Fermilab

Particle Physics Division
Mechanical Department Engineering Note

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Project: NOvA

Title: Block Pivoter Hydraulic Cylinder Loads

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Reviewer(s):

Key Words: NOvA, Block Raiser, Block Pivot Table, Hydraulic Cylinder

Abstract Summary:

The NOvA Block Pivoter uses two long hydraulic cylinders to control the table rotation. This engineering note calculates the hydraulic cylinder loads for the three loading conditions; Pivoter table empty; Pivoter table loaded with a pallet; and Pivoter table loaded with a pallet and 31 plane PVC detector block.

Cylinder loads are calculated for table rotation from horizontal to vertical in 5 degree increments.

These loads will be used as the specification basis when purchasing the hydraulic cylinders.

Applicable Codes: not applicable. This note only calculates loads.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	**Dave Pushka's Block Raiser (Pivoter) Calculations for lowering scheme April 2009**												
2	**Detector Block Weights and Dimensions and Loads to Table:**												
3	Weight of a PVC Block (empty) Nominal	321,117	pounds	160.6	tons (short)								
4	Weight of a PVC Block (empty) minimal	268,351	pounds	134.2	tons (short)								
5	Weight of a PVC Block (empty) maximum	394,828	pounds	197.4	tons (short)								
6	Weight of a block Used for Calculations below	394,828	pounds	197.4	tons (short)								
7	Nominal Thickness of a block	2053.6	millimeters	80.85	inches								
8	Nominal H or W of a Block	15.748	m	620	in	51.6666667	ft						
9	Volume of Block	17,985	ft3			51.6666667							
10	Apparent Density of Empty Block	22.0	#/ft3										
11	Block loading on table when horizontal	147.91	#/square foot										
12													
13	**Geometry of Block relative to Table Pivot:**												
14	Weight of a block Used for Calculations below	394,828	pounds	Assume to be the maximum weight of the PVC block calculated from the extrusion weights based on mechanical tolerances									
15	Distance from table top to pivot (vertical direction when table horizontal)	8	inches	positive means that the pivot is below the top surface of the table when the table is horizontal									
16	Vertical Distance from pivot to block c.g when table is horizontal	48.425	inches	equals half the thickness of a block plus the goal distance from the table top to the pivot shown right above									
17	Horizontal Distance from Pivot to block c.g. when table is horizontal (positive number is toward the forks)	-16.000	inches	zero undicates that the pivot is right under the block c.g., positive means that the pivot is towards the forks									
18	Moments Generated by the Block Weight on the Table When Table is Vertical:	19,119,615	in-lbs	Vertical Distance (B16) to block c.g. times the Block weight (B14)									
19	Moments Generated by the Block Weight on the Table When Table is Horizontal:	(6,317,245)	in-lbs	Horizontal Distance (B17) to block c.g. times the Block weight (B14)									
20													
21	**Geometry of Pallet relative to Table Pivot:**												
22	Weight of the Pallet Nominal	12,000	pounds	Pallet weight comes from the Ideas Solid Model of the pallet									
23	Distance from Pallet surfact to Pallet c.g.	3	inches	Pallet c.g. location relative to surface taken from the Ideas 3D model of the pallet									
24	Vertical Distance from pivot to block c.g when table is horizontal	48.425	inches	assumed same as the distance for the PVC block calculated above									
25	Horizontal Distance from Pivot to pallet c.g. when table is horizontal (positive number is toward the forks)	297.000	inches	zero undicates that the pivot is right under the block c.g., positive means that the pivot is towards the forks									
26	Moments Generated by the Pallet Weight on the Table When Table is Vertical:	581,102	in-lbs	Vertical Distance (B24) to Pallet c.g. times the Pallet weight (B22)									
27	Moments Generated by the Pallet Weight on the Table When Table is Horizontal:	3,564,000	in-lbs	Horizontal Distance (B25) to Pallet c.g. times the Pallet weight (B22)									
28													
29	**Geometry of Table relative to Table Pivot:**												
30	Weight of Table, Nominal	137,038	pounds	calculated by taking the FHEP table weight from Ideas solid and multipling by 6 to get full table width.									
31	Vertical Distance from pivot to table c.g when table is horizontal	-16.140	inches	negative means the c.g. is below the pivot elevation when table is horizontal									
32	Horizontal Distance from Pivot to table c.g. when table is horizontal (positive number is toward the forks)	69.000	inches	zero undicates that the pivot is right under the block c.g., positive means that the pivot is towards the forks									
33	Moments Generated by the Table Weight on the Table When Table is Vertical:	(2,211,787)	in-lbs	Vertical Distance (B31) to Table c.g. times the Table weight (B30)									
34	Moments Generated by the Table Weight on the Table When Table is Horizontal:	9,455,594	in-lbs	Horizontal Distance (B32) to Table c.g. times the Table weight (B30)									
35													

