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Methodology Supporting Civil Works Implementation of Trunnion Rod Testing

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PURPOSE: The purpose of this Coastal and Hydraulics Engineering Technical Note (CHETN) is to provide guidance on the applicability of trunnion rod testing at navigation dams with Tainter gates.

BACKGROUND: The U.S. Army Corps of Engineers (USACE) operates and maintains several hundred steel Tainter (radial) gate control structures. Tainter gates must be reliably anchored to the dam structure to resist the hydrostatic and hydrodynamic forces required to control water spillage. Spillway gate failure may lead to downstream flooding and loss of dam pool. Either of these consequences may cause significant loss of life, damage to public and private property, damage to ecosystems, loss of hydropower availability, loss of local benefits associated with the water reservoir, and/or loss of river navigability.

Several projects across the Civil Works portfolio have observed trunnion anchor failures or decreased performance due to tension relaxation. Because they are embedded in concrete, trunnion rods cannot be visually inspected beyond the exposed ends. Loss of tension, flaws, and loss of section due to corrosion mechanisms are not visually detectable. Conventional lift-off testing is costly and may have safety concerns. Consequently, alternative methods have been developed. Dispersive-wave testing senses the tension in trunnion rods. Guided-wave testing senses damage in the rods. Together, they provide valuable insight into the state of a Tainter gate trunnion anchor. This document describes a risk-informed process by which USACE Civil Works navigation projects have been screened for the potential of trunnion rod testing to reduce risk.

METHODS

Trunnion Rod Testing Methods. Dispersive-wave propagation predicts the tension in post-tensioned trunnion rods. A transverse wave is induced at the end of the rod, and the frequencies of the rod's responses are related to the rod's tension (Holt et al. 2013). Thus, the rod's tension can be detected.

In contrast, guided-wave methods apply longitudinal acoustic waves (Evans and Haskins 2014, 2015). The high frequency of these waves allows them to travel long distances down the trunnion rod. Cracks orthogonal to the rod will affect the guided-waves and can be detected. Thus, damage, such as certain cracks or flaws and loss of section due to corrosion, may be detected.

Screening. Based on discussions with USACE subject-matter experts, spillway gates may pose more significant risk to navigability than other types of failure consequences. Therefore, only navigation dams are considered for testing in this effort.

All Tainter spillway gate subcomponents were extracted from the Asset Management Operational Risk Assessment (ORA) database, along with the corresponding District, project name, latest Operational Condition Assessment (OCA) ratings, all component and group ID numbers, and the assumed shipper-carrier costs associated with gate failure. These data were obtained through USACE Headquarters Asset Management.

Once the data were collected, gates and projects were removed from consideration that have $0 of shipper-carrier costs (SCC) or no recorded SCC value. The SCC values in the ORA tool are derived from the SSC model, which is updated annually by the Planning Center of Expertise for Inland Navigation. Also, to simplify computations, all OCA ratings with "+" or "-" were changed to the base rating (e.g., "B-" became "B"). Finally, due to an observation that there is a very short period of time, on average, between an "F" rating and "CF," all "CF" ratings were changed to "F."

Because trunnion rods are not visually observable, the anchorage condition for every gate was assumed to be uncertain, and both "B" and "D" conditions were modeled so that a range of risk could be explored, risk being the probability of failure times the consequence of failure. These bounds were chosen because (1) most rods are not new and thus are at best in "B" condition and (2) the computations assume the rods have not failed. Data suggest that there is very little time on average between "F" and "CF" ratings, implying that "F" ratings are practically failed for all intents and purposes. Therefore, "D" was chosen as the worse bound, not "F."

It was assumed that the probability of gate failure due to trunnion rod problems is described by a Weibull distribution with a shape parameter of 4.3 and a scale parameter of 91, corresponding to Curve #22 in the ORA tool. Curve #22 is in the ORA for dam gate anchorages. Each OCA rating was assumed to imply an effective age according to Table 1 below. For each of 10 years, the component was assumed to age by 1 year. The likelihood of failure, given the component is a certain age and has not failed up to that year, was computed using Bayes rule.

Table 1. Assumed gate age given OCA rating.

