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CASE FILE COPY

STUDY OF SOLID ROCKET MOTOR FOR A SPACE SHUTTLE BOOSTER

FINAL REPORT

APPENDIX A
SRM WATER ENTRY LOADS



Report 1917-FR1

15 March 1972



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P. O. BOX 13400 SACRAMENTO, CALIFORNIA 95813 • A DIVISION OF AEROJET-GENERAL

Report 1917-FR1

STUDY OF SOLID ROCKET MOTOR
FOR A
SPACE SHUTTLE BOOSTER

FINAL REPORT

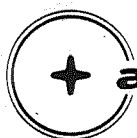
APPENDIX A
SRM WATER ENTRY LOADS

Contract NAS8-28428
Data Procurement Document 314
Data Requirement MA-02

15 March 1972

Prepared for:

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812



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SUBJECT

SRM WATER ENTRY LOADS

DATE

FEB 28, 1972

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1917-01-200

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OBJECTIVE:

INVESTIGATE WATER ENTRY LOADS AND RESULTANT EFFECTS ON FLIGHT HARDWARE,
AS OUTLINED BELOW.

LOADS AND INPUT DATA:

- 1) INERT STAGE WEIGHT : 117,000 LB.
- 2) IMPACT VELOCITY, VERTICAL : 20 FT / SEC
- 3) IMPACT VELOCITY, HORIZONTAL : 30 FT / SEC (20 MPH)
- 4) ORIENTATION AT IMPACT :
 - CASE I - VERTICAL, NOSE DOWN
 - CASE II - 45° TO VERTICAL, NOSE DOWN

SPECIFIC REQUIRED RESULTS:

- 1) LOADS ON SRM STRUCTURE DUE TO IMPACT
- 2) LOADS ON SRM STRUCTURE DUE TO POUNCE-BACK } NO WIND
- 3) LOADS ON SRM STRUCTURE INDUCED BY SIDE VELOCITY COMBINED WITH VERTICAL VELOCITY
- 4) LOADS DUE TO WATER PENETRATION @ 20 FT/SEC.

DATA SOURCES:

- 1) ENGINEERING MEMORANDUM EM: LS-03-M1-4, LOCKHEED MISSILE & SPACE CO., DATE: 1/31/72
- 2) ENGINEERING MECHANICS, BY BROOKS & WILCOX, 1929.
- 3) ROM STRUCTURAL ANALYSIS OF 156" MOTOR FOR WATER ENTRY LOADS, BY HANS KUOPICH, DATED 4 FEB 1972
- 4) FORMULAS FOR STRESS AND STRAIN, BY R.J. ROARK, 4TH EDITION
- 5) RIGID RING FRAMES, REPORT NO. A25-27-276, DATED 20 OCT, 1957, CONVIA ASTRONAUTICS.

SUMMARY OF RESULTS AND DISCUSSION:

REFER TO PAGES 13 AND 14.



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DISCUSSION:

CASE I - VERTICAL MOTION

A FIRST APPROXIMATION OF PENETRATION CAN BE DETERMINED BY SEPARATION OF THE PROBLEM INTO TWO PARTS. FOR RELATIVELY SLOW ENTRY VELOCITY, THE PENETRATION IS CONSERVATIVELY EQUAL TO THE EQUILIBRIUM PENETRATION PLUS THE DISTANCE REQUIRED TO DECELERATE THE SRM FROM INITIAL ENTRY CONDITIONS.

EVENT SEQUENCE:

- 1/ CONTACT WATER SURFACE AT 20 FT/SEC
- 2/ DECELERATE FROM IMPACT @ 0.4 TO 0.5 g's, NOT CONSIDERING DRAG.
- 3/ DECELERATE FROM BUOYANT FORCE, WHICH INCREASES WITH PENETRATION

ANALYTICAL SEQUENCE:

- 1/ PLOT WATER IMPACT MAXIMUM g's VERSUS SPEED, IN ORDER TO DETERMINE g LOAD AT 20 FT/SECOND CONTACT VELOCITY
- 2/ PLOT BUOYANT FORCE VERSUS DEPTH OF PENETRATION



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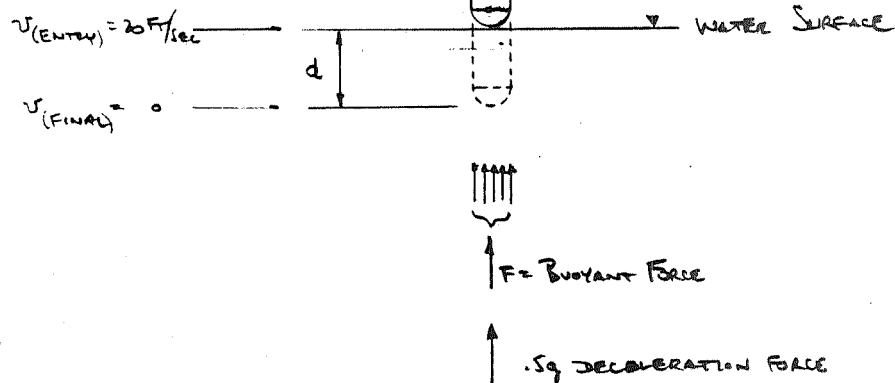
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ANALYSIS:

CASE I - VERTICAL MOTION

DETERMINE BUOYANT FORCE:

$$\begin{aligned}
 \text{BUOYANT FORCE} &= F = (\text{VOLUME DISPLACED}) (\text{DENSITY}) \\
 &= \frac{\pi}{4} (156.0)^2 \left(\frac{62.5}{1728} \right) \\
 &= 19,113 (.0361) = 690 \text{ LB/INCH}
 \end{aligned}$$

DETERMINE (PENETRATION) DECELERATION AFTER IMPACT:

APPLYING EQUATION (7), P. 214, DATA SOURCE 2:

$$\begin{aligned}
 V_f^2 &= V_0^2 + 2ax & V_f &= \text{FINAL VELOCITY} = 0 \\
 0 &= 20^2 + 2(16)(x) & V_0 &= V_{\text{ENTRY}} = 20 \text{ FT/SEC} \\
 0 &= 400 + 32x & a &= 0.5g = 16 \text{ FT/SEC}^2 \\
 x &= \frac{400}{32} = 12.41 \text{ FEET} = 149 \text{ INCHES}
 \end{aligned}$$

DETERMINE EQUILIBRIUM PENETRATION:

FROM PAGE 4 PENETRATION = 170 INCHES

TOTAL PENETRATION $\times (149 + 170) \times 319$ INCHES



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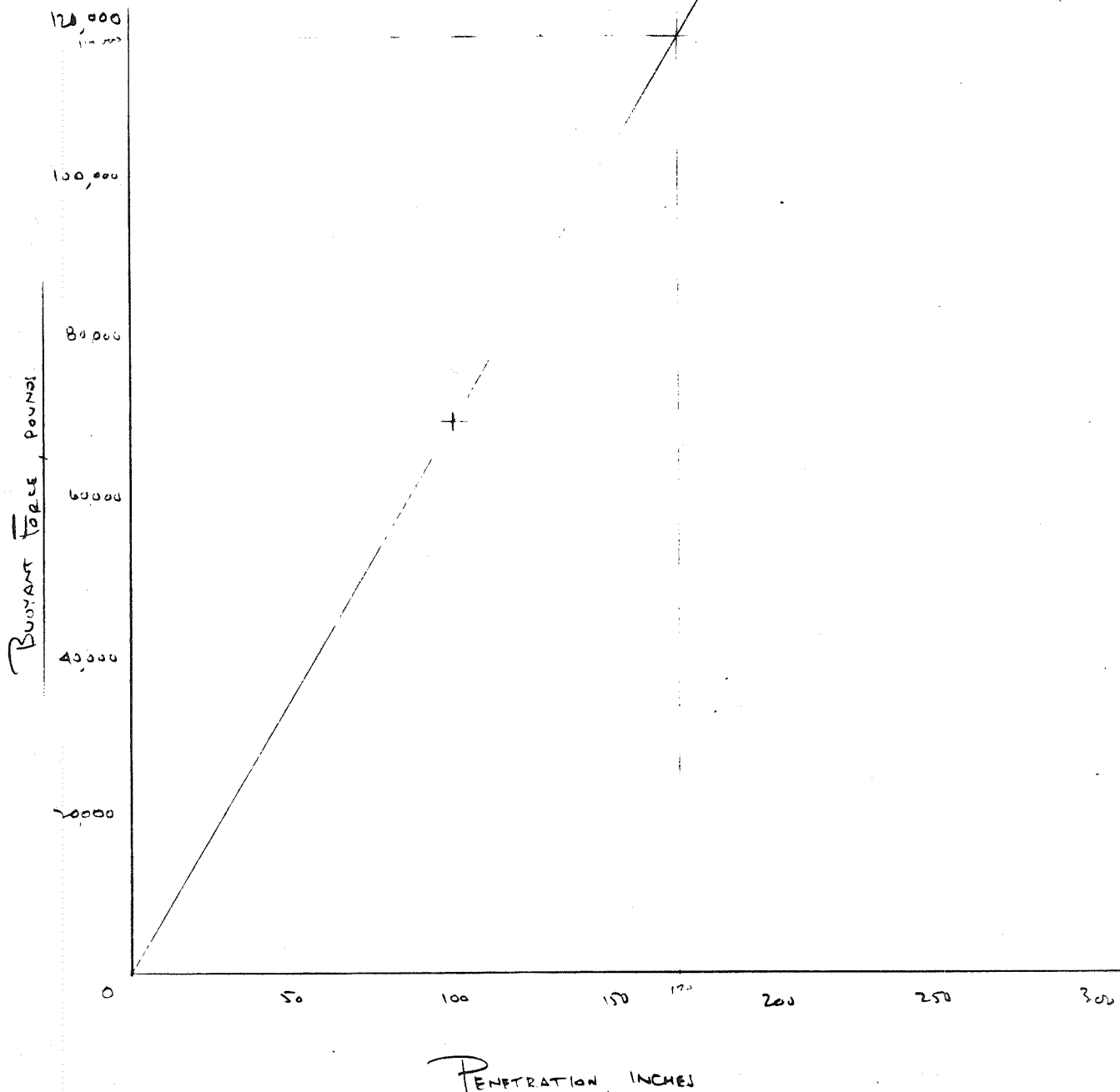
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ANALYSIS:

CASE I - VERTICAL MOTION





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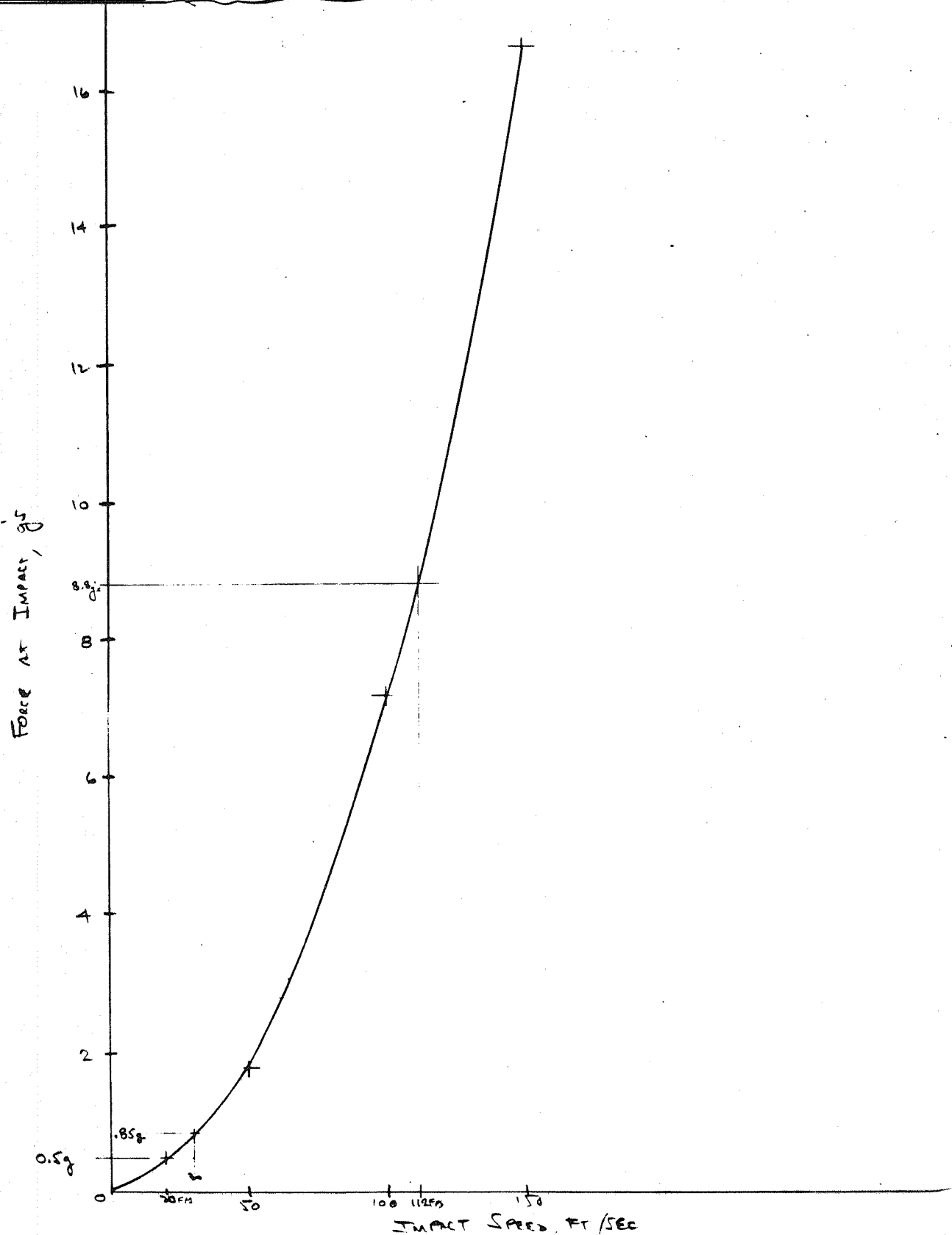
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ANALYSIS: CASE I - Vertical Motion





