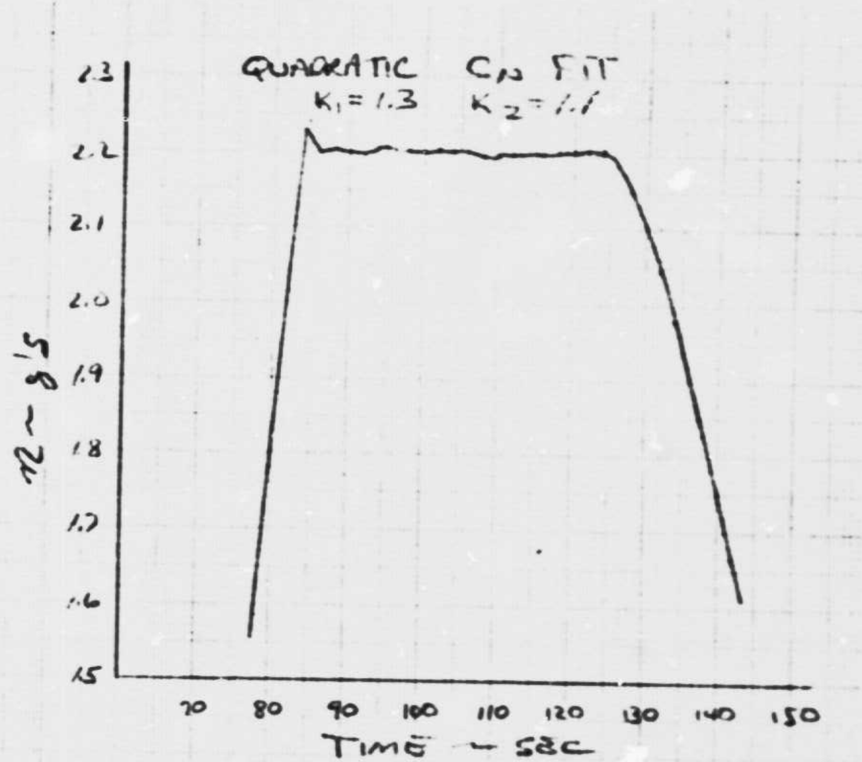


Figure 3.1-13
NORMAL LOAD FACTOR v. TIME
DISPERSION POINT 2

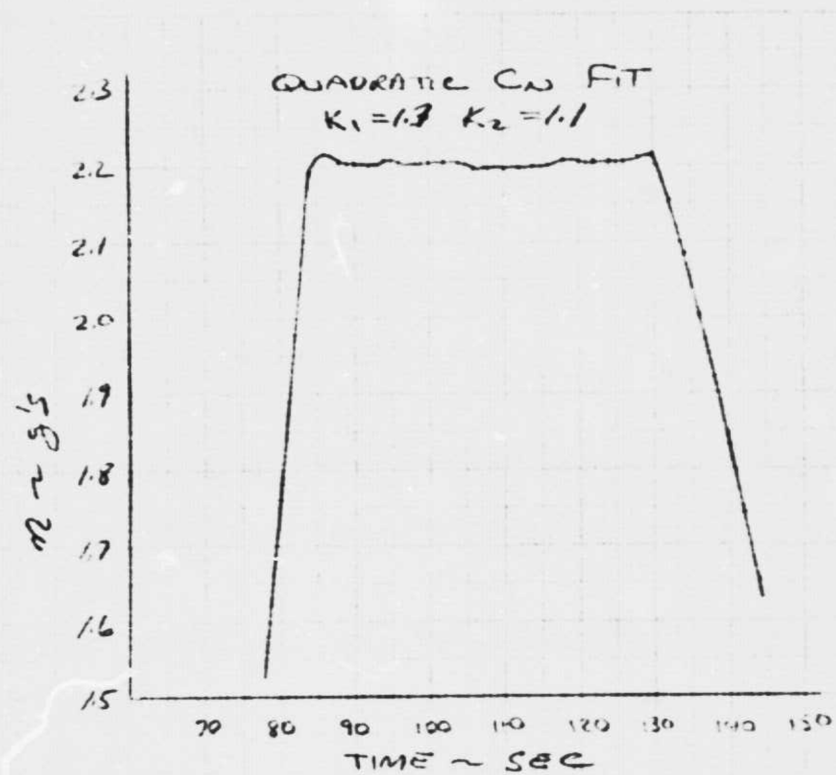


Figure 3.1-14

NORMAL LOAD FACTOR υ. TIME

DISPERSION POINT 3

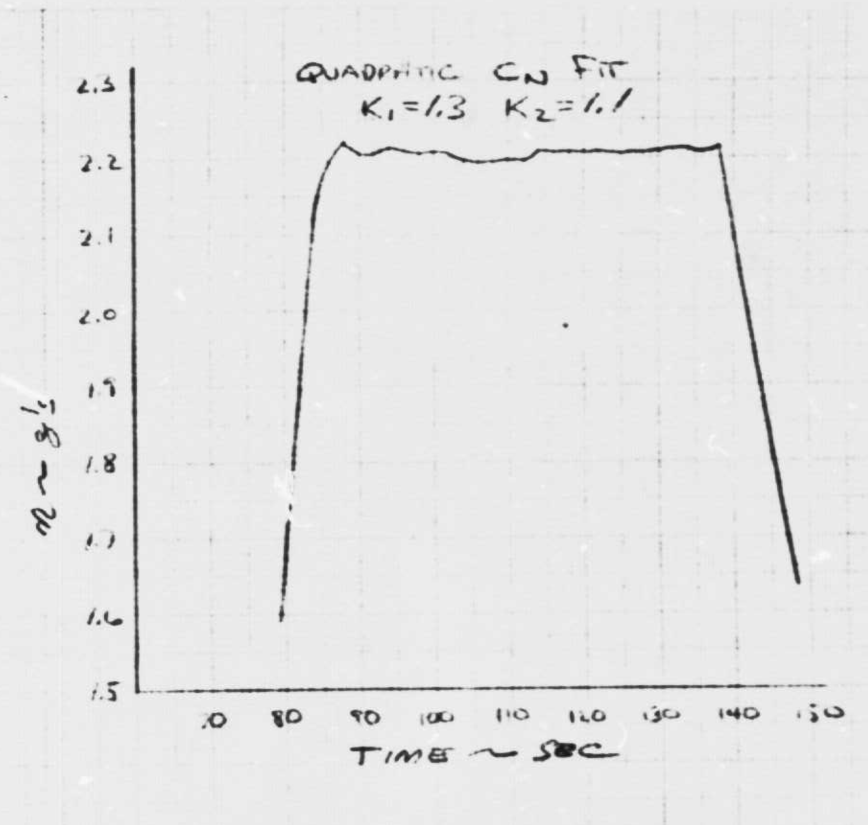


Figure 3.1-15

NORMAL LOAD FACTOR υ. TIME

DISPERSION POINT 4

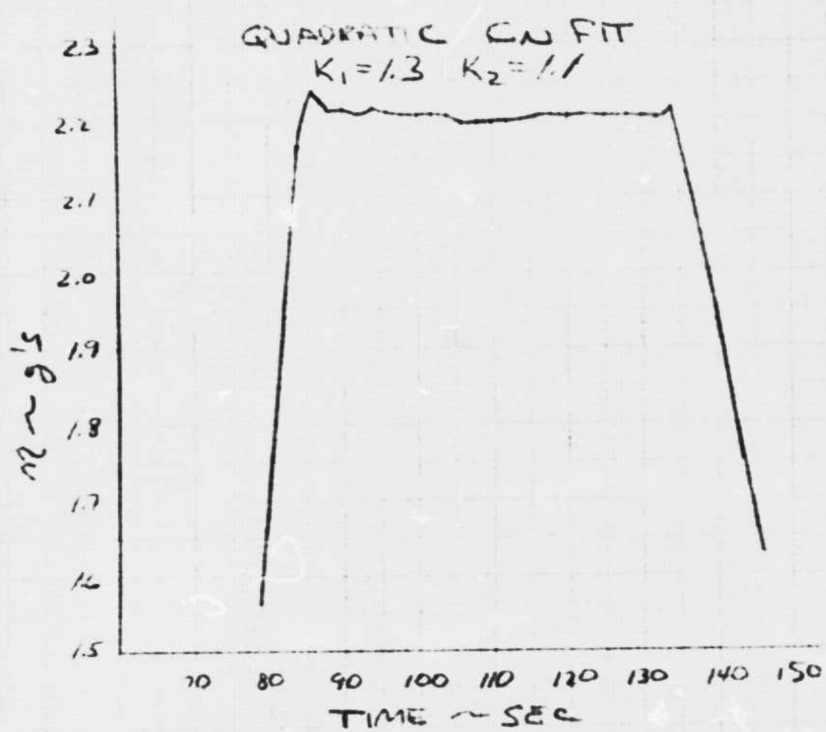


Figure 3.1-16

NORMAL LOAD FACTOR v. TIME

DISPERSION POINT 5

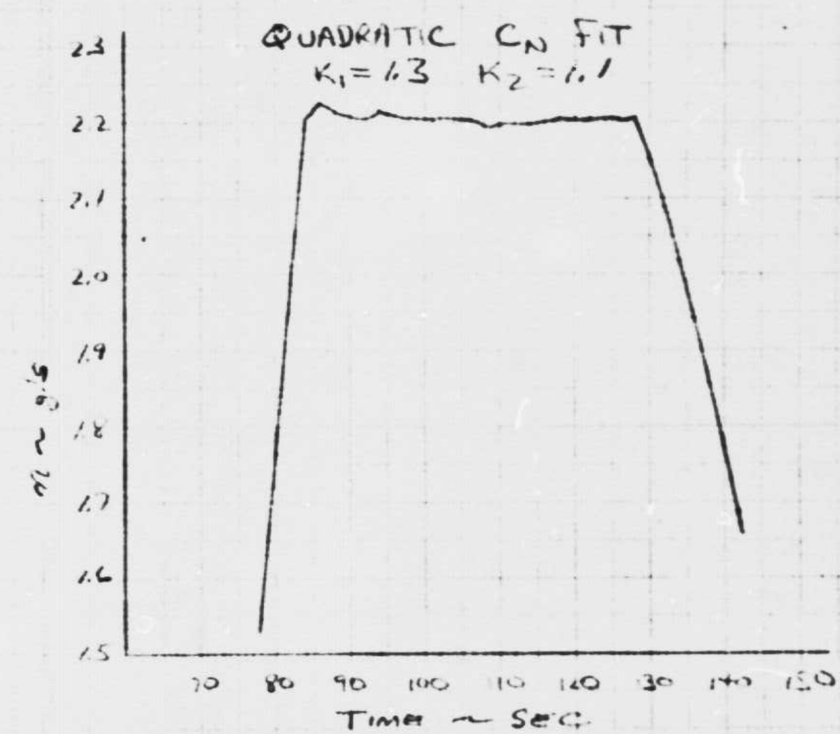


Figure 3.1-17

NORMAL LOAD FACTOR v. TIME

DISPERSION POINT 6

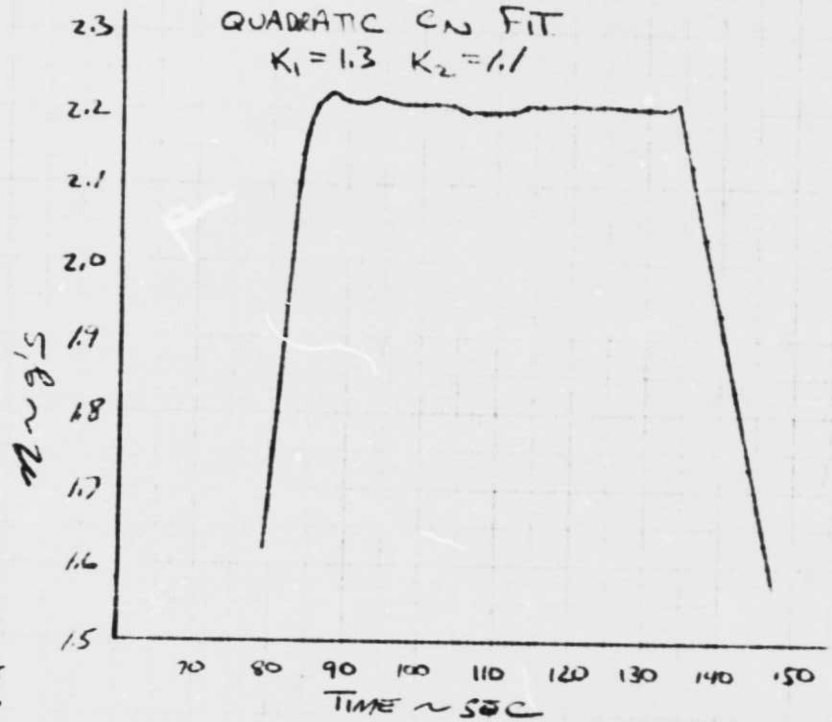


Figure 3.1-18

NORMAL LOAD FACTOR υ. TIME

IMPROVED SMOOTHING CONSTANT

DISPERSION POINT 5

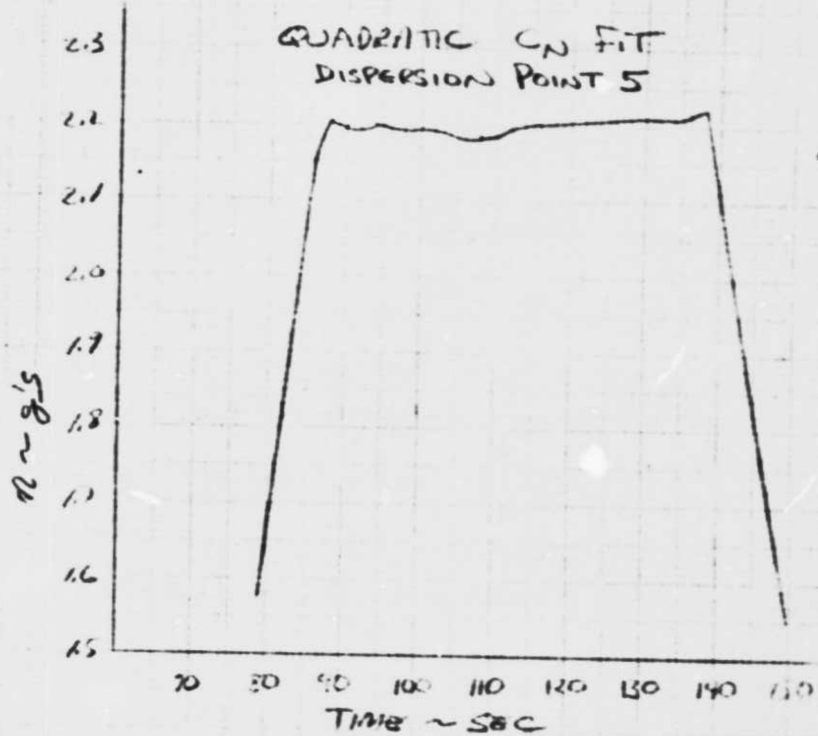


Figure 3.1-19

NORMAL LOAD FACTOR υ. TIME

K_1 = 1.1 K_2 = 1.2

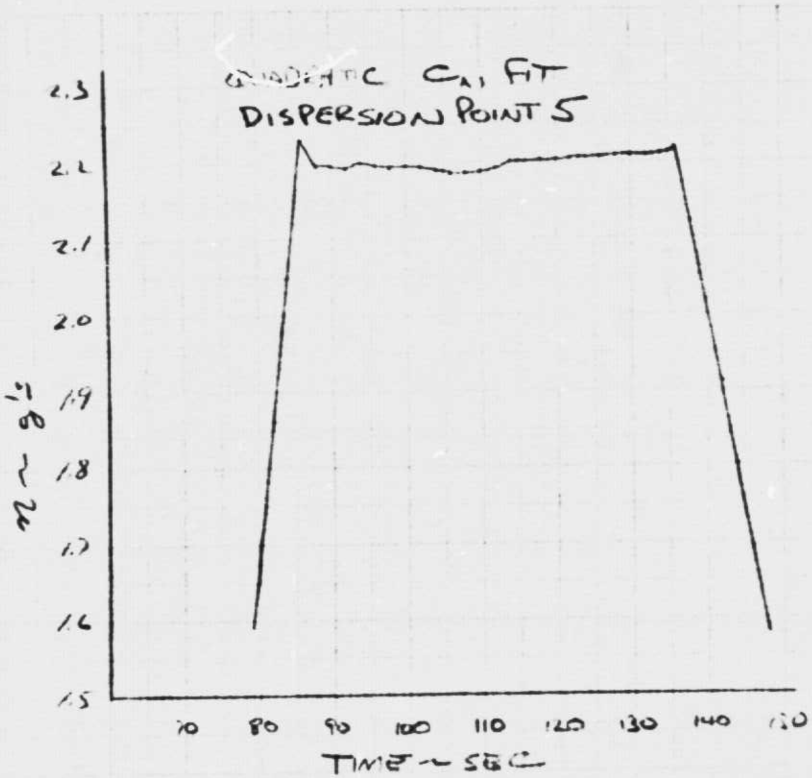


Figure 3.1-20

<u>NORMAL LOAD FACTOR υ. TIME</u>