OCA Rating	Assumed Age in Years
B	43
D	80

For each project, and for each year from 1 to 10, the likelihood that at least one gate failed during that year was computed. Then, an event tree was constructed showing the likelihood of gates failing somewhere along the dam for each year. The SCC costs were used in this event tree, with a 3% discount rate for future years, to estimate the annual expected risk. Finally, the total risk was computed over the next 10-year period for each project. It was then assumed that rod testing allows proactive responses that completely prevent rod failure over the next 10 years, so the full expected consequence value was used as the risk buy-down for testing.

The costs of dispersive-wave testing were estimated at a base of $66,000 + ($26,500 per gate) + ($287 per rod). Based on data available from the USACE Risk Management Center on trunnion rod testing, an average of 92 rods are assumed per gate at every dam. This results in a cost estimate of a base \$66,000 + (\$52,904 per gate) for dispersive-wave testing. The costs of guided-wave testing were estimated at a base of \$2,500 + (\$2,160 per gate). Both testing types combined result in costs of \$68,500 + (\$55,064 per gate).

The net benefit from testing all greased trunnion rods at a project was computed as the 10-year risk of gates minus the testing costs. Projects that show a net benefit of over \$100,000 over 10 years are included on the list for testing. \$100,000 is considered a reasonable amount for procurement costs, overhead, and operation and maintenance labor. The exact numbers at a particular project should be estimated at the project level.

RESULTS: The described methodology is applied to 100 projects. To further clarify the process, the methodology is described in detail for the Dresden Island project.

Example Risk Computation. Dresden Island lock in USACE Rock Island District (MVR) has nine Tainter gates. Using ORA curve 22, with a shape parameter of 4.3 and a scale parameter of 91, the cumulative probability of failure for each gate was computed at each year, starting with those ages in Table 1 and increasing by 1 year each year for 10 years. Table 2 shows these values. The equation for the cumulative probability at age *x* of a Weibull distribution with these particular parameters is the following:

$$1 - e^{-\left(\frac{x}{85}\right)^{3.8}} \qquad (1)$$

Table 2. Cumulative probability of failure.

OCA B		OCA D	
Age	**Prob.**	**Age**	**Prob.**
43	0.039032	80	0.437102
44	0.042999	81	0.454574
45	0.047257	82	0.472196
46	0.051818	83	0.489937
47	0.056693	84	0.507765
48	0.061895	85	0.525646
49	0.067436	86	0.543547
50	0.073327	87	0.561433
51	0.079578	88	0.579268
52	0.0862	89	0.597018
53	0.093204	90	0.614648

Bayes rule was used to find the likelihood, in each year, that a gate with the assumed age fails, given that it has not failed previously. The equation used is the following:

$$\mathrm{P}\left[T \leq j+1 | T > j\right] = \frac{\mathrm{CDF}(j+1) - \mathrm{CDF}(j)}{1 - \mathrm{CDF}(j)} \tag{2}$$

where P is probability, T is the age of failure, j is the age at the beginning of the period of consideration, and CDF is the probability from the cumulative distribution function evaluated at age j. Table 3 shows these results for each OCA rating.

Table 3. Conditional probability of failure in each year given age and component currently operable.

Year	OCA B	OCA D
1	0.004128	0.031039
2	0.004449	0.032309
3	0.004787	0.033613
4	0.005142	0.034952
5	0.005515	0.036327
6	0.005906	0.037737
7	0.006316	0.039184
8	0.006746	0.040668
9	0.007195	0.042189
10	0.007665	0.043747

In each year, the likelihood that no gate fails was computed by assuming each gate failure is independent from the others. The equation used is the following:

$$p = \left(1 - p_{fi}\right)^{9} \tag{3}$$

where p is the likelihood that no gate fails in a particular year and p_{fi} is the likelihood that a gate with rating i will fail in that year. Table 4 shows the likelihood that no gate fails in each year, given that the nine gates have the particular initial OCA ratings mentioned above.

Table 4. Probability that no gate fails in each year.