	A	B	C	D	E	F	G	H	I	J	K	L	M
36	**Combined PVC Block and Pallet Moments:**												
37	Weight of PVC Block and Pallet	406,828	pounds	Sum of cells B14 + B22 to sum the weight									
38	Moments Generated by the Block + Pallet Weight on the Table When Table is Vertical:	19,700,718	in-lbs	Sum of cells B18 + B26 to sum the Moment									
39	Moments Generated by the Block + Pallet Weight on the Table When Table is Horizontal:	(2,753,245)	in-lbs	Sum of cells B19 + B27 to sum the Moment									
40													
41	**Combined Table, PVC Block and Pallet Moments:**												
42	Weight of Table, PVC Block and Pallet	543,865	pounds	Sum of cells B14 + B22 + B30 to sum the weight									
43	Moments Generated by the Block + Pallet + Table Weight on the Table When Table is Vertical:	17,488,931	in-lbs	Sum of cells B18 + B26 + B33 to sum the Moment									
44	Moments Generated by the Block + Pallet + Table Weight on the Table When Table is Horizontal:	6,702,349	in-lbs	Sum of cells B19 + B27 + B34 to sum the Moment									
45													
46	**Location of Combined C.G. values for Table, PVC Block and Pallet:**												
47	Vertical Distance for C.G. ofTable, PVC Block and Pallet	32.157	inches	Calculated by dividing the sum of the moments (B43) by the Combined weight (B42)									
48	Horizontal Distance for c.g. of Table, PVC Block and Pallet	12.324	inches	Calculated by dividing the sum of the moments (B44) by the Combined weight (B42)									
49													
50	**Cylinder, Pivot, and Anchor Locations:**												
51	Horizontal distance (when table is horz) from pivot to cylinder connection	208.000	inches	labled as distance "x" on sketch 1									
52	Vertical distance (when table is horz) from pivot to cylinder connection	60.000	inches	labled as distance "y" on sketch 1									
53	Horizontal distance from pivot to cylinder stationary connection	132.000	inches	labled as distance "u" on sketch 1									
54	Vertical distance from pivot to cylinder stationary connection	208.000	inches	labled as distance "v" on sketch 1									
55													
56													
57	**Cylinder Distances when table Horizontal:**												
58	horizontal length	340.000	inches	Sum of Horizontal distances (B51) + (B53)									
59	vertical length	148.000	inches	Change in Vertical disances (B54) - (B52)									
60	Overall length	370.815	inches	square of the sum of the squares of (B58) and (B59)									
61	Angle of Cylinder above horizontal	0.4106	radians	calculated using the inverse tangent of (B59) over (B58)									
62	Angle of Cylinder above horizontal	23.52	degrees	(B61) converted to degrees									
63													
64	**Cylinder Loads with Table Horizontal:**												
65	Moment to counter	6,702,349	in-lbs	Moment is due to Block + Pallet + Table and is equal to the value calculated in (B44)									
66	Lever arm pivot to cylinder connection	208	in	Value from (B51)									
67	Vertical Component of Cylinder Force	32,223	lbs	(B65) divided by (B66)									
68	Horizontal Component of Cylinder Force	74,025	lbs	Square root of the sum of the squared = sqrt((B69)^2 - (B67)^2)									
69	Axial component of cylinder force	80,735	lbs	Calculated by (B67)/sin(B61)									
70													