$K_1 = 1.2 \quad K_2 = 1.2$

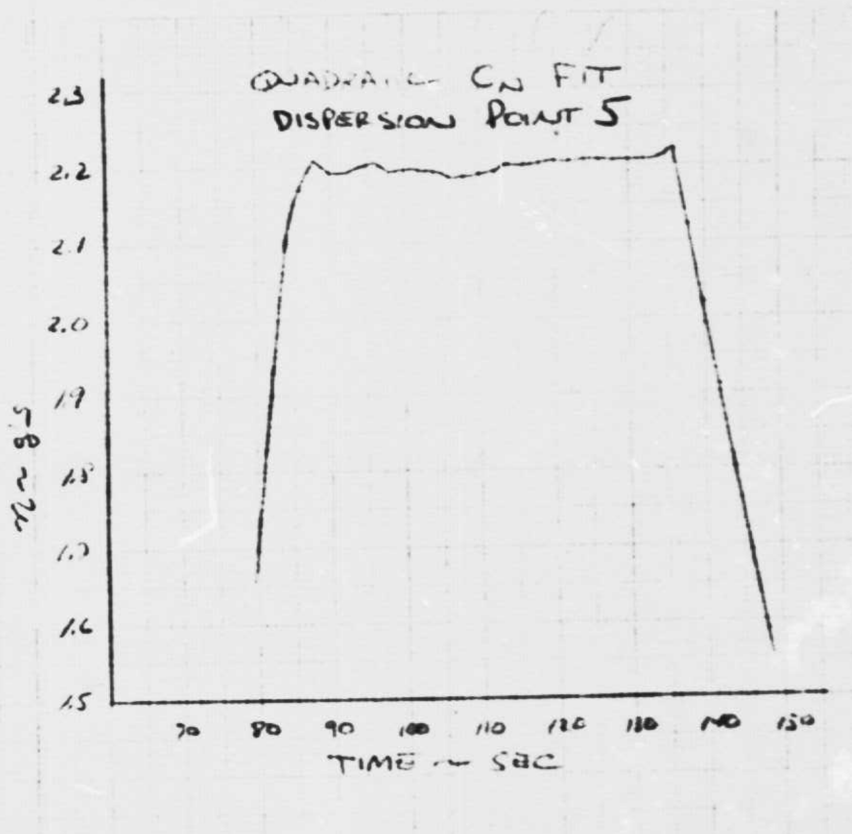


Figure 3.1-21

<u>NORMAL LOAD FACTOR υ. TIME</u>

$K_1 = 1.3 \quad K_2 = 1.2$

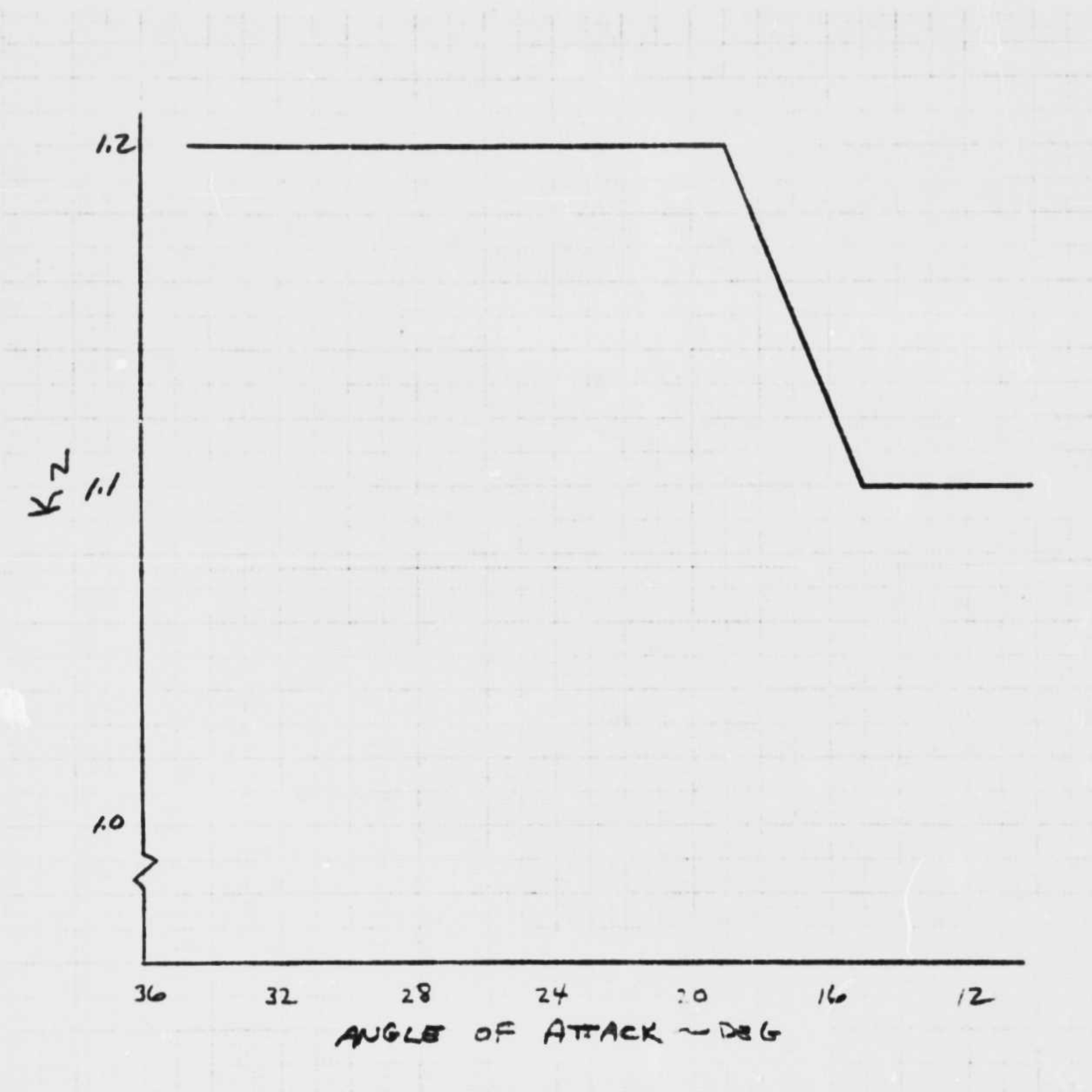


Figure 3.1-22

K_2 GAIN SCHEDULE

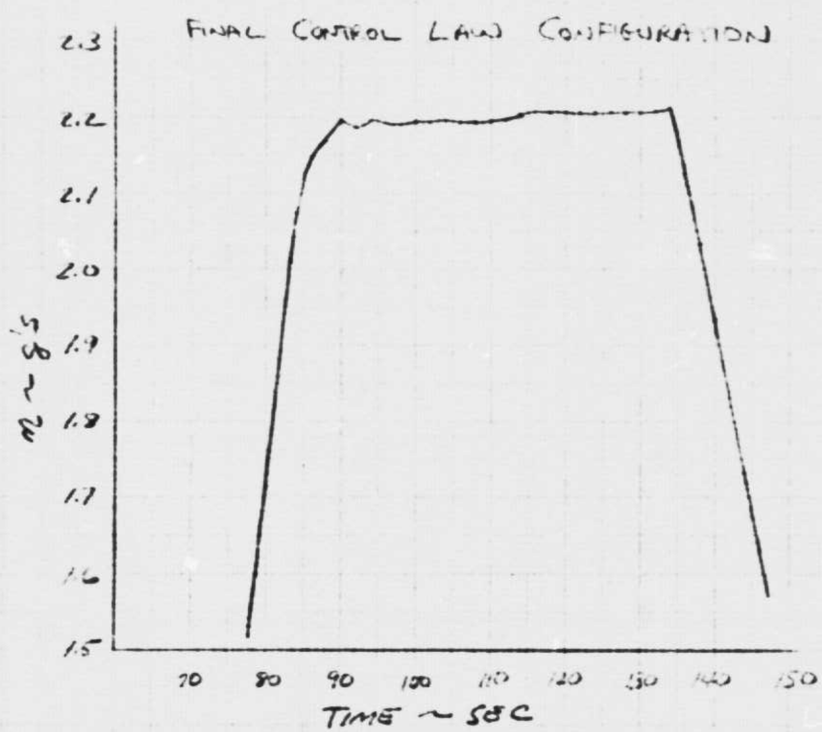


Figure 3.1-23

NORMAL LOAD FACTOR υ. TIME

NO DISPERSIONS

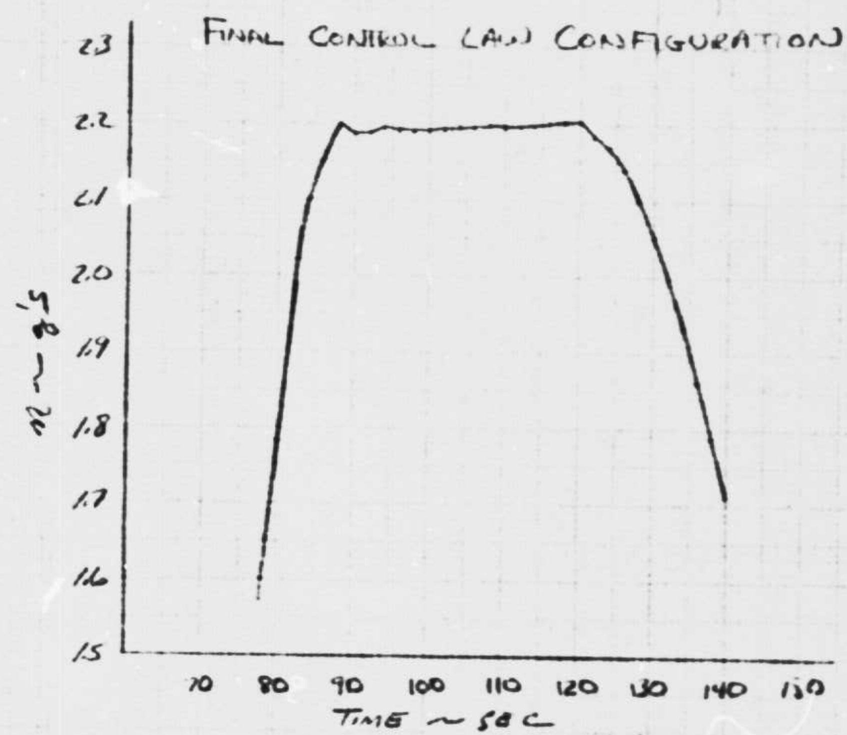


Figure 3.1-24

NORMAL LOAD FACTOR υ. TIME

DISPERSION POINT 1

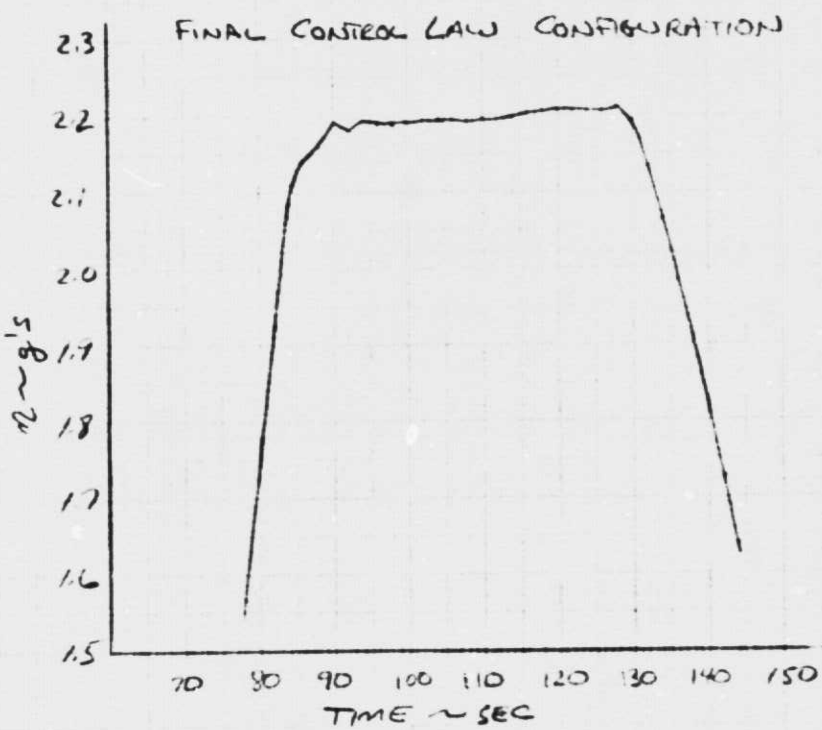


Figure 3.1-25

NORMAL LOAD FACTOR υ. TIME

DISPERSION POINT 2

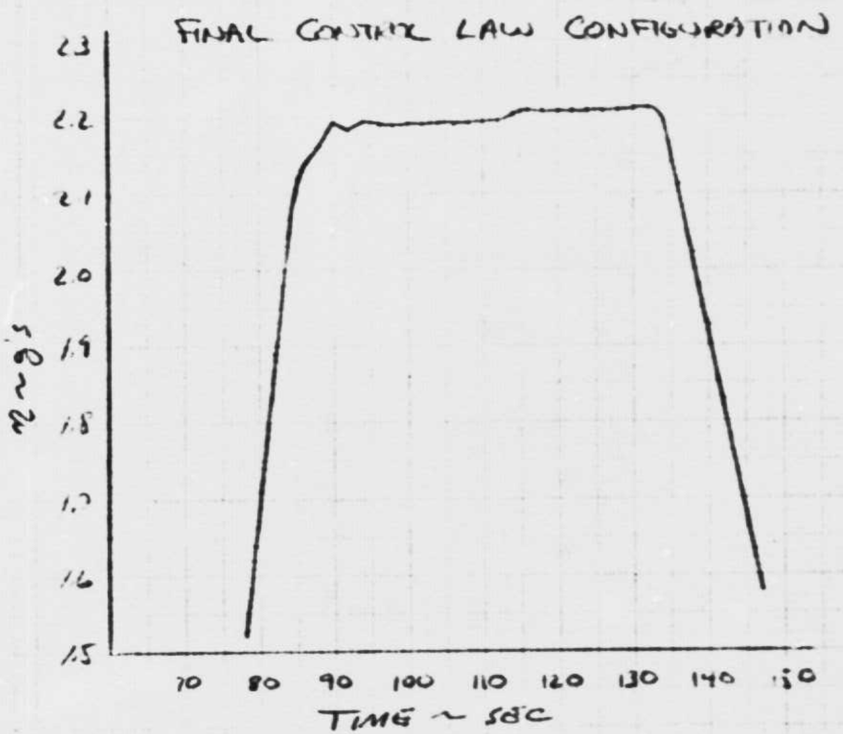


Figure 3.1-26

NORMAL LOAD FACTOR υ. TIME

DISPERSION POINT 3

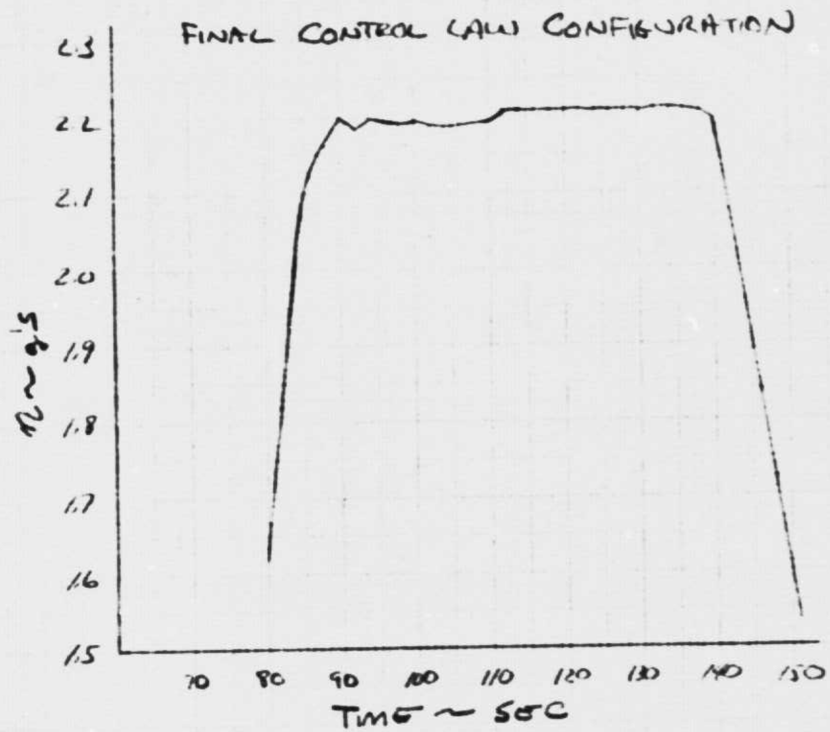


Figure 3.1-27

NORMAL LOAD FACTOR υ. TIME

DISPERSION POINT 4

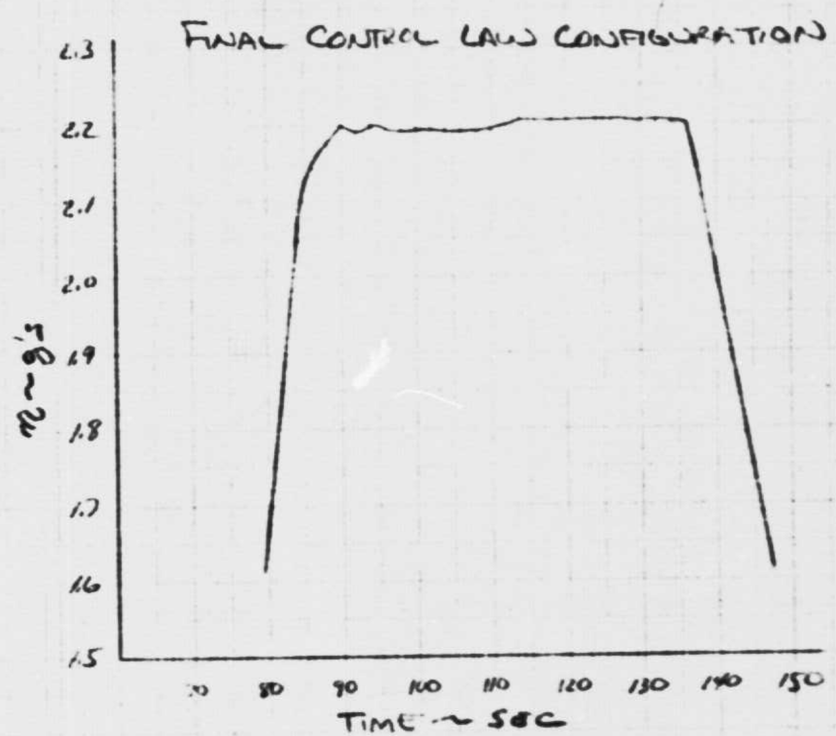


Figure 3.1-28

NORMAL LOAD FACTOR υ. TIME