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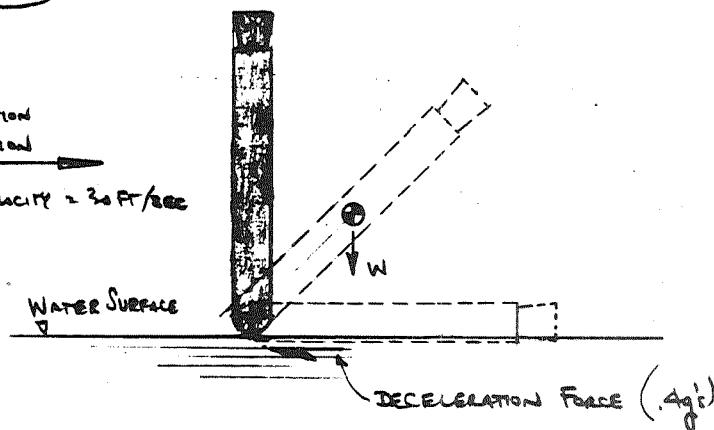
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ANALYSIS : **CASE I - HORIZONTAL MOTION****EVENT SEQUENCE :**

- 1) CONTACT WATER SURFACE @ 30 FT/SECOND
- 2) DOME DECELERATES, IMPARTING INITIAL ANGULAR ACCELERATION (ω_0)
- 3) SRM CONTINUES TO ROTATE ABOUT FWD DOME.
- 4) SRM CONTACTS WATER SURFACE IN HORIZONTAL ATTITUDE.
- 5) SRM DECELERATES BY DISPLACEMENT.

DIRECTION
OF MOTION

VELOCITY = 30 FT/SEC

**ANALYTICAL SEQUENCE :**

- 1) DETERMINE LATERAL DECELERATION CHARACTERISTICS (A FUNCTION OF PENETRATION DEPTH AND VELOCITY).
- 2) DETERMINE INITIAL ANGULAR VELOCITY OF SRM (RESULTING FROM DECELERATION OF IMMERSED PORTION).
- 3) DETERMINE ANGULAR VELOCITY OF SRM AT WATER IMPACT.
- 4) DETERMINE ANGULAR DECELERATION AT WATER IMPACT.
- 5) DETERMINE DECELERATION PRESSURE ON SRM CASE.
- 6) EVALUATE RESULTANT EFFECTS ON SRM CASE.



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ANALYSIS :CASE I - HORIZONTAL MOTIONDETERMINE INITIAL ANGULAR VELOCITY (ω_0) RESULTING FROM 0.85g DECELERATION AT FWD END :

PENETRATION: FULL

INITIAL VELOCITY = 30 FT/SEC

FINAL VELOCITY = 0 (AT IMMERSED END)

DECELERATION FORCE = .85g @ 30 FT/SEC (FROM PAGES)

NOTE: THE .85g IS BASED ON THE CROSS-SECTIONAL AREA OF THE CYLINDER. THE PENETRATION DUE TO VERTICAL MOTION STABILIZES AT A DEPTH OF TWO DIAMETERS, HENCE THE DECELERATION FORCE IS ABOUT 2(.85) OR 1.70 g's AND GOES TO ZERO WHEN THE TANGENTIAL VELOCITY (DUE TO ANGULAR ROTATION OF THE SRM) NEARLY OR EQUALS THE FORWARD VELOCITY OF THE SRM.

DETERMINE TIME/VELOCITY CHARACTERISTICS OF SRM ROTATION:

$$I_{END} = \frac{ML^2}{3} = \frac{WL^2}{3g} = \frac{117,000 (1200)^2}{3 (386)} = \frac{117,000 (1200)^2}{3 (386)}$$

APPLY EQUATION (3), P. 256, DATA SOURCE 2:

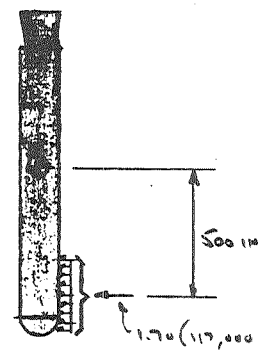
$$N = I\alpha ; \alpha = \frac{N}{I}$$

$$\alpha = \frac{1.70 (117,000) (500)}{\frac{117,000 (1200)^2}{3 (386)}} = \frac{1.70 (500) (3) (386)}{(1200)^2} = \frac{985,000}{1,440,000} = 0.684 \text{ RAD/SEC}^2$$

$$\text{FORWARD END VELOCITY} = V = 660 \left(\frac{\omega t^2}{2} \right) = 660 \left(\frac{\alpha t^2}{2} \right) = \frac{660 (0.684) t^2}{2} = 226 t^2$$

t	t ²	226 t ²
.1	.01	2 FT/SEC
.2	.04	9 FT/SEC
.3	.09	20 FT/SEC
.4	.16	36 FT/SEC

NOTE: THE ABOVE CALCULATION, BASED ON TWO DIAMETERS PENETRATION, INDICATES AN IMMERSED END DECELERATION TIME OF 0.4 SECONDS, HOWEVER, THE SRM CANNOT PENETRATE THE WATER TO A DEPTH OF TWO DIAMETERS IN THAT SHORT A TIME, THEREFORE, ANOTHER APPROXIMATION BASED ON A DEEPER PENETRATION IS IN ORDER.