	A	B	C	D	E	F	G	H	I	J	K	L	M
71	**Cylinder Loads with Table Vertical**												
72	Moment to counter	17,488,931	in-lbs	Moment is due to Block + Pallet + Table and is equal to the value in cell (B43)									
73	Lever arm pivot to cylinder connection	208	in	Value from (B54)									
74	Horizontal Component of Cylinder Force	84,081	lbs	Calculated by (B72)/ (B73); Cylinder axis is horzontal at this condition									
75													
76	**Cylinder Loads with Table Vertical**												
77	Moment to counter	(2,211,787)	in-lbs	Moment is due to Table and equals the value in cell (B33)									
78	Lever arm pivot to cylinder connection	208	in	Value from (B54)									
79	Horizontal Component of Cylinder Force	(10,634)	lbs	Calculated by (B77)/ (B78); Cylinder axis is horzontal at this condition									
80													
81													
82	**Geometry Calculations:**												
83	Length "a"	246.349	inches	this is the distance from the pivot to the stationary pin for the cylinder; calculated using the Pythagorean theorem									
84	Length "b"	216.480946	inches	this is the distance from the pivot to the table mounted (moving) pin for the cylinder; calculated using the Pythagorean theorem									
85	Length "c" (initial)	370.8153179	inches	this is the length of the cylinder when extended to put the table surface horizontal cylinder open length; calculated using the law of cosines									
86	length "c" (final)	72.000	inches	this is the length of the cylinder when the table is vertical, cylinder closed length; calculated using the Pythagorean theorem									
87	Angle 'phi' φ (constant)	16.09081635	degrees	angle below horizontal from table pivot to the table mounted (moving) pin for the cylinder; calculated using the Puthagorean theorem									
88	Angel 'alpha closed', α	106.091	degrees	angle alpha when the table is vertical; calculated using complementary angle with angle phi,φ									
89	Angle 'Theta closed' θ	16.30902383	degrees	angle theta when the table is vertical; calculated using the law of cosines									
90	Angle 'Theta open'	106.3090238	degrees	angle from table cylinder pivot, vertex at pivot, to cylinder stationary connection when the table is horizontal; calculated by adding 90 degrees (table rotation) to Theta closed, θ									
91	Angle 'alpha open' α	39.614	degrees	angle alpha when the table is horizontal; calculated using the law of cosines									
92	Angle 'Beta open' β	34.077	degrees	angle from cylinder moving pivot, vertiex at cyl stational pivot, to table pivot wne the table is horizontal; calculated using the sum of the triangle angles = 180									
93													
94													
95													