Year	Prob. B	Prob. D
1	0.963452	0.752933
2	0.960663	0.744101
3	0.957734	0.735123
4	0.954663	0.726006
5	0.951447	0.716751
6	0.948083	0.707364
7	0.944568	0.697849
8	0.9409	0.68821
9	0.937077	0.678454
10	0.933095	0.668584

Table 5 depicts an event tree for 10 years, showing how the expected SCC was computed for each year for "B" condition rods. Using the tree to compute the expected SCC, the total risk of "B" condition rods was computed to be $873,119 over the next 10 years. "D" condition rods, similarly, were computed to have a 10-year risk of $2,214,640.

The costs of testing are $68,500 + ($55,064 × 9 gates) for a total of $564,076. The net benefit was computed by subtracting the testing cost from the risk. The final net benefit for Dresden Island is $309,043 for "B" condition rods and as much as $1,650,500 for "D" condition rods.

Screening Results. The described methodology's application to 100 projects is shown in Appendix A. The screening process yields 39 projects for which there is a net benefit for implementing trunnion rod testing.

Table 5. Expected value tree for 10 years of potential gate failures in condition "B."

Year	No failure (1-*p*)		Failure (*p*)	
	Prob.	SCC	Prob.	SCC
1	0.963452	0	0.036548	$2,452,964
2	0.960663	0	0.039337	$2,381,518
3	0.957734	0	0.042266	$2,312,154
4	0.954663	0	0.045337	$2,244,810
5	0.951447	0	0.048553	$2,179,427
6	0.948083	0	0.051917	$2,115,948
7	0.944568	0	0.055432	$2,054,319
8	0.9409	0	0.0591	$1,994,484
9	0.937077	0	0.062923	$1,936,392
10	0.933095	0	0.066905	$1,879,993

FURTHER ACTIONS: The 39 projects that are selected require further screening that is difficult at the national level. The trunnion rod testing methodology is only applicable for greased rod-type trunnion anchors. The following questionnaire is recommended to determine applicability of testing at each of the 39 identified sites.

1. Are some of the Tainter gate anchorages at the dam of the greased (or ungrouted) post-tensioned rod type? If yes, continue. If no, done. Not applicable.
2. Are there known or suspected current or past issues with broken, failed, mis-tensioned, or untensioned rods? If no, continue. If yes, request funding for rod testing.
3. Is the safety factor less than 2 if a single rod in a group breaks or becomes ineffective, or less than 1.3 if two rods in a group break or become ineffective on a single anchorage? If no, risk is low. Done. If yes, continue.
4. Are approved emergency bulkheads or stoplogs available for rapid closure of a single failed gate? If yes, continue. If no, request funding for rod testing.

5. Can the river pool be adequately managed safely, sufficiently, and reliably if a single gate is inoperable but barricaded with emergency bulkheads or stoplogs? If yes, risk is low. Done. If no, request funding for rod testing.

If the questionnaire results in a need for action, it is recommended that dispersive-wave testing for tension and guided-wave testing for flaws be performed. Dispersive-wave and guided-wave testing by a contractor or the U.S. Army Engineer Research and Development Center (ERDC) can be estimated to be $68,500 + ($55,064 per gate). This does not include costs of contracting or site access. Pull-off tests are also possible following appropriate USACE Engineering and Construction guidance.

POINT OF CONTACT: The point of contact for technical inquiries regarding this USACE Coastal and Hydraulics Engineering Technical Note (CHETN) is Dr. Matthew D. Smith, U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), Vicksburg, MS. Dr. Smith may be contacted by email at Matthew.D.Smith@erdc.dren.mil or by phone at 601-634-7429. This CHETN should be cited as follows:

Smith, Matthew D. and Travis B. Fillmore. 2018. *Methodology Supporting Civil Works Implementation of Trunnion Rod Testing*. ERDC/CHL CHETN-IX-48. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://dx.doi.org/10.21079/11681/30773

REFERENCES

Evans, J., and R. Haskins. 2014. *Development of a Guided-Wave Technology Capable of the Detection of Open Cracks and Microcracks in Embedded Trunnion Anchor Rods*. ERDC/CHL CHETN-IX-36. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Evans, J., and R. Haskins. 2015. *Detection of Microcracks in Trunnion Rods Using Ultrasonic Guided Waves.* ERDC/ITL TR-15-1. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Holt, J., G. Poiroux, R. Lindyberg, and M. Cesare. 2013. Detection without danger. *Civil Engineering Magazine Archive* 83 (1):68–77.