DISPERSION POINT 5

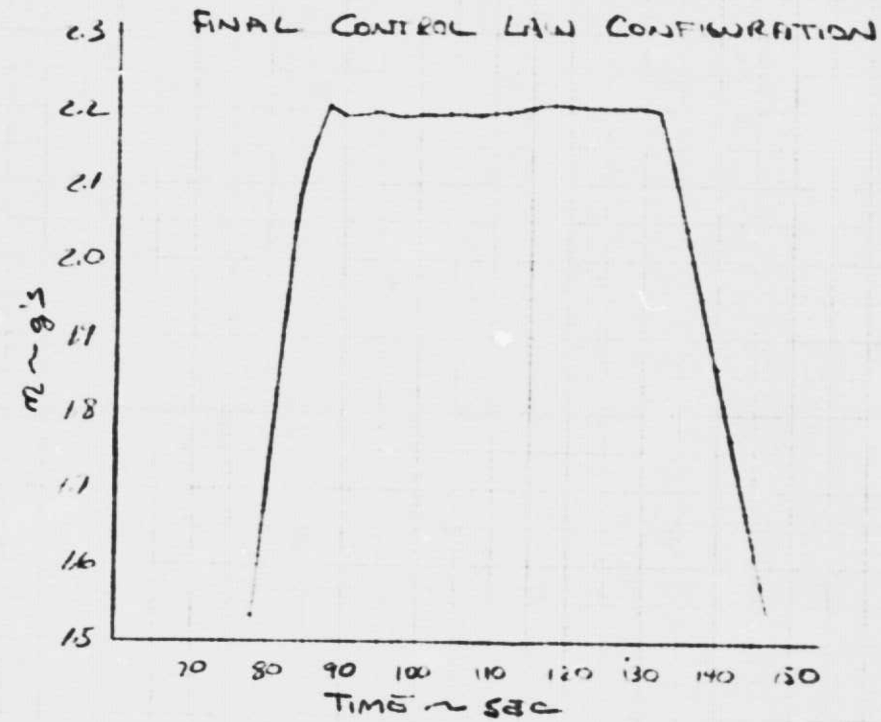


Figure 3.1-29

<u>NORMAL LOAD FACTOR v. TIME</u>

<u>DISPERSION POINT 6</u>

3.2 Guidance Cycle Time Selection

The effect of guidance cycle time was investigated by evaluating the control law performance for .5, 1., and 2. second time steps. The cycle time steps were evaluated for nominal aerodynamics, dispersion points 5 and 6 of Figure 3.1-11, and special ramped aerodynamic dispersions. The special dispersions were obtained by ramping the aerodynamic dispersions as a function of angle of attack to disperse not only the magnitude of C_L and C_D but also the slope of the C_L vs. α and C_D vs. α curves. These special dispersions were devised for test purposes only and were not intended to represent any expected aerodynamic uncertainty. The special dispersion schedule is presented in Figure 3.2-1.

The nominal aerodynamic case for a 2. second cycle was presented previously in Figure 3.1-23. The special ramped dispersions are presented in Figures 3.2-2, 3.2-3, and the cases for dispersion points 5 and 6 were previously presented in Figures 3.1-28 and 3.1-29. The comparable cases for a 1. second cycle time are presented in Figure 3.2-4 to Figure 3.2-8. For a .5 second cycle time, see Figure 3.2-9 to Figure 3.2-13.

The results show a general improvement in all cases for decreases in cycle time. The profiles are smoother and maintain the load limit better as cycle time decreases. For a cycle time of 1. second and .5 second, virtually no deviation from the desired load is obtained for either the nominal case or for dispersion points 5 and 6. The special ramped dispersions resulted in gross overshoot