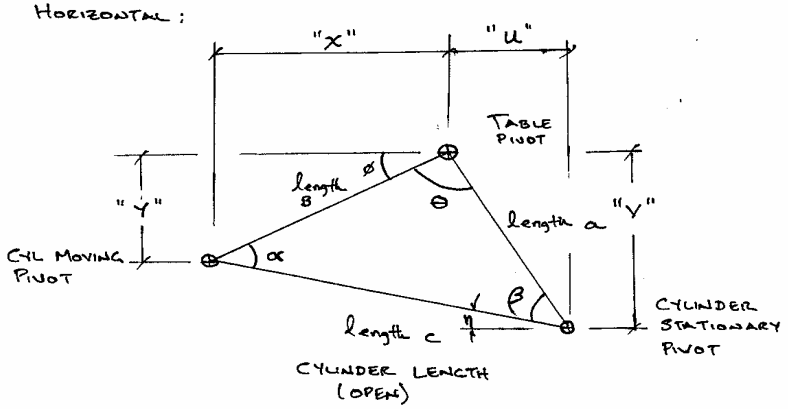
	A	B	C	D	E	F	G	H	I	J	K	L	M
96	**TABLE 1**	Weights calculated above used in					Table Wt	Pallet Wt	Block Wt				
97		calculating the Moments in the table					137,038	12,000	394,828				
98	Table angle relative to horizontal, rho ρ, in degrees	Angle Theta, θ	Cylinder Length	Angle Alpha, α	Angle Beta, β	Cylinder Angle above horizontal, η,	Table Moment	Pallet Moment	Block Moment	Sum of Moments from Table + Pallet	Sum of Moments from Table+Pallet +Block		
99		degrees	inches	degree	degree	degree	in-lbs	in-lbs	in-lbs	in-lbs	in-lbs		
100	0	106.309	370.82	39.614	34.077	23.52	9,455,594	3,564,000	(6,317,245)	13,019,594	6,702,349		
101	-5	101.309	358.42	42.374	36.317	21.28	9,226,843	3,601,084	(4,626,822)	12,827,927	8,201,105		
102	-10	96.309	345.36	45.153	38.538	19.06	8,927,870	3,610,762	(2,901,186)	12,538,632	9,637,446		
103	-15	91.309	331.65	47.955	40.736	16.86	8,560,950	3,592,960	(1,153,470)	12,153,910	11,000,441		
104	-20	86.309	317.31	50.783	42.908	14.69	8,128,877	3,547,813	603,025	11,676,690	12,279,715		
105	-25	81.309	302.38	53.643	45.048	12.55	7,634,937	3,475,665	2,354,930	11,110,603	13,465,533		
106	-30	76.309	286.89	56.541	47.150	10.45	7,082,892	3,377,066	4,088,913	10,459,957	14,548,870		
107	-35	71.309	270.87	59.486	49.205	8.40	6,476,941	3,252,765	5,791,776	9,729,705	15,521,482		
108	-40	66.309	254.35	62.487	51.204	6.40	5,821,696	3,103,708	7,450,561	8,925,404	16,375,965		
109	-45	61.309	237.37	65.560	53.131	4.47	5,122,145	2,931,030	9,052,643	8,053,175	17,105,818		
110	-50	56.309	219.97	68.721	54.970	2.63	4,383,612	2,736,045	10,585,828	7,119,657	17,705,485		
111	-55	51.309	202.18	71.998	56.693	0.91	3,611,716	2,520,238	12,038,449	6,131,954	18,170,403		
112	-60	46.309	184.05	75.427	58.264	-0.66	2,812,334	2,285,249	13,399,450	5,097,583	18,497,033		
113	-65	41.309	165.63	79.060	59.631	-2.03	1,991,547	2,032,869	14,658,473	4,024,416	18,682,889		
114	-70	36.309	146.98	82.979	60.711	-3.11	1,155,604	1,765,017	15,805,936	2,920,621	18,726,558		
115	-75	31.309	128.16	87.314	61.377	-3.78	310,866	1,483,733	16,833,107	1,794,599	18,627,706		
116	-80	26.309	109.27	92.282	61.409	-3.81	(536,238)	1,191,156	17,732,167	654,918	18,387,085		
117	-85	21.309	90.47	98.279	60.412	-2.81	(1,379,261)	889,514	18,496,275	(489,747)	18,006,528		
118	-90	16.309	72.00	106.091	57.600	0.00	(2,211,787)	581,102	19,119,615	(1,630,685)	17,488,931		
119													
120	Angle Theta, θ for the initial condition of 0 degrees rotation comes from the value calculated in cell (B90), subsequent values are calculated by adding the angle rho (ρ) from this initial value												
121	Cylinder Length is calculated using the law of cosines (same as above for cell B85) but using the current value of angle theta θ in column B												
122	Angle Alpha, α is calculated using the law of cosines (same as above for cell B89) but using the current value of cylinder length in column C												
123	Angle Beta, β is calculated by subtraction angle Alpha, α and angle Theta, θ from 180 degrees												
124	Cylinder Angle above horizontal, η, = arcsin((v-b*(sin(ρ + η))) / cylinder length)												
125	Table Moments are calculated by weight (in cell G97) * ((cell (B32)*cos (η) + cell (B31)* sin (η))												
126	Block Moments are calculated by weight (in cell H97) * ((cell (B25)*cos (η) + cell (B24)* sin (η))												
127	Pallet Moments are calculated by weight (in cell I97) * ((cell (B17)*cos (η) + cell (B16)* sin (η))												
128	Sum of Moments from Table + Pallet is the sum of value in column G + value in column H												
129	Sum of Moments from Table + Pallet + Block is the sum of value in column G + value in column H + value in column I												
130													