Appendix A. Risk-informed project ranking for trunnion rod testing benefits.

Rank	DistrictName	ProjectName	# Gates	Cost $	Risk B	Risk D	NetBenefit B	NetBenefit D
1	Louisville	Smithland Lock and Dam	11	$674.204	$3.542.907	$7.948.269	$2.868.703	$7.274.065
2	Louisville	John T. Myers Lock and Dam	10	$619.140	$3.356.408	$7.983.214	$2.737.268	$7.364.074
3	Louisville	Cannelton Lock And Dam	12	$729.268	$3.021.534	$6.427.302	$2.292.266	$5.698.034
4	St. Louis	Melvin Price	9	$564.076	$2.764.825	$7.012.894	$2.200.749	$6.448.818
5	Louisville	Newburgh Lock and Dam	9	$564.076	$2.735.231	$6.937.832	$2.171.155	$6.373.756
6	Louisville	McAlpine Lock and Dam	9	$564.076	$2.552.683	$6.474.802	$1.988.607	$5.910.726
7	Louisville	Markland Lock and Dam	12	$729.268	$2.698.267	$5.739.661	$1.968.999	$5.010.393
8	Huntington	Cpt. Anthony Meldahl Lock	12	$729.268	$2.343.713	$4.985.465	$1.614.445	$4.256.197
9	Huntington	Greenup Lock and Dam	9	$564.076	$1.941.623	$4.924.868	$1.377.547	$4.360.792
10	St. Louis	Lock No. 24	15	$894.460	$2.107.880	$3.924.113	$1.213.420	$3.029.653
11	Rock Island	Lock No. 18	14	$839.396	$1.747.625	$3.387.994	$908.229	$2.548.598
12	Rock Island	Lock No. 16	15	$894.460	$1.800.642	$3.352.148	$906.182	$2.457.688
13	St. Louis	Lock No. 25	14	$839.396	$1.733.166	$3.359.964	$893.770	$2.520.568
14	Rock Island	Lock No. 22	10	$619.140	$1.442.303	$3.430.518	$823.163	$2.811.378
15	Rock Island	Lock No. 21	10	$619.140	$1.426.909	$3.393.903	$807.769	$2.774.763
16	Huntington	Belleville Lock and Dam	8	$509.012	$1.204.208	$3.278.485	$695.196	$2.769.473
17	Huntington	Racine Lock and Dam	8	$509.012	$1.183.533	$3.222.195	$674.521	$2.713.183
18	Rock Island	Lock No. 17	8	$509.012	$1.132.926	$3.084.418	$623.914	$2.575.406
19	Rock Island	Lock No. 14	13	$784.332	$1.390.249	$2.817.251	$605.917	$2.032.919
20	Rock Island	Lock No. 11	13	$784.332	$1.357.900	$2.751.696	$573.568	$1.967.364
21	Huntington	Willow Island Lock and Dam	8	$509.012	$1.070.681	$2.914.955	$561.669	$2.405.943
22	Rock Island	Lock No. 13	10	$619.140	$1.148.170	$2.730.923	$529.030	$2.111.783
23	Pittsburgh	Hannibal Lock and Dam	8	$509.012	$1.027.403	$2.797.129	$518.391	$2.288.117
24	St. Paul	Lock No. 10	8	$509.012	$1.019.735	$2.776.251	$510.723	$2.267.239
25	Pittsburgh	New Cumberland Lock and Dam	11	$674.204	$1.166.953	$2.617.980	$492.749	$1.943.776
26	Rock Island	Starved Rock	10	$619.140	$1.101.431	$2.619.754	$482.291	$2.000.614
27	Rock Island	Lock No. 20	40	$2.271.060	$2.722.357	$3.279.813	$451.297	$1.008.753
28	Pittsburgh	Pike Island Lock and Dam	9	$564.076	$986.402	$2.501.980	$422.326	$1.937.904
29	Rock Island	Lock No. 12	7	$453.948	$842.203	$2.478.803	$388.255	$2.024.855
30	Rock Island	Lagrange	10	$619.140	$989.020	$2.352.383	$369.880	$1.733.243