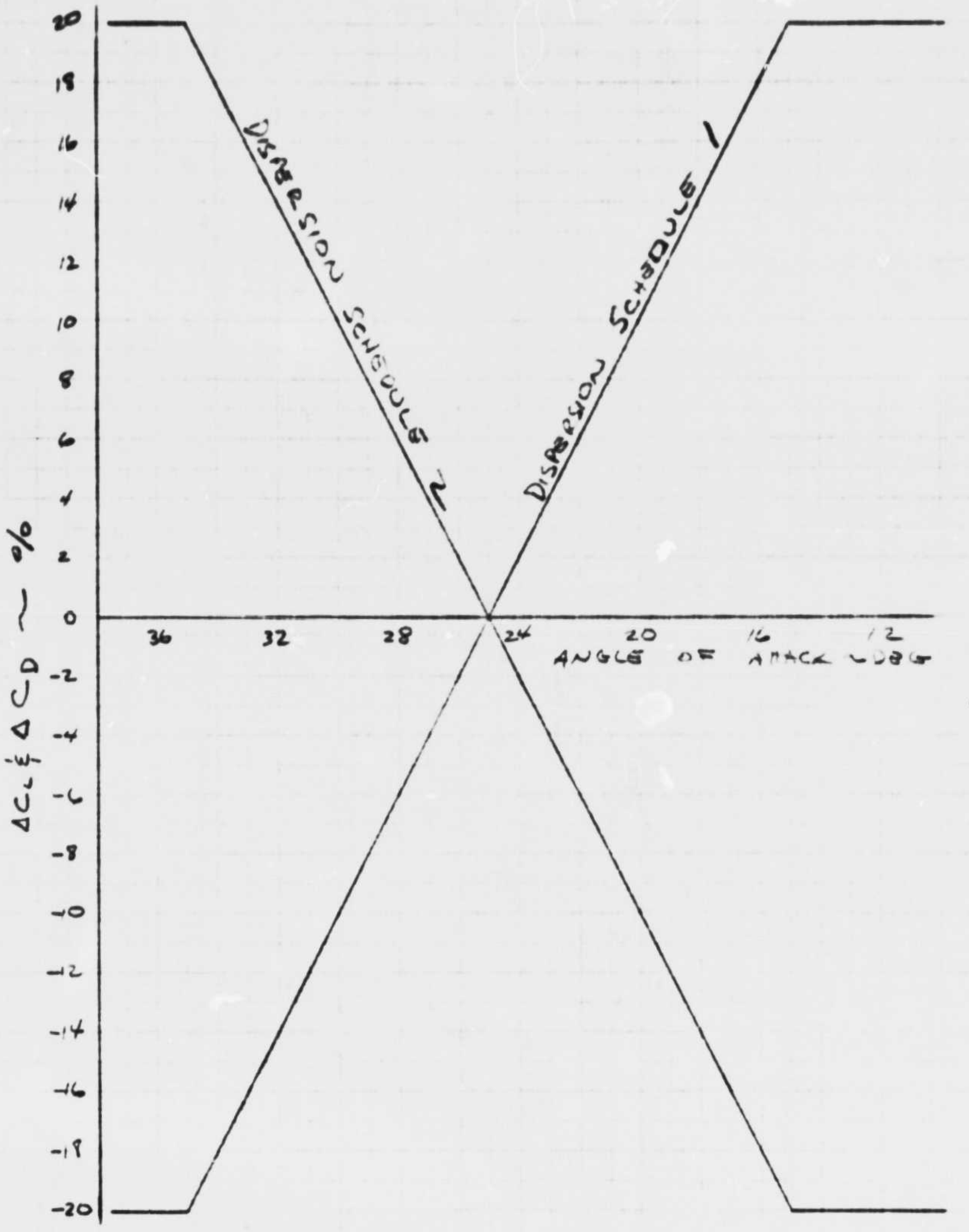


Figure 3.2-1

C_L and C_D RAMPED DISPERSION SCHEDULE

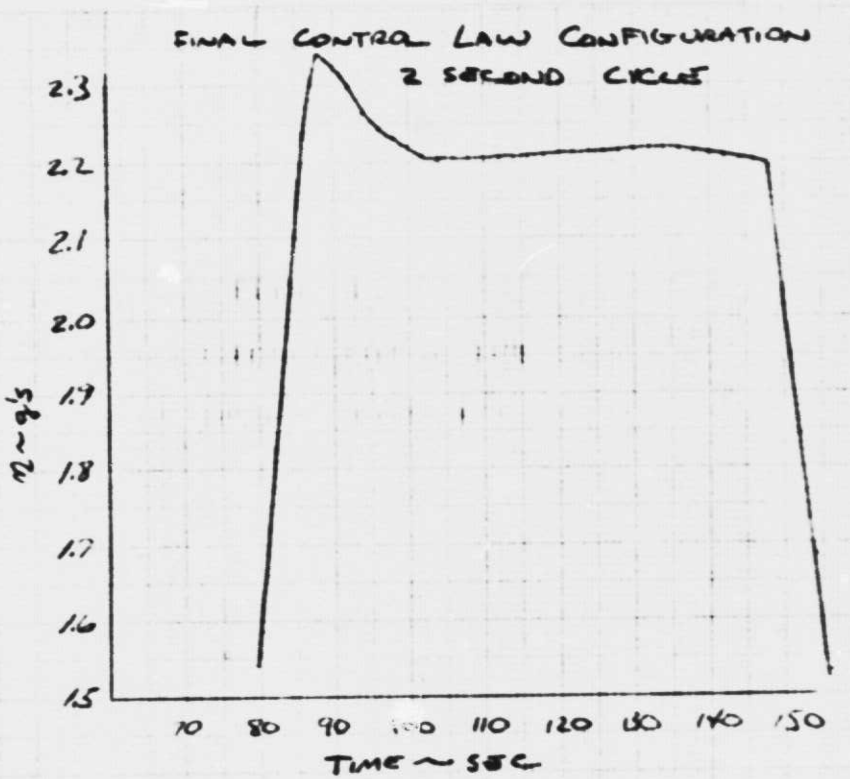


Figure 3.2-2

NORMAL LOAD FACTOR υ. TIME

DISPERSION SCHEDULE 1

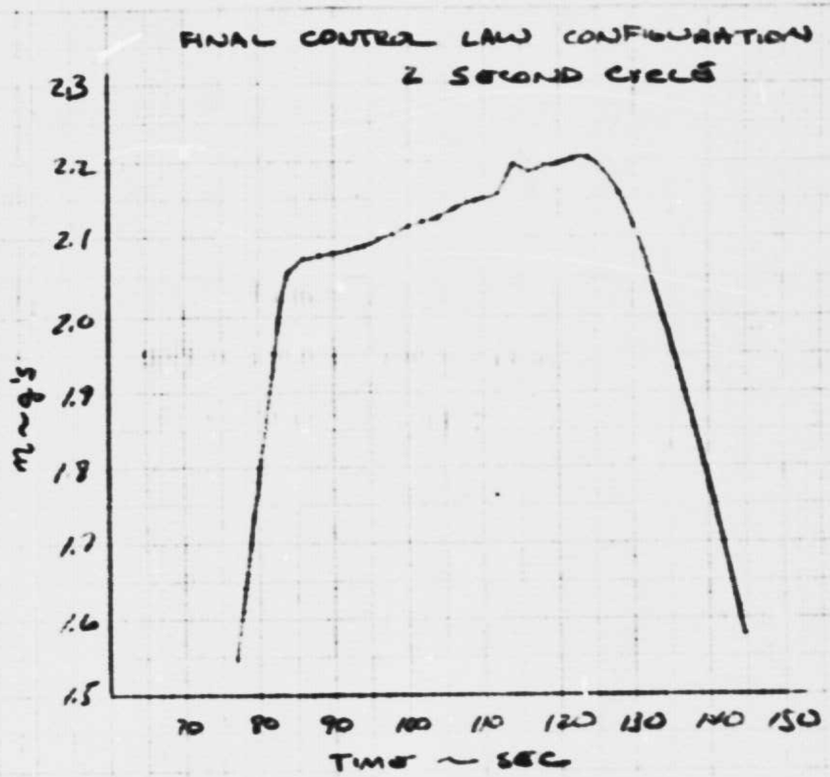


Figure 3.2-3

NORMAL LOAD FACTOR υ. TIME

DISPERSION SCHEDULE 2

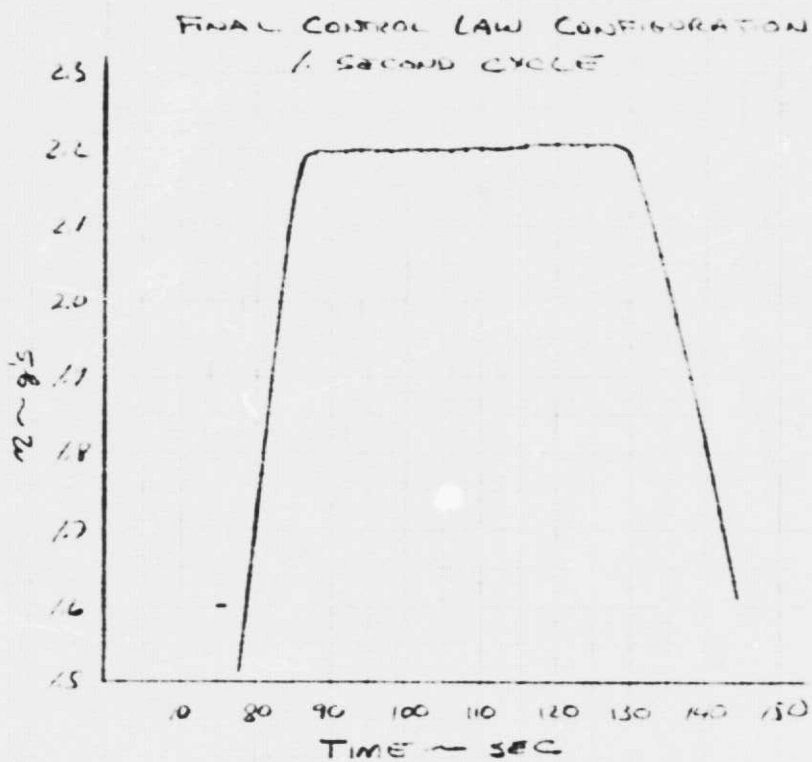


Figure 3.2-4

NORMAL LOAD FACTOR υ. TIME

NO DISPERSIONS

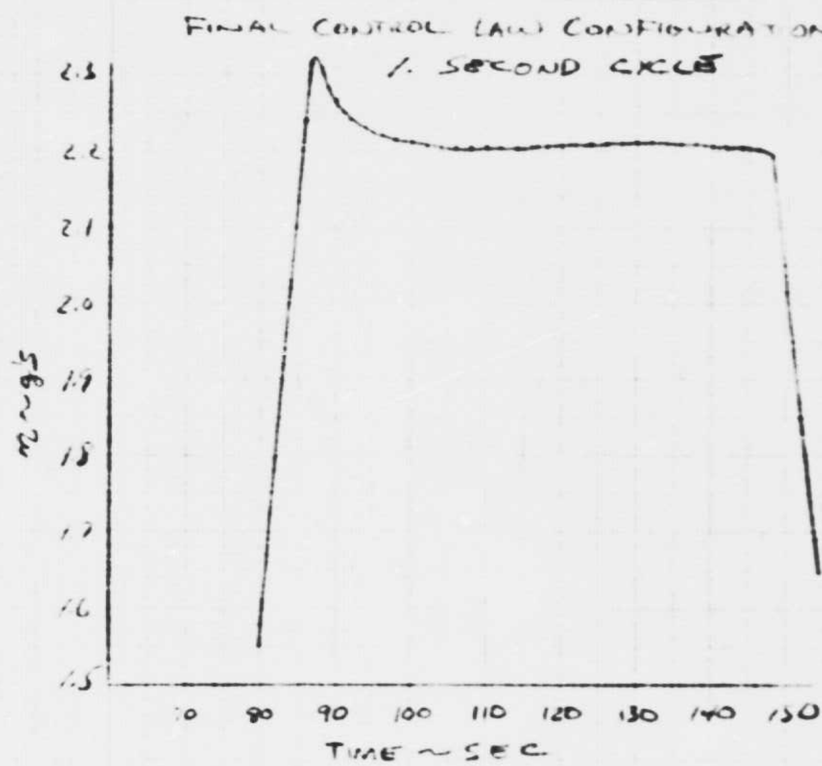


Figure 3.2-5

NORMAL LOAD FACTOR υ. TIME

DISPERSION SCHEDULE 1

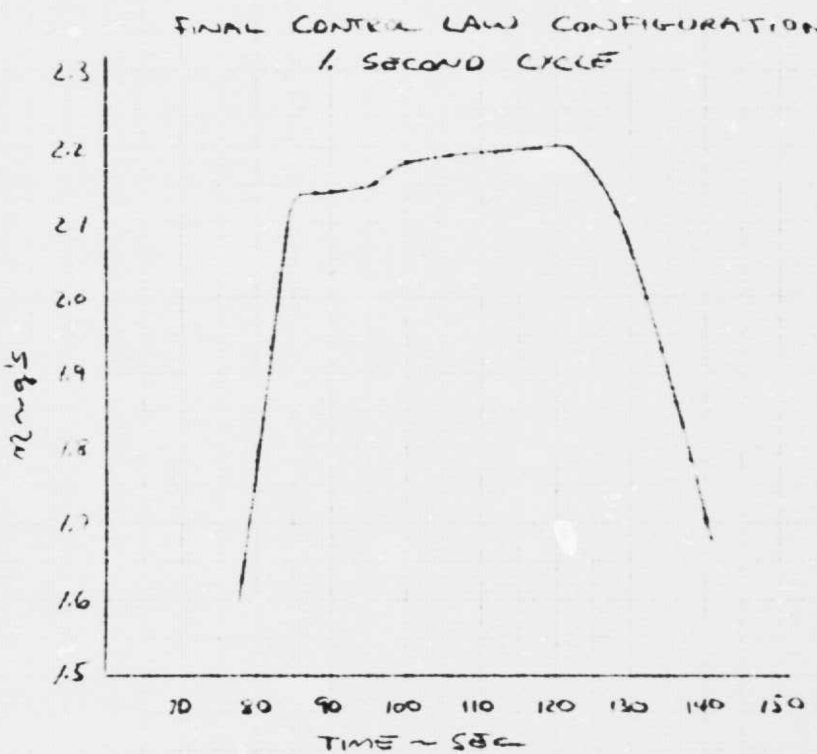


Figure 3.2-6

<u>NORMAL LOAD FACTOR υ. TIME</u>

<u>DISPERSION SCHEDULE 2</u>

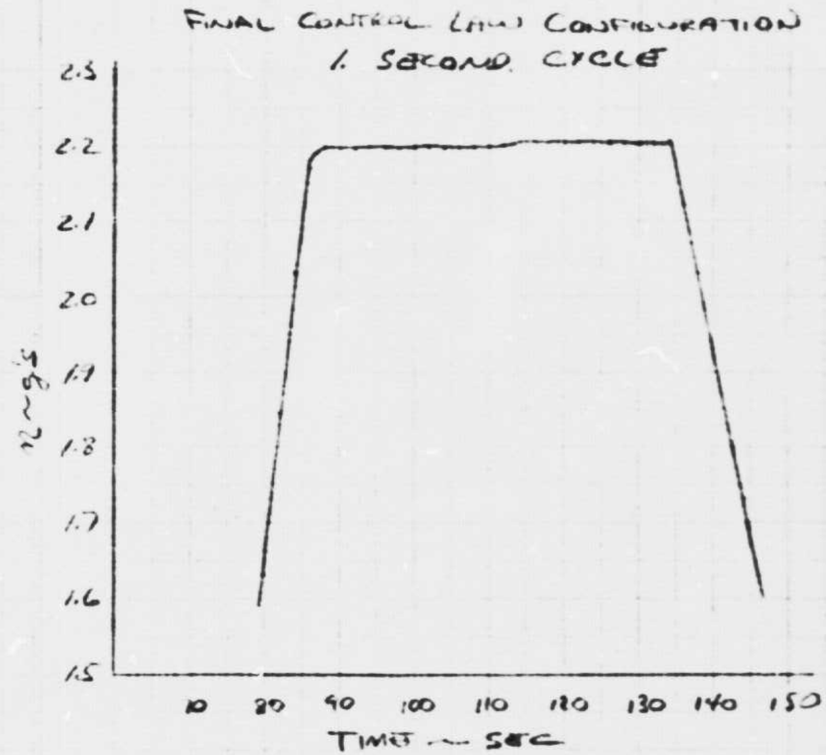


Figure 3.2-7

<u>NORMAL LOAD FACTOR υ. TIME</u>

<u>DISPERSION POINT 5</u>

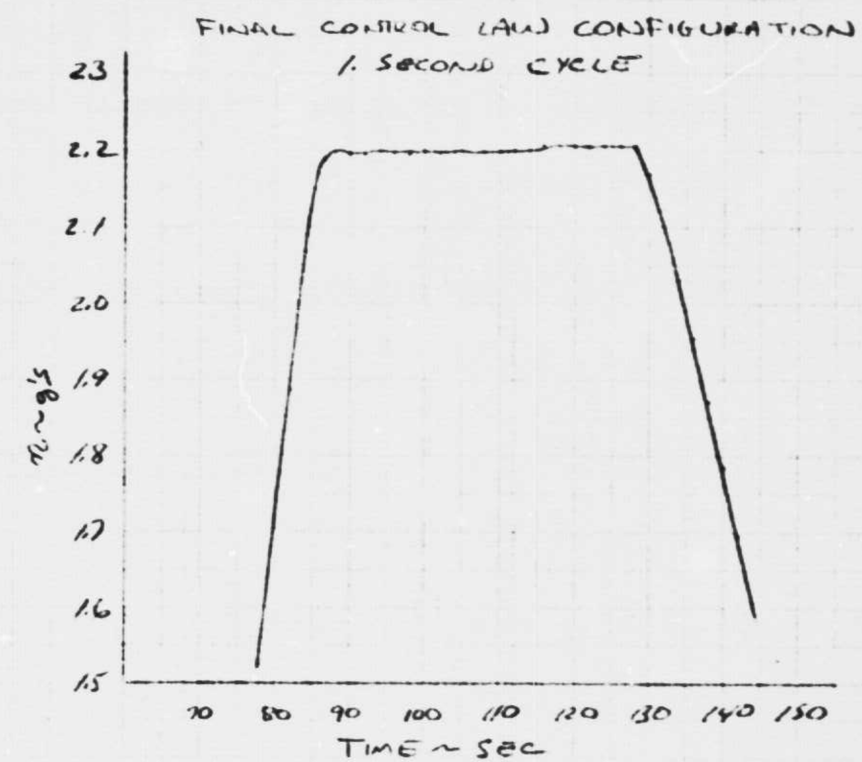


Figure 3.2-8

NORMAL LOAD FACTOR v. TIME

DISPERSION POINT 6

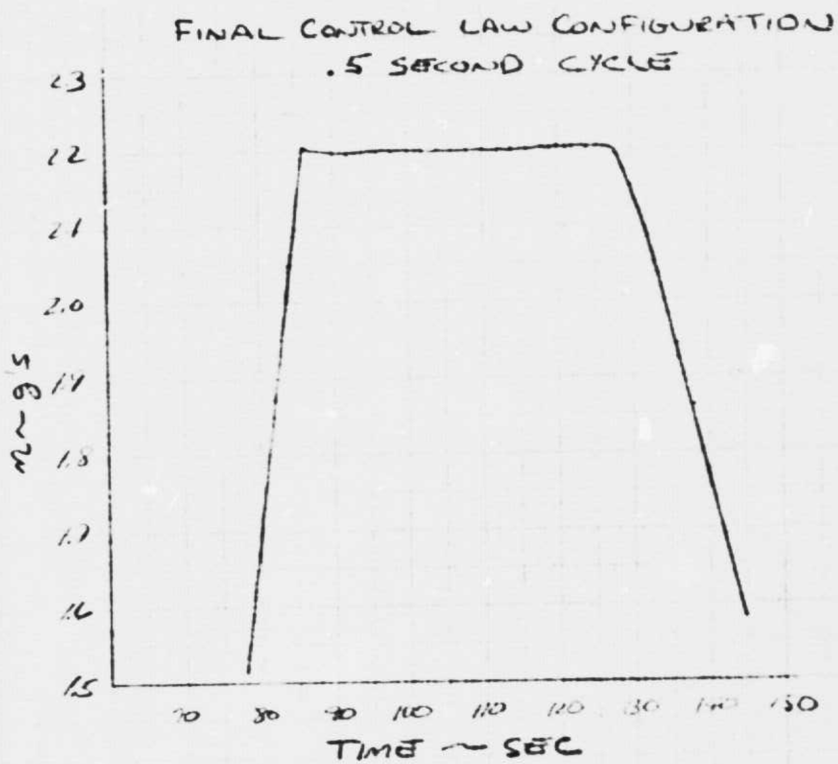


Figure 3.2-9

NORMAL LOAD FACTOR υ. TIME

NO DISPERSIONS

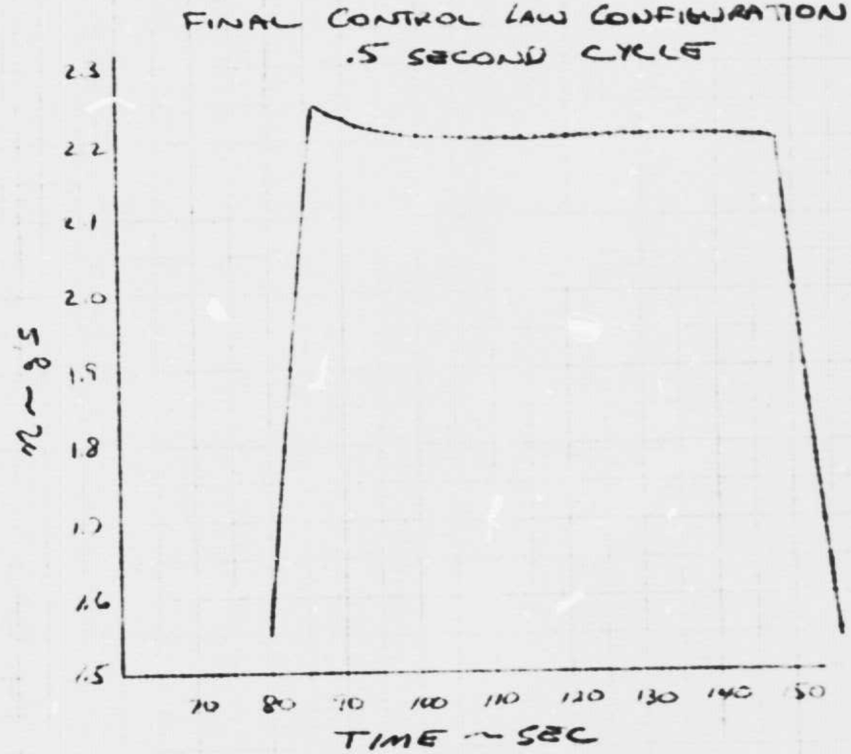


Figure 3.2-10

NORMAL LOAD FACTOR υ. TIME

DISPERSION SCHEDULE 1

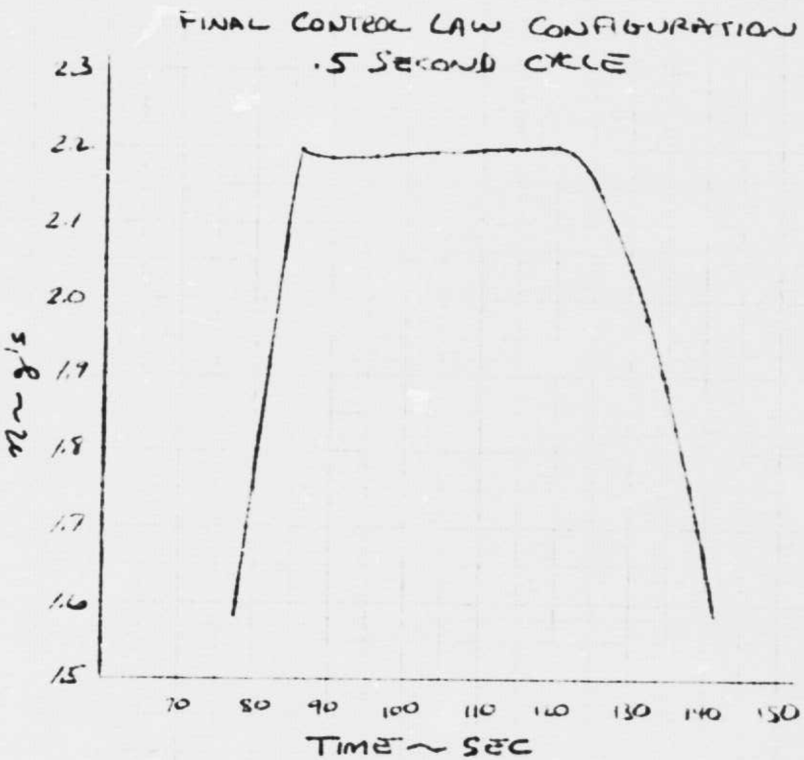


Figure 3.2-11

<u>NORMAL LOAD FACTOR υ. TIME</u>

<u>DISPERSION SCHEDULE 2</u>

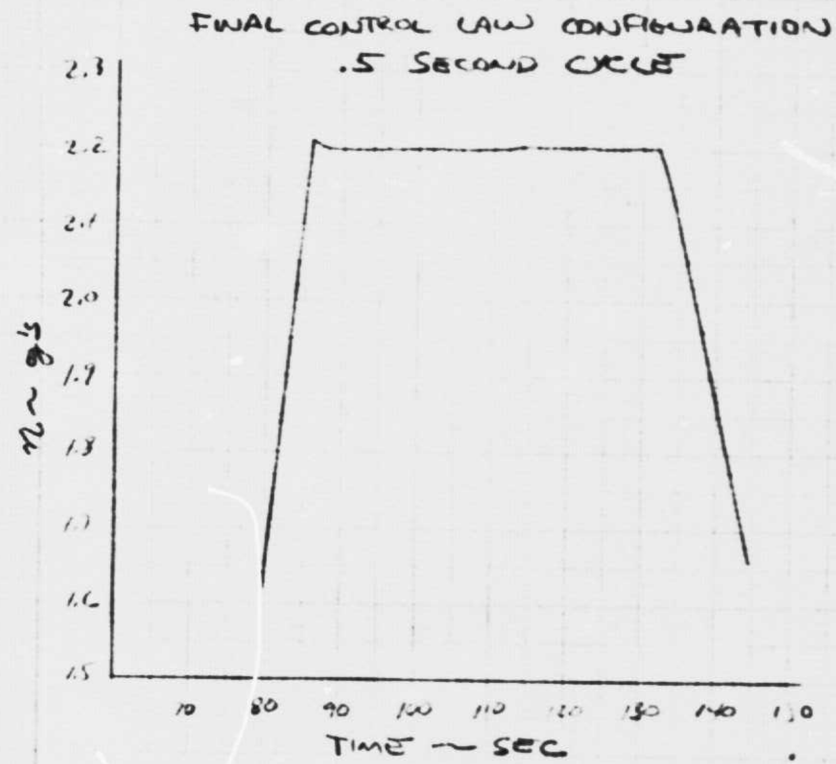


Figure 3.2-12

<u>NORMAL LOAD FACTOR υ. TIME</u>

<u>DISPERSION POINT 5</u>

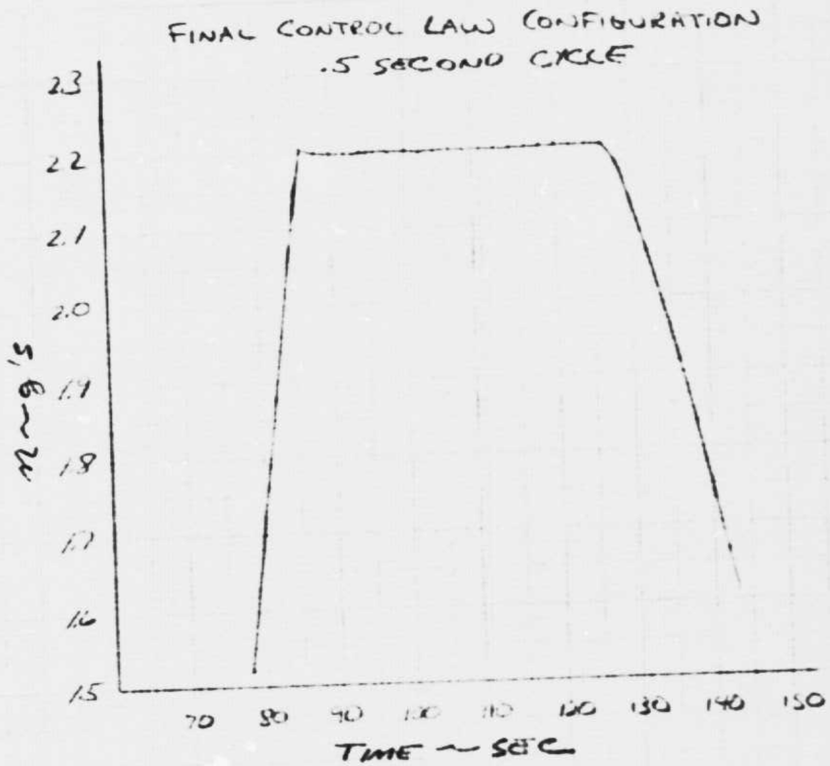


Figure 3.2-13

NORMAL LOAD FACTOR v. TIME

DISPERSION POINT 6

and undershoot for a 2. second cycle time. Some improvement is gained with a 1. second cycle time and much improved results (an overshoot less than .05g) are obtained for a .5 second cycle time. Based on these results, a .5 second cycle time is recommended to assure smooth and adequate load relief for whatever aerodynamic dispersions may be encountered.

4.0 CONCLUSIONS