	A	B	C	D	E	F	G	H	I	J	K	L	M
131	**TABLE 2:**												
132	Table angle relative to horizontal, rho ρ, in degrees	combined cylinder normal load to counter act moment for T+P+B	combined Cylinder axial load, to counter act moment for T+P+B	individual cylinder load, to counter act moment for T+P+B	combined Cylinder normal load, to counter act moment for T+P	combined Cylinder axial load, to counter act moment for T+P	individual cylinder load, to counter act moment for T+P	combined Cylinder normal load, to counter act moment for Table only	combined Cylinder axial load, to counter act moment for Table only	individual cylinder load, to counter act moment for Table only	Cylinder Length, feet		
133		pounds	kips	kips	kips	kips	kips	kips	kips	kips	feet		
134	0	30,960	77.57	38.8	60,142	150.7	75	43,679	109	55	30.9		
135	-5	37,884	85.55	42.8	59,257	133.8	67	42,622	96	48	29.9		
136	-10	44,519	91.65	45.8	57,920	119.2	60	41,241	85	42	28.8		
137	-15	50,815	96.26	48.1	56,143	106.4	53	39,546	75	37	27.6		
138	-20	56,724	99.66	49.8	53,939	94.8	47	37,550	66	33	26.4		
139	-25	62,202	102.06	51.0	51,324	84.2	42	35,268	58	29	25.2		
140	-30	67,206	103.59	51.8	48,318	74.5	37	32,718	50	25	23.9		
141	-35	71,699	104.36	52.2	44,945	65.4	33	29,919	44	22	22.6		
142	-40	75,646	104.46	52.2	41,230	56.9	28	26,892	37	19	21.2		
143	-45	79,018	103.96	52.0	37,200	48.9	24	23,661	31	16	19.8		
144	-50	81,788	102.91	51.5	32,888	41.4	21	20,249	25	13	18.3		
145	-55	83,935	101.35	50.7	28,326	34.2	17	16,684	20	10	16.8		
146	-60	85,444	99.33	49.7	23,547	27.4	14	12,991	15	8	15.3		
147	-65	86,303	96.89	48.4	18,590	20.9	10	9,200	10	5	13.8		
148	-70	86,504	94.05	47.0	13,491	14.7	7	5,338	6	3	12.2		
149	-75	86,048	90.88	45.4	8,290	8.8	4	1,436	2	1	10.7		
150	-80	84,936	87.46	43.7	3,025	3.1	2	(2,477)	(3)	(1)	9.1		
151	-85	83,178	83.96	42.0	(2,262)	(2.3)	(1)	(6,371)	(6)	(3)	7.5		
152	-90	80,787	80.79	40.4	(7,533)	(7.5)	(4)	(10,217)	(10)	(5)	6.0		
153													
154													
155	combined cylinder normal load to counter act moments for T + P + B is the moment from column K in the table above * the cylinder to pivot lever arm (length b) from cell B84												
156	combined cylinder axial load, to counter act moment for T + P + B is calculated by dividing the value in cell B by the sin (ρ) and by 1000 to convert unit to kips												
157	individual cylinder load to counter act moment for T + P + B assume two cylinders equally share the load so this is the value of cell C divided by 2												
158	combined cylinder normal load to counter act moments for T + P is the moment from column J in the table above * the cylinder to pivot lever arm (length b) from cell B84												
159	combined cylinder axial load, to counter act moment for T + P is calculated by dividing the value in cell B by the sin (ρ) and by 1000 to convert unit to kips												
160	individual cylinder load to counter act moment for T + P assume two cylinders equally share the load so this is the value of cell C divided by 2												
161	combined cylinder normal load to counter act moments for Table only is the moment from column G in the table above * the cylinder to pivot lever arm (length b) from cell B84												
162	combined cylinder axial load, to counter act moment for Table only is calculated by dividing the value in cell B by the sin (ρ) and by 1000 to convert unit to kips												
163	individual cylinder load to counter act moment for Table assume two cylinders equally share the load so this is the value of cell C divided by 2												
164	Cylinder Length in feet is calculated by dividing the value in cell C in the above table (the cylinder length) by 12 to convert from inches to feet.												
165													
166													
167													