Rank	DistrictName	ProjectName	# Gates	Cost $	Risk B	Risk D	NetBenefit B	NetBenefit D
31	Rock Island	Marseilles	11	$674.204	$1.024.283	$2.297.909	$350.079	$1.623.705
32	Rock Island	Dresden Island	9	$564.076	$873.119	$2.214.640	$309.043	$1.650.564
33	St. Paul	Lock No. 9	8	$509.012	$791.042	$2.153.630	$282.030	$1.644.618
34	St. Paul	Lock No. 8	10	$619.140	$885.495	$2.106.150	$266.355	$1.487.010
35	St. Paul	Lock No. 6	10	$619.140	$864.642	$2.056.550	$245.502	$1.437.410
36	Rock Island	Peoria	11	$674.204	$906.626	$2.033.953	$232.422	$1.359.749
37	St. Paul	Lock No. 7	11	$674.204	$904.405	$2.028.972	$230.201	$1.354.768
38	Mobile	Coffeeville	8	$509.012	$667.839	$1.818.208	$158.827	$1.309.196
39	Little Rock	Lock Num. 2 & Mills Dam	16	$949.524	$1.052.867	$1.888.598	$103.343	$939.074
40	Mobile	Armistead I. Selden	6	$398.884	$478.393	$1.534.206	$79.509	$1.135.322
41	St. Paul	Lock No. 5a	5	$343.820	$399.710	$1.408.811	$55.890	$1.064.991
42	Little Rock	COL Maynard	15	$894.460	$909.172	$1.692.551	$14.712	$798.091
43	Little Rock	Emmett Sanders	17	$1.004.588	$1.000.123	$1.733.835	-$4.465	$729.247
44	St. Paul	Lock No. 4	22	$1.279.908	$1.275.284	$1.932.397	-$4.624	$652.489
45	Little Rock	David D. Terry	17	$1.004.588	$950.501	$1.647.810	-$54.087	$643.222
46	Little Rock	Murray	14	$839.396	$778.670	$1.509.551	-$60.726	$670.155
47	Pittsburgh	Braddock Locks and Dam 02	4	$288.756	$218.682	$855.015	-$70.074	$566.259
48	Tulsa	Newt Graham Lock	3	$233.692	$162.499	$711.863	-$71.193	$478.171
49	Little Rock	Joe Hardin	18	$1.059.652	$988.204	$1.660.250	-$71.448	$600.598
50	Tulsa	Chouteau	3	$233.692	$153.372	$671.882	-$80.320	$438.190
51	St. Paul	Lock No. 2	19	$1.114.716	$1.017.986	$1.661.527	-$96.730	$546.811
52	Mobile	Holt Lock and Dam	14	$839.396	$740.828	$1.436.190	-$98.568	$596.794
53	Tulsa	W.D. Mayo	12	$729.268	$622.815	$1.324.831	-$106.453	$595.563
54	Pittsburgh	Charleroi Lock and Dam	5	$343.820	$206.559	$728.033	-$137.261	$384.213
55	Little Rock	Arthur V. Ormond	14	$839.396	$696.223	$1.349.718	-$143.173	$510.322
56	Mobile	Rankin	3	$233.692	$88.099	$385.939	-$145.593	$152.247
57	Mobile	Bevill	4	$288.756	$138.604	$541.921	-$150.152	$253.165
58	Mobile	Howell Heflin	5	$343.820	$189.344	$667.358	-$154.476	$323.538
59	Mobile	Amory	4	$288.756	$125.862	$492.099	-$162.894	$203.343
60	Mobile	Fulton	4	$288.756	$122.537	$479.103	-$166.219	$190.347