$$\begin{array}{r} 1200 \times 600 \\ + 600 \\ 600 \\ - 1200 \\ \hline 500 \end{array}$$



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ANALYSIS : CASE I - HORIZONTAL MOTIONSECOND APPROXIMATION OF ω_0 (SEE PAGE 7) :

PENETRATION : ONE DIAMETER OR LESS

INITIAL VELOCITY : 30 FT/SEC

FINAL VELOCITY : 0 (AT IMMERSED END)

DECELERATION FORCE = $0.85g @ 30 \text{ FT/SEC}$ (FROM PAGE 5)DETERMINE REVISED α (ANGULAR ACCELERATION OF SRM)

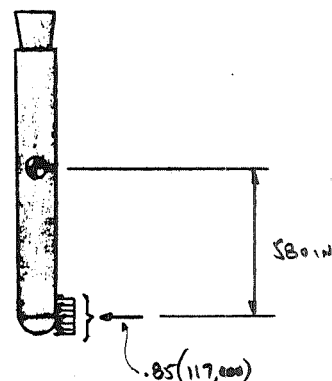
$$N = I \alpha$$

$$\alpha = \frac{N}{I} = \frac{.85(117,000)(30)}{\frac{117,000(1200)}{3(386)}} = \frac{.85(580)(3)(30)}{1,240,000} = 0.396 \text{ RAD/SEC}^2$$

$$\begin{aligned} \text{FORWARD END VELOCITY} &= r \theta = 660(\omega_{AV} t) \\ &= 660\left(\frac{\alpha t^2}{2}\right) = \frac{660(.396)(t^2)}{2} = 131 t^2 \end{aligned}$$

t	t ²	131 t ²
.1	.01	1.3 FT/SEC
.2	.04	5 FT/SEC
.3	.09	12 FT/SEC
.4	.16	21 FT/SEC
.5	.25	33 FT/SEC

LIM 20



NOTE : THE TABULATION INDICATES THAT THE FORWARD IMMERSED END ACHIEVES ITS INITIAL ROTATION IN A SHORT TIME INTERVAL (LESS THAN $\frac{1}{2}$ SECOND) AND THEN TOPPLES DUE TO GRAVITY ATTRACTION. THIS MEANS THAT ANGULAR ACCELERATION (α) IS VERY HIGH FOR SUCH A SHORT TIME THAT THIS LOAD CONDITION CAN BE REDUCED TO A TOPPLING CONDITION WITH AN INITIAL ANGULAR VELOCITY (ω_0)



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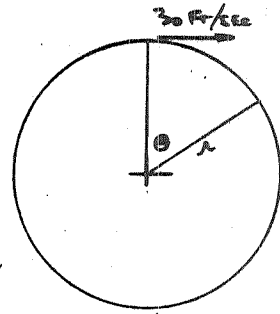
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ANALYSIS: Case I - Horizontal MotionKINEMATICS OF TOPPLING CONDITION WITH INITIAL TIP SPEED (FWD END) OF 30 FT/SECOND:DETERMINE INITIAL ANGULAR VELOCITY (ω_0):ONE RADIAN IN FEET = $R\theta = R \frac{\text{FEET}}{\text{RADIAN}}$

$$\omega_0 = \frac{\text{RADIAN}}{\text{SEC}} = \frac{\text{FEET/SECOND}}{\text{FEET/RADIAN}}$$

$$\omega_0 = \frac{30 \text{ FT/SEC}}{R \text{ FT/RAD}} = \frac{30 \text{ RAD/SEC}}{R} = \frac{30 \text{ RAD/SEC}}{\frac{1200}{12} \text{ FT}} = .545 \text{ RAD/SEC}$$



APPLY EXAMPLE 2, PAGE 257, DATA SOURCE 2:

ANGULAR VELOCITY $\frac{d\theta}{dt}$ AFTER FALLING THROUGH AN ANGLE θ
IS BASED ON THE RELATIONSHIP:

$$\frac{1}{2} \left(\frac{d\theta}{dt} \right)^2 = \frac{3g}{2l} (1 - \cos \theta) + \frac{1}{2} \omega_0^2$$

MULTIPLY BOTH SIDES BY 2

$$2 \left(\frac{1}{2} \left(\frac{d\theta}{dt} \right)^2 \right) = 2 \left[\frac{3g}{2l} (1 - \cos \theta) \right] + 2 \left[\frac{1}{2} \omega_0^2 \right]$$

$$(\omega_p)^2 = \left(\frac{d\theta}{dt} \right)^2 = \frac{3g}{l} (1 - \cos \theta) + \omega_0^2$$

$$\left(\text{For } \theta = 90^\circ, \cos \theta = 0 \right)$$

$$\omega_p = \left(\frac{d\theta}{dt} \right) = \sqrt{\frac{3g}{l} + \omega_0^2}$$

$$l = 1200 \text{ INCHES}$$

$$g = 386 \text{ INCHES/SEC}^2$$

$$\omega_0 = .545 \text{ RAD/SEC}^2$$

$$(\omega_0)^2 = .297$$

$$\omega_p = \sqrt{\frac{3(386)}{1200} + .297}$$

$$\begin{matrix} .905 \\ .297 \\ 1.262 \end{matrix}$$

$$\omega_p = 1.123 \text{ RAD/SEC}$$

AT END IMPACT VELOCITY AT HORIZONTAL IMPACT

$$= R \omega_p = 1200 (1.123) = 1350 \text{ INCHES/SECOND, OR } 112 \text{ FT/SECOND}$$