	A	B	C	D	E	F	G	H	I	J	K	L	M
168	**Maximum Reaction on Table Pivot, Cylinder Ends, assumes two cylinders sharing the total load and load from Table + Pallet + Block (T + P + B):**												
169	**TABLE 3**												
170	Table angle relative to horizontal, rho ρ, in degrees	Horizontal Load on stationary cylinder pivot, pounds	Vertical Load on stationary cylinder pivot, pounds	Horizontal Load on table pivot, pounds	Vertical Load on table pivot, pounds								
171													
172	0	35,563	15,480	(35,563)	256,452								
173	-5	39,859	15,527	(39,859)	256,406								
174	-10	43,311	14,966	(43,311)	256,967								
175	-15	46,059	13,962	(46,059)	257,971								
176	-20	48,201	12,638	(48,201)	259,294								
177	-25	49,809	11,090	(49,809)	260,843								
178	-30	50,934	9,395	(50,934)	262,538								
179	-35	51,622	7,618	(51,622)	264,314								
180	-40	51,907	5,819	(51,907)	266,114								
181	-45	51,824	4,050	(51,824)	267,882								
182	-50	51,402	2,362	(51,402)	269,571								
183	-55	50,671	803	(50,671)	271,130								
184	-60	49,664	(576)	(49,664)	272,508								
185	-65	48,413	(1,717)	(48,413)	273,649								
186	-70	46,957	(2,552)	(46,957)	274,485								
187	-75	45,344	(2,993)	(45,344)	274,926								
188	-80	43,636	(2,905)	(43,636)	274,838								
189	-85	41,928	(2,059)	(41,928)	273,992								
190	-90	40,394	(0)	(40,394)	271,933								
191													
192	Horizontal Load on Stationary Cylinder Pivot is calculated by multiplying the cylinder axial load (cells in column D in above table 2) by the COSINE of cylinder angle ρ in column F Table 1 above												
193	Vertical Load on Stationary Cylinder Pivot is calculated by multiplying the cylinder axial load (cells in column D in above table 2) by the SIN of cylinder angle ρ in column F Table 1 above												
194	Horizontal Load on the table pivot is calculaed by suming the forces in the horizontal direction and setting equal to zero, then solving for this value												
195	Vertical Load on the table pivot is calculaed by suming the forces in the vertical direction (including table, pallet and block weights) and setting equal to zero, then solving for this value												
196													

SKETCH 1 4-17-09 DAVE PUSHKA

GEOMETRY WHEN TABLE IS HORIZONTAL:



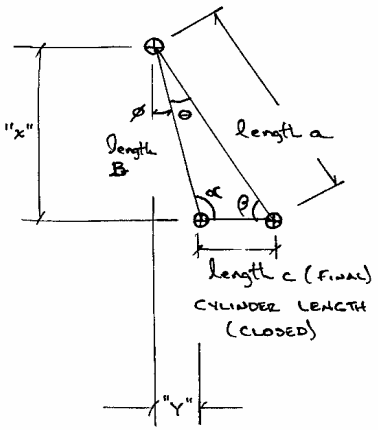
angle γ IS THE ANGLE OF THE CYLINDER ABOVE HORIZONTAL.

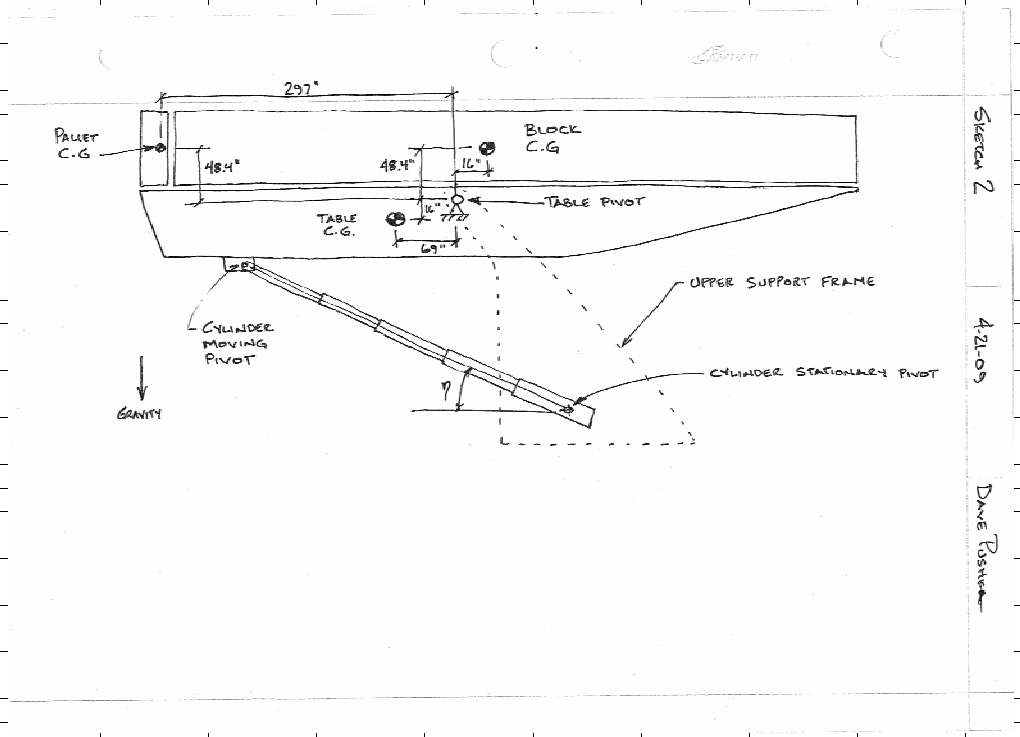
GEOMETRY WHEN TABLE IS VERTICAL:

length a IS CONSTANT

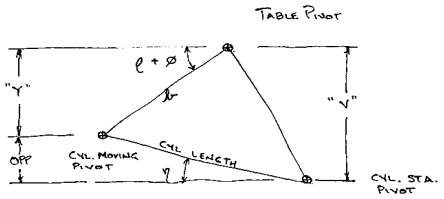
length B IS CONSTANT

$\alpha_{CLOSED} = 90 + \phi$




297"
PALLET C.G
48.4"
48.4"
BLOCK C.G
16"
TABLE PIVOT
TABLE C.G.
16"
77.7"
69"
UPPER SUPPORT FRAME
CYLINDER MOVING PIVOT
CYLINDER STATIONARY PIVOT
GRAVITY
SKETCH 2
4-21-09
DAVE PUSHKA

SKETCH 3 4-21-09 DAVE PUSHKA



CYLINDER ANGLE, η =

$$\sin\eta = \frac{OPP}{HYP} = \frac{OPP}{\text{CYLINDER LENGTH}}$$

OPP = LENGTH "V" − LENGTH "Y"

$\angle\phi$ = CONSTANT

$\angle\rho$ = TABLE ROTATION

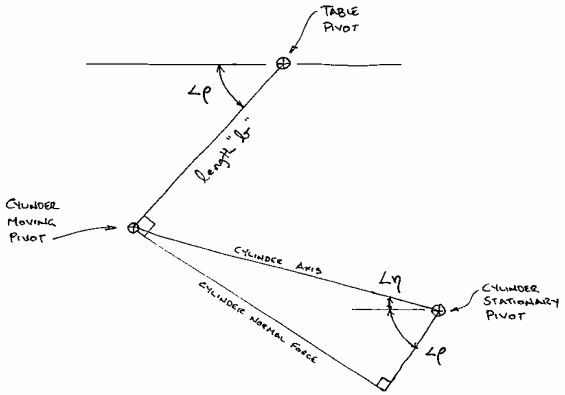
LENGTH "Y" = $l_T \sin(\phi+\rho)$

OPP = "V" − $l_T \sin(\phi+\rho)$

$$\sin\eta = \frac{V - l_T \sin(\phi+\rho)}{\text{CYL. LENGTH}}$$

$$\therefore \eta = \text{ARCSIN}\left(\frac{V - l_T \sin(\phi+\rho)}{\text{CYL. LENGTH}}\right)$$