The load relief control law performed well with the optimized gains and an updated smoothing constant for the transition from the load buildup phase to the constant normal load phase. No undesirable deviations from the desired load level were encountered for either the nominal aerodynamics or the aerodynamic dispersion points tested.

A study of load relief performance for various guidance cycle times indicated the load relief phase performance could be made virtually insensitive to aerodynamic dispersions by using a .5 second cycle time.

5.0 REFERENCES

1. "Aerodynamic Design Data Book, Volume 1, Orbiter Vehicle," Rockwell International, Space Division, June 13, 1974.

APPENDIX A

Control Law Derivation

η	normal load factor (g)
N_F	normal force (lb)
C_N	normal force coefficient
ρ	atmospheric density (SLUG/FT^3)
V	relative velocity (FPS)
S	reference area (FT^2)
$\mathcal{D}$	drag acceleration (FPS^2)
h	altitude (FT)
h_s	density scale height (FT)
α	angle of attack (deg)
Δt	cycle time (sec)
ω	vehicle weight (lbs)

$$\eta = N_F/\omega$$

$$\dot{\eta} = \dot{N}_F/\omega$$

$$N_F = 1/2\rho V^2 C_N S$$

$$\dot{N}_F = 1/2\dot{\rho}V^2 C_N S + 1/2\rho V^2 \dot{C}_N S + \rho V\dot{V} C_N S$$

$$\frac{\dot{N}_F}{N_F} = \frac{\dot{\rho}}{\rho} + \frac{\dot{C}_N}{C_N} + \frac{2\dot{V}}{V}$$

$$\dot{V} \simeq -\mathcal{D}$$

$$\rho = \rho_o e^{-h/h_s}$$

$$\dot{\rho} = \rho_o \left(-\dot{h}/h_s\right) e^{-h/h_s}$$

$$\frac{\dot{\rho}}{\rho} = -\dot{h}/h_s$$

Approximate C_N as a quadratic function of α:

$$C_N = C_{N_0} + C_{N_1}\alpha + C_{N_2}\alpha^2$$

$$\dot{C}_N = (C_{N_1} + 2C_{N_2}\alpha)\,\dot{\alpha}$$

$$\frac{\dot{N}_F}{N_F} = -\frac{\dot{h}}{h_s} + \frac{\left(C_{N_1} + 2C_{N_2}\alpha\right)\dot{\alpha}}{C_N} - \frac{2\mathcal{D}}{V}$$

$$\frac{\dot{n}}{n} = \frac{\left(C_{N_1} + 2C_{N_2}\alpha\right)}{C_N}\,\dot{\alpha} - \frac{\dot{h}}{h_s} - \frac{2\mathcal{D}}{V}$$

$$\dot{\alpha} = \frac{\dot{n}/n + \dot{h}/h_s + 2\mathcal{D}/V}{\left(\dfrac{C_{N_1} + 2C_{N_2}\alpha}{C_N}\right)}$$