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ANALYSIS: CASE I

DETERMINE STRESS LEVELS AND SRM CHAMBER INTEGRITY:

CHAMBER:

WEIGHT = 117,000 LB

156 INCHES O.D.

t = .45 MIN

155.1 INCHES I.D.

I = 13,549,279 IN⁴

A = 21,991 IN²

AXIAL LOAD AT 20 FT/SEC VERTICAL IMPACT = 0.5g (117,000)

$$\text{AXIAL COMPRESSION STRESS AT 20 FT/SEC IMPACT} = \frac{\text{LOAD}}{\text{AREA}} = \frac{.5(117,000)}{21,991} = 2700 \text{ LB/IN}^2 \text{ LOW}$$

M.S. = + HIGH

NOTE: AXIAL BUCKLING IS HIGH BY COMPARISON WITH DATA SOURCE 3, PAGE 1.

LATERAL LOAD AT 30 FT/SEC HORIZONTAL IMPACT = 0.85g (117,000)

$$\text{BENDING STRESS AT 30 FT/SEC IMPACT} = \frac{Mc}{I} = \frac{.85(117,000)(580)(78)}{13,549,279} = 400 \text{ LB/IN}^2 \text{ LOW}$$

M.S. = + HIGH

MEMBRANE EXTERNAL PRESSURE STRESS: @ MAX PENETRATION OF 319 INCHES

$$P_{\text{EXTERNAL}} = (\text{DENSITY})(\text{PENETRATION}) = (.0361)(319) = 11.52 \text{ LB/IN}^2$$

$$f_c = \frac{P_n}{t} = \frac{11.52(78)}{.45} = 2000 \text{ LB/IN}^2 \text{ M.S.} = + \text{HIGH}$$

APPLY CASE Q.31, P.354, DATA SOURCE 4:

$$P_{\text{CRITICAL}} = .807 \frac{Et^2}{L^2} \sqrt{\left(\frac{1}{1-\nu^2}\right)^3 \frac{1}{12}}$$

$$= \frac{.867 E t^{2.5}}{L^{1.5}}$$

$$= \frac{.867 (29,000,000) (.136)}{160 (680)}$$

$$= 31.5 \text{ LB/IN}^2$$

$$f_c = \frac{P_n}{t} = \frac{31.5(78)}{.45} = 5500 \text{ LB/IN}^2$$

$$\text{M.S.} = \frac{31.5}{11.5} - 1 = +1.74$$

M.S. COMP STRESS = + HIGH

E = 29,000,000

$\nu = .3$

t = .45

$t^{2.5} = .136$

L = 78

$L^{1.5} = 680$

L = 160



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ANALYSIS: CASE I

DETERMINE STRESS LEVELS AND SRM CHAMBER INTEGRITY - CONTINUED:

LATERAL EXTERNAL PRESSURE LOAD @ 30 FT/SEC HORIZONTAL IMPACT:

COMPARE COSINE PRESSURE DISTRIBUTION TO CRITICAL BUCKLING PRESSURE (P_{cr})

↓
LOAD CONDITION 18,
DATA SOURCE 5

FROM PAGE 10

$$P_{max} = \frac{W}{2l_{eff}} = \frac{.5(117,000)}{78(156)} = 4.8 \text{ LB/IN}^2 \text{ LOW.}$$

$$M.S. = \frac{31.5}{4.8} - 1 = + \text{ HIGH}$$



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ANALYSIS:

CASE I

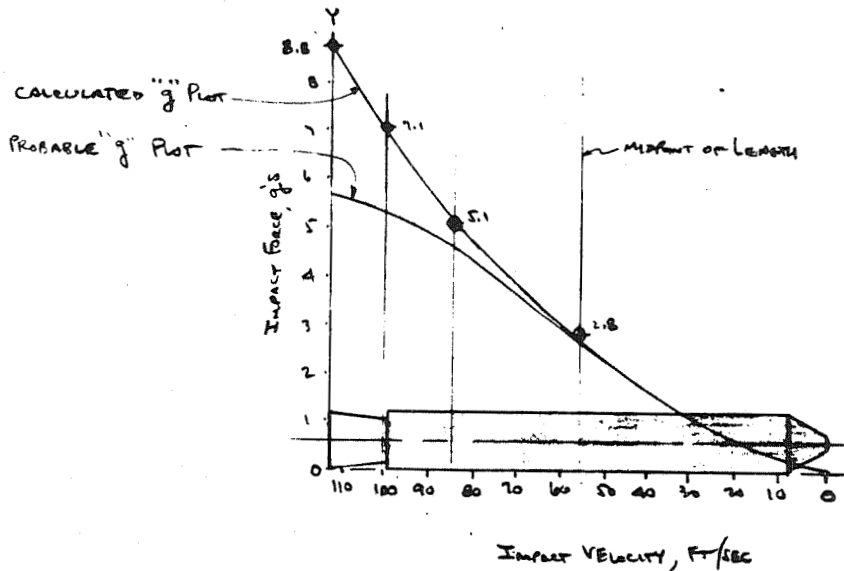
DETERMINE STRESS LEVELS AND SRM CHAMBER INTEGRITY - CONTINUED:

LATERAL EXTERNAL PRESSURE LOAD @ 112 FT/SEC TOPPLING IMPACT:

COMPARE COSINE PRESSURE DISTRIBUTION TO CRITICAL BUCKLING PRESSURE (P_{cr}):

↳ Load Condition 20, DATA SOURCE 5

↳ FROM PAGE 10



Plot of g loading vs Length

BASED ON NOZZLE IMPACT VELOCITY OF 112 FT/SEC

FROM THE ABOVE PLOT:

CONSIDER $g_{EQUIVALENT} = 6.0g's$ ACTING OVER A 300 INCH PORTION OF SRM CHAMBER.

THEN, COMPARE COSINE PRESSURE DISTRIBUTION TO CRITICAL BUCKLING PRESSURE (P_{cr}):

$$\text{CALCULATED } P_{MAX} = \frac{W}{n L_{EFF}} = \frac{6.0 (117,000)}{78 (300)} = 30 \text{ LB/IN}^2 \quad M.S. = \frac{31.5}{30} - 1.0 = +0.05$$

$$\text{PROBABLE } P_{MAX} = \frac{4.5}{6.0} 30 = 22.5 \text{ LB/IN}^2$$

$$M.S. = \frac{31.5}{22.5} - 1.0 = +0.40$$



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SUMMARY OF RESULTS — TABULATION: CASE IVERTICAL ENTRY ATTITUDE:LOAD CONDITIONS:

- ① VERTICAL IMPACT @ 20 FT/SEC ; VERTICAL VELOCITY VECTOR.
- ② LATERAL IMPACT @ 30 FT/SEC ; HORIZONTAL VELOCITY VECTOR.
- ③ PENETRATION AFTER IMPACT ; VERTICAL VELOCITY VECTOR.
- ④ TOPPLING FROM VERTICAL ATTITUDE TO HORIZONTAL ATTITUDE AFTER IMPACT ; VERTICAL AND HORIZONTAL VELOCITY VECTORS.
- ⑤ COMBINATION OF ① AND ②.

LOAD CONDITION	METHOD OF EVALUATION		MARGIN OF SAFETY	
	UNIT STRESS LEVEL	BUCKLING CAPABILITY	UNIT STRESS LEVEL	BUCKLING CAPABILITY
①	✓	✓	+ HIGH	+ HIGH
②	✓	✓	+ HIGH	+ HIGH
③	✓	✓	+ HIGH	+1.74
④	✓	✓	+ HIGH	+0.05 ↔ +0.40
⑤	✓	✓	+ HIGH	+ HIGH

NOTE: FOR DISCUSSION OF RESULTS — SEE PAGE 14.



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SUMMARY OF RESULTS - DISCUSSION : CASE I

LOAD CONDITION (4) - TOPPLING :

THIS IS THE CRITICAL LOAD CONDITION, FOR WHICH THE MARGINS OF SAFETY AS TABULATED ON PAGE 13 ARE CONSIDERED CONSERVATIVE FOR THE FOLLOWING REASONS:

- a) THE SRM CHAMBER DOES NOT TOPPLE BY ROTATION ABOUT THE FORWARD TIP, AS ANALYTICALLY CONSIDERED, BUT ABOUT A POINT LOCATED SOME 300 INCHES AFT OF THE NOSE, BECAUSE THE CHAMBER REACHES FULL PENETRATION INTO THE WATER DURING TOPPLING, THUS REDUCING THE EFFECTIVE LENGTH OF ROTATION AND REDUCING THE EXTREME END IMPACT VELOCITY AS WELL.
- b. THE SRM CHAMBER DOES NOT IMPACT IN A TRUE HORIZONTAL ATTITUDE AT FULL LENGTH WATER CONTACT, BUT AT AN ANGLE OF ABOUT 10° TO THE HORIZONTAL, THUS DISTRIBUTING THE DECELERATION PRESSURE OVER A LONGER EFFECTIVE PORTION OF THE CHAMBER LENGTH THAN THE ANALYTICALLY CONSIDERED 300 INCHES.