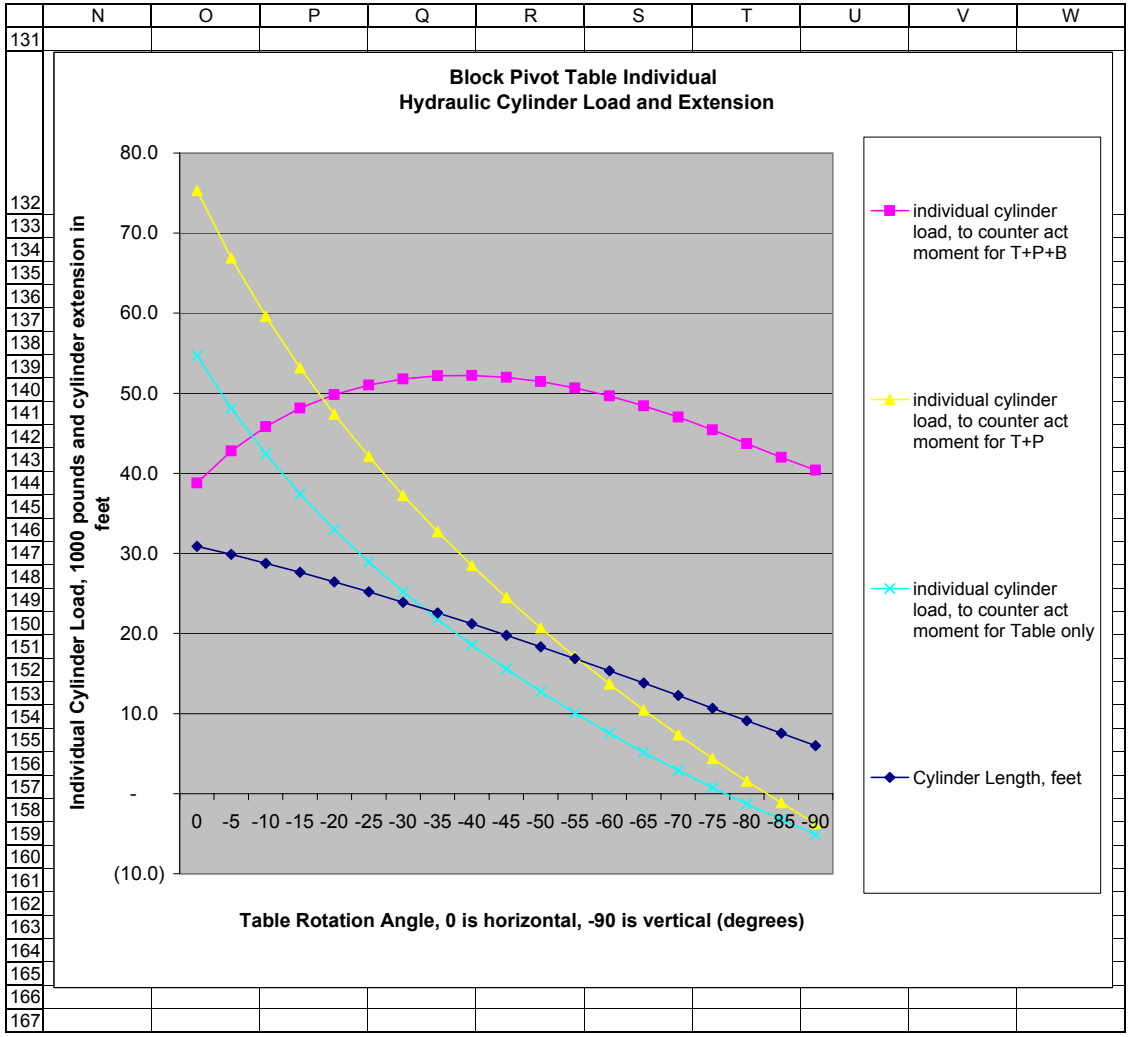
SKETCH #4 4-21-09 DAVE PUSHKA



$$\Sigma M_{\text{TABLE PIVOT}} = 0 = M_{\text{TABLE}} + M_{\text{PALLET}} + M_{\text{BLOCK}} - \text{"b"} \times (\text{CYL. NORMAL FORCE})$$

$$\therefore \text{CYLINDER NORMAL FORCE} = \frac{M_T + M_P + M_B}{\text{"b"}}$$

$$\text{CYLINDER AXIAL FORCE} = \frac{\text{CYLINDER NORMAL FORCE}}{\sin(\eta + \rho)}$$


Block Pivot Table Individual
Hydraulic Cylinder Load and Extension
Individual Cylinder Load, 1000 pounds and cylinder extension in feet
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
-
(10.0)
0 -5 -10 -15 -20 -25 -30 -35 -40 -45 -50 -55 -60 -65 -70 -75 -80 -85 -90
Table Rotation Angle, 0 is horizontal, -90 is vertical (degrees)
individual cylinder load, to counter act moment for T+P+B
individual cylinder load, to counter act moment for T+P
individual cylinder load, to counter act moment for Table only
Cylinder Length, feet

	N	O	P	Q	R	S	T	U	V	W
168										
169										
170										
171										
172										
173										
174										
175										
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