Using finite differences:

$$\Delta\alpha = \frac{\left(\dfrac{n_{REF} - n}{n}\right) + \dfrac{\dot{h}\Delta t}{h_s} + \dfrac{2\mathcal{D}\Delta t}{V}}{\left(\dfrac{C_{N_1} + 2C_{N_2}\alpha}{C_N}\right)}$$

Introduce scale factors K_1 and K_2 to achieve proper response:

$$\Delta\alpha = \left[K_1\left(\frac{n_{REF} - n}{n}\right) + K_2\Delta t\left(\frac{\dot{h}}{h_s} + \frac{2\mathcal{D}}{V}\right)\right]\left[\frac{C_{N_0} + C_{N_1}\alpha + C_{N_2}\alpha^2}{C_{N_1} + 2C_{N_2}\alpha}\right]$$

To project the buildup of normal load while approaching the load limit (α = constant), derive an expression for $\Delta\eta$

$$\eta = N_F/_\omega$$

$$\dot{\eta} = \dot{N}_F/_\omega$$

$$N_F = 1/2\rho V^2 C_N S$$

$$\dot{N}_F = 1/2\dot{\rho}V^2 C_N S + \rho V\dot{V}C_N S \qquad \text{for constant } \alpha \text{ and } \therefore C_N$$

$$\frac{\dot{N}_F}{N_F} = \frac{\dot{\rho}}{\rho} + \frac{2\dot{V}}{V}$$

$$\frac{\dot{\rho}}{\rho} = \frac{-\dot{h}}{h_s}$$

$$\dot{V} \simeq -\mathcal{D}$$

$$\frac{\dot{N}_F}{N_F} = \frac{\dot{\eta}}{\eta} = -\frac{\dot{h}}{h_s} - \frac{2\mathcal{D}}{V}$$

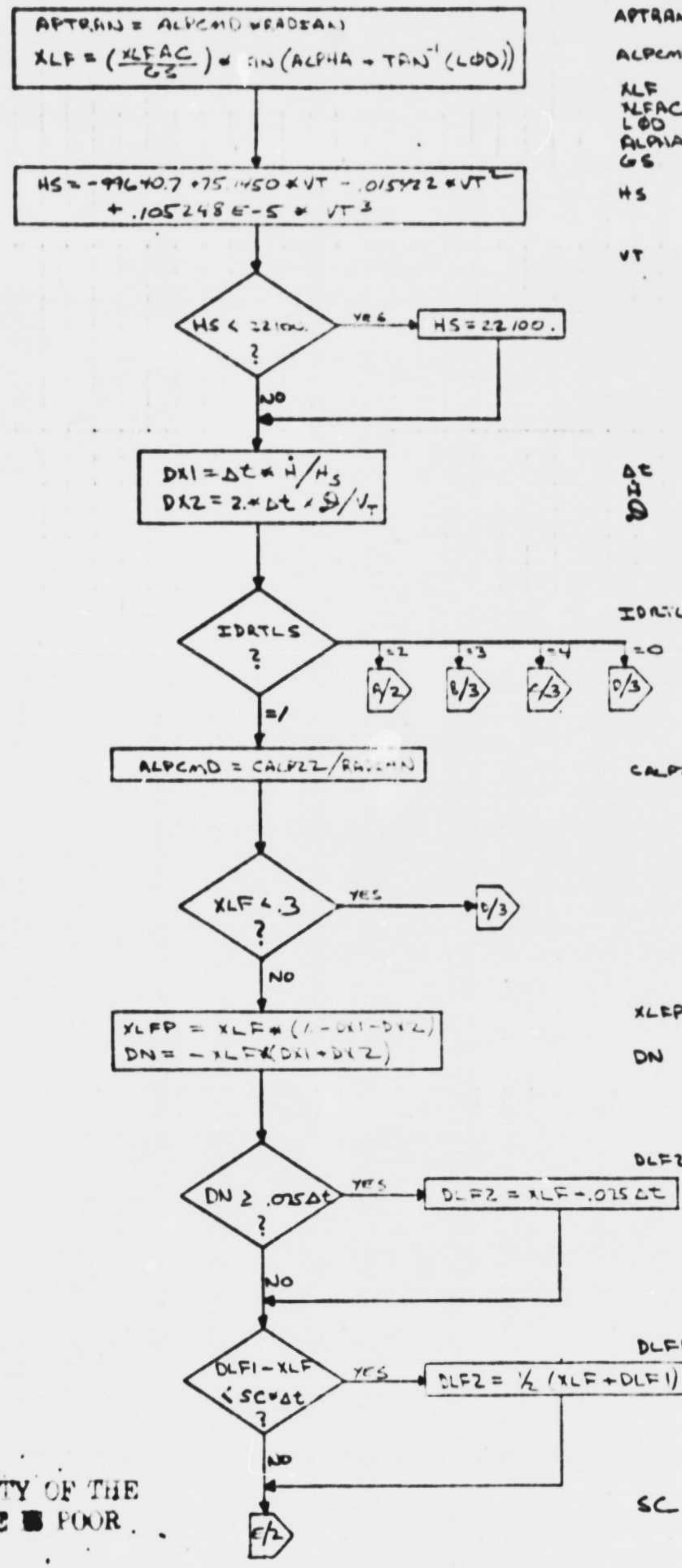
$$\dot{\eta} = -\eta\left(\frac{\dot{h}}{h_s} + \frac{2\mathcal{D}}{V}\right)$$

Over a computation cycle of Δt

$$\Delta\eta = -\eta\Delta t\left(\frac{\dot{h}}{h_s} + \frac{2\mathcal{D}}{V}\right)$$

APPENDIX B

RTLS LOAD RELIEF LOGIC



- **APTRAN** — Nominal transition phase α in degrees
- **ALPCMD** — Alpha command in rad computed by nominal transition logic
- **XLF** — Normal load factor (g's)
- **XLFAC** — Total aero. acceleration (FPS²)
- **LOD** — Current L/D
- **ALPHA** — Current angle of attack (rad)
- **GS** — Acceleration of gravity (32.2 FPS²)
- **HS** — Density scale height (FT) curve fit as a function of relative velocity
- **VT** — Relative velocity (FPS)

Limit scale height to be greater than 22100.