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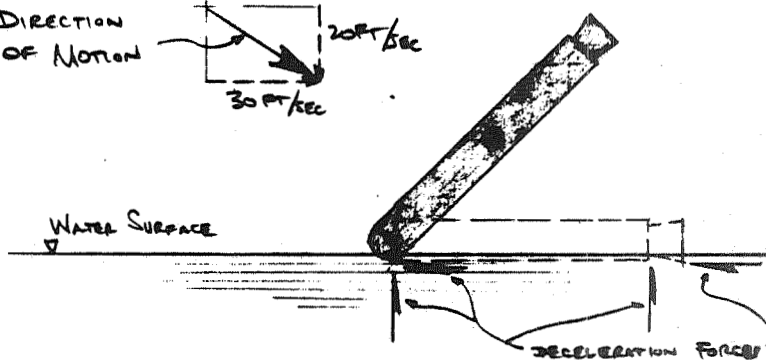
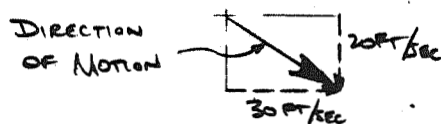
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ANALYSIS: CASE IIDISCUSSION:

THE CRITICAL LOAD ON THE SRM IS THE "SLAP-DOWN" IMPACT IN THE HORIZONTAL POSITION, WITH THE NOSE SECTION IN A TRAILING POSITION AT THE TIME OF IMPACT.

EVENT SEQUENCE:

- 1) CONTACT WITH WATER SURFACE; INITIAL ANGULAR VELOCITY (ω_0) CORRESPONDING TO END VELOCITY OF 20 FEET/SECOND.
- 2) ROTATION ABOUT FORWARD END, WITH INCREASING ANGULAR VELOCITY DUE TO GRAVITY
- 3) CONTACT WATER IN HORIZONTAL ATTITUDE.
- 4) SRM DECELERATES DUE TO DISPLACEMENT.

ANALYTICAL SEQUENCE:

- 1) ESTABLISH INITIAL ANGULAR VELOCITY (ω_0) OF SRM.
- 2) DETERMINE ANGULAR VELOCITY OF SRM AT "SLAP-DOWN".
- 3) DETERMINE DECELERATION PRESSURE ON SRM CASE.
- 4) EVALUATE RESULTANT EFFECTS ON SRM CASE.



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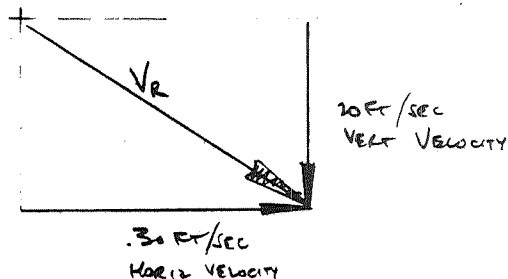
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ANALYSIS: CASE IIDETERMINE INITIAL ANGULAR VELOCITY ω_0 :

$$\text{RESULTANT VELOCITY} = V_R = \sqrt{20^2 + 30^2} = \sqrt{1300} = 36 \text{ FT/SEC}$$

NOTE: CONSIDERING THAT THE SRM CHAMBER RAPIDLY ACHIEVES A TIP VELOCITY EQUAL TO V_R ,



$$\left. \begin{array}{l} \text{REF} \\ \text{P. 9} \end{array} \right\} \omega_0 = \frac{\text{RADIANS/SEC}}{\text{FEET/RADIAN}} = \frac{\text{FEET/SECOND}}{\text{FEET/RADIAN}}$$

$$= \frac{36 \text{ FT/SEC}}{2 \text{ FT/RADIAN}} = \frac{36}{2} \text{ RAD/SEC} = \frac{36}{660} = \frac{36}{12} = .655 \text{ RAD/SEC}$$

APPLY EXAMPLE 2, PAGE 259, DATA SOURCE 2:ANGULAR VELOCITY (ω_f) AS DERIVED ON PAGE 9 OF CALCULATIONS:

$$\omega_f^2 = \frac{3g}{L} (1 - \cos \theta) + \omega_0^2$$

$$\omega_f = \sqrt{\frac{3g}{L} (1 - \cos \theta) + \omega_0^2}$$

$$\omega_f = \sqrt{\frac{3(386)(.293)}{1200} + .428}$$

$$\omega_f = \sqrt{.711} = .843 \text{ RAD/SEC}$$

$$\text{FOR } \theta = 45^\circ$$

$$\cos \theta = .707$$

$$(1 - \cos \theta) = .293$$

$$g = 32.2 \text{ FT/SEC}^2 = 386 \text{ IN/SEC}^2$$

$$\omega_0 = .655 \text{ RAD/SEC}^2$$

$$\omega_0^2 = .428$$

NOTE: BY COMPARISON, ω_f (AND THE CORRESPONDING IMPACT VELOCITY) WILL BE LESS THAN THAT AS CALCULATED ON PAGE 9, THEREFORE THIS LOAD CONDITION IS NON-CRITICAL