Rank	DistrictName	ProjectName	# Gates	Cost $	Risk B	Risk D	NetBenefit B	NetBenefit D
61	St. Louis	Kaskaskia	2	$178,628	$12,123	$60,137	-$166,505	-$118,491
62	Little Rock	James W. Trimble	15	$894,460	$727,620	$1,354,566	-$166,840	$460,106
63	Little Rock	Toad Suck Ferry	16	$949,524	$782,379	$1,403,406	-$167,145	$453,882
64	Jacksonville	Ortona	2	$178,628	$439	$2,176	-$178,189	-$176,452
65	Mobile	Stennis	5	$343,820	$165,126	$582,001	-$178,694	$238,181
66	Tulsa	Webbers Falls	12	$729,268	$543,838	$1,156,833	-$185,430	$427,565
67	St. Paul	Lower St. Anthony Falls	3	$233,692	$43,437	$190,285	-$190,255	-$43,407
68	Mobile	Montgomery	5	$343,820	$143,152	$504,551	-$200,668	$160,731
69	Pittsburgh	Maxwell Lock and Dam	5	$343,820	$142,243	$501,347	-$201,577	$157,527
70	Little Rock	Dardanelle	20	$1,169,780	$962,517	$1,529,585	-$207,263	$359,805
71	St. Paul	Lock No. 5	28	$1,610,292	$1,394,040	$1,897,037	-$216,252	$286,745
72	Little Rock	Ozark-Jeta Taylor	15	$894,460	$676,831	$1,260,016	-$217,629	$365,556
73	Mobile	Aberdeen	6	$398,884	$175,052	$561,393	-$223,832	$162,509
74	Rock Island	Brandon Road	21	$1,224,844	$993,159	$1,539,759	-$231,685	$314,915
75	Vicksburg	Felsenthal	3	$233,692	$722	$3,162	-$232,970	-$230,530
76	Vicksburg	H.K. Thatcher	3	$233,692	$230	$1,007	-$233,462	-$232,685
77	Vicksburg	John H. Overton	5	$343,820	$103,068	$363,273	-$240,752	$19,453
78	Seattle	Hiram M. Chittenden	6	$398,884	$136,447	$437,587	-$262,437	$38,703
79	Nashville	Cheatham Lock and Dam	7	$453,948	$186,720	$549,562	-$267,228	$95,614
80	Huntington	Winfield Lock - New Lock - Gate Bay	16	$949,524	$677,683	$1,215,606	-$271,841	$266,082
81	Vicksburg	Columbia	4	$288,756	$12,664	$49,515	-$276,092	-$239,241
82	Pittsburgh	Opekiska Lock and Dam	4	$288,756	$55	$215	-$288,701	-$288,541
83	Tulsa	Robert S. Kerr	18	$1,059,652	$765,644	$1,286,334	-$294,008	$226,682
84	Vicksburg	Jonesville	5	$343,820	$32,920	$116,031	-$310,900	-$227,789
85	Vicksburg	Russell B. Long	5	$343,820	$32,133	$113,255	-$311,687	-$230,565
86	Vicksburg	Joe D. Waggonner	5	$343,820	$31,878	$112,357	-$311,942	-$231,463
87	New Orleans	Calcasieu Barrier	5	$343,820	$20,105	$70,861	-$323,715	-$272,959
88	Pittsburgh	Point Marion Lock and Dam	6	$398,884	$43,598	$139,819	-$355,286	-$259,065
89	Vicksburg	Lock and Dam No. 3	6	$398,884	$40,387	$129,521	-$358,497	-$269,363
90	Pittsburgh	Morgantown Lock and Dam	6	$398,884	$4,497	$14,421	-$394,387	-$384,463

Rank	DistrictName	ProjectName	# Gates	Cost $	Risk B	Risk D	NetBenefit B	NetBenefit D
91	Mobile	Wilkins	11	$674,204	$258,328	$579,541	-$415,876	-$94,663
92	Walla Walla	Lower Monumental	8	$509,012	$77,678	$211,481	-$431,334	-$297,531
93	Walla Walla	Little Goose	8	$509,012	$70,322	$191,452	-$438,690	-$317,560
94	Jacksonville	St. Lucie	7	$453,948	$1,901	$5,595	-$452,047	-$448,353
95	Vicksburg	Lindy Claiborne Boggs	11	$674,204	$215,497	$483,452	-$458,707	-$190,752
96	Walla Walla	Lower Granite	8	$509,012	$45,018	$122,561	-$463,994	-$386,451
97	Walla Walla	Ice Harbor	10	$619,140	$114,573	$272,513	-$504,567	-$346,627
98	Mobile	R. F. Henry	11	$674,204	$148	$332	-$674,056	-$673,872
99	Portland	The Dalles	23	$1,334,972	$480,559	$712,862	-$854,413	-$622,110
100	Mobile	Millers Ferry	17	$1,004,588	$245	$424	-$1,004,343	-$1,004,164