- **Δt** — Guidance time step (sec)
- **Ḣ** — Altitude rate (FPS)
- **D** — Drag acceleration (FPS²)
- **IDRTLS** — Internal control flag initialized to 1

Alpha recovery phase

- **CALP22** — Value alpha is recovered to (deg); input

Exit if LF < .3

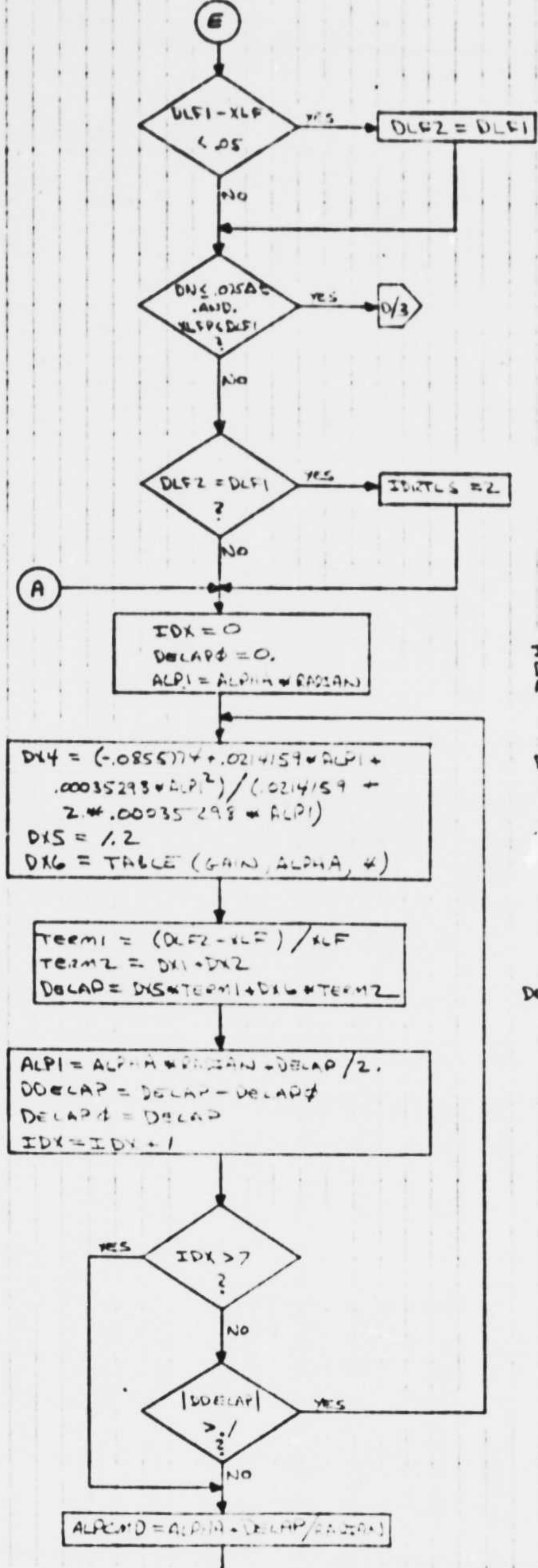
- **XLFP** — Projected load factor for next cycle (g's)
- **DN** — Projected load factor increment (g's)
- **DLF2** — Desired load factor for next cycle (g's)

Limit load factor buildup each cycle to .075 Δt

- **DLF1** — Target load factor; input

Begin smoothing into target load factor level when (SC*Δt) g's below DLF1

- **SC** — Smoothing constant; controls level at which smoothing logic is initiated; input as .15



SET THE DESIRED LOAD FACTOR FOR THE NEXT CYCLE TO THE TARGET LOAD FACTOR WHEN .05 g BELOW TARGET LOAD FACTOR

IF LOAD FACTOR IS NOT GOING TO CHANGE BY MORE THAN .025ΔC AND THE PROJECTED LOAD FACTOR IS BELOW THE TARGET LOAD FACTOR, EXIT.

SET INTERNAL FLAG WHEN TARGET LOAD FACTOR IS REACHED

INITIALIZE Δα ITERATION

IDX Δα ITERATION COUNTER
DELAPØ PAST VALUE OF Δα
ALPI PROJECTED α NEXT CYCLE

BEGIN Δα ITERATION

DX4 $C_N/(dC_N/d\alpha)$; THE NORMAL FORCE COEFFICIENT, C_N, IS APPROXIMATED BY A QUADRATIC CURVE FIT VERSUS α

DX6 LINEARLY INTERPOLATED FROM THE FOLLOWING TABLE:

ALPHA (RAD)	0.	.26[illegible]	.3[illegible]	.[illegible]
DX6	1.1	1.1	1.2	1.2

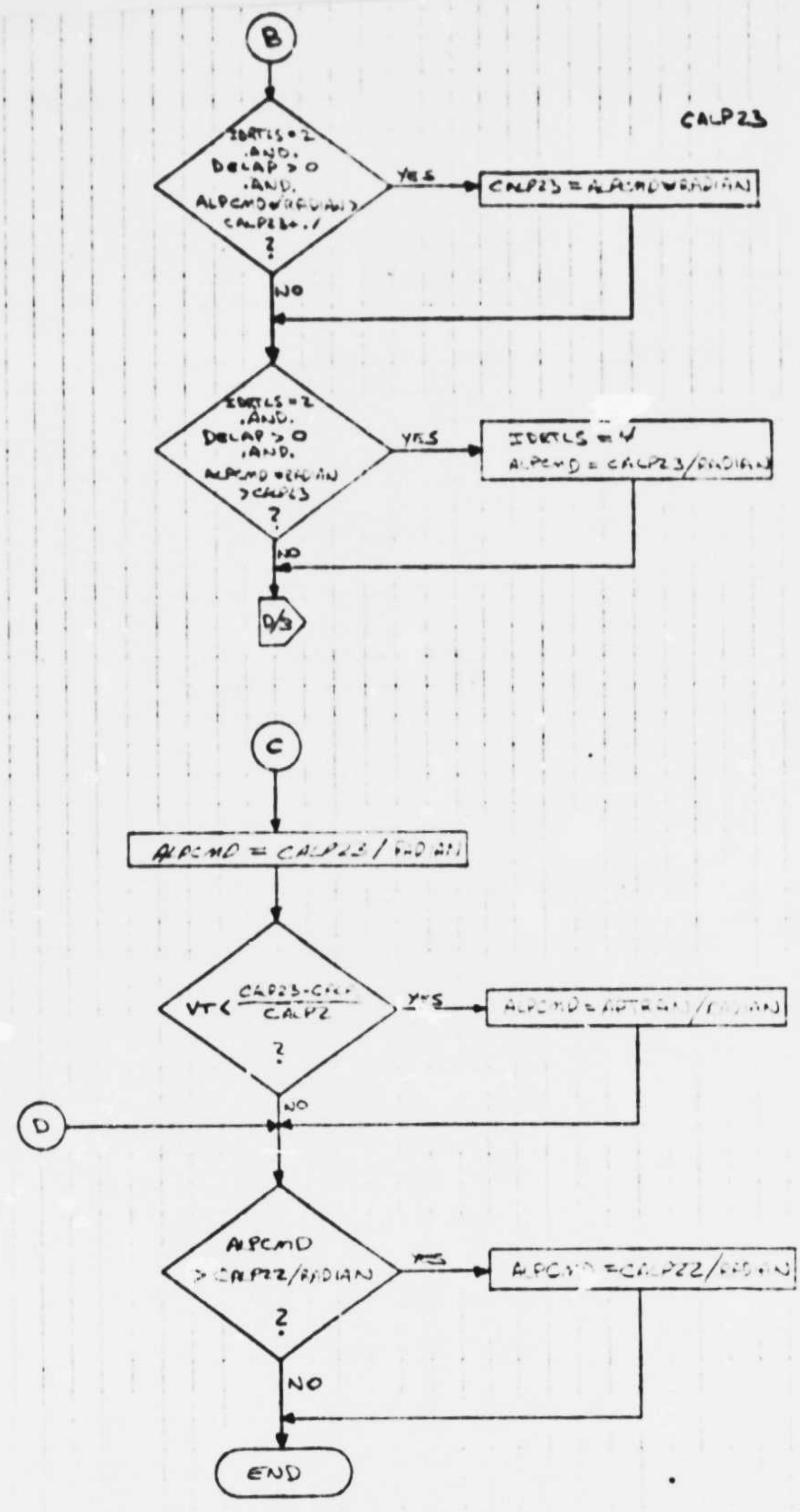
DELAP Δα REQUIRED FOR LOAD RELIEF

APPROXIMATE α OVER NEXT CYCLE BY ADDING ONE HALF THE α INCREMENT TO THE CURRENT VALUE

LIMIT THE NUMBER OF Δα ITERATIONS TO 7

IF Δα CHANGES BY LESS THAN .1, THE ITERATION IS COMPLETE

SET α_{CMD} TO CURRENT α PLUS THE Δα SOLUTION



VALUE OF α MAINTAINED FOLLOWING LOAD RELIEF UNTIL THE NOMINAL TRANSITION ALPHA-VELOCITY PROFILE IS INTERSECTED. CALP23 IS INPUT, HOWEVER IF ALPHA CONTINUES TO INCREASE BEFORE CALP23 IS REACHED, CALP23 IS DEFINED AS THE MINIMUM ALPHA.

TERMINATE ALPHA CONTROL FOR LOAD RELIEF IF α IS INCREASING (DELAP > 0) AND ALPCMD IS GREATER THAN CALP23.

DETERMINE IF NOMINAL TRANSITION ALPHA-VELOCITY PROFILE HAS BEEN INTERSECTED. IF SO, COMMAND TRANSITION α (APTRAN DETERMINED NORMAL TRANSITION ALPHA COMMAND). CALP1 AND CALP2 DEFINE TRANSITION PROFILE.