COE CST Fifth Annual Technical Meeting

Task 299: Nitrous Oxide Composite Case Testing

PI: Warren Ostergren
Co-PIs: Bin Lim, Andrei Zagrai

COE CST Program Manager: Ken Davidian (FAA)
Technical Monitor: Yvonne Tran (FAA)
Technical Monitor: Don Sargent (FAA)

October 27-28, 2015
Arlington, VA

COE CST
Center of Excellence for Commercial Space Transportation

Agenda

- Team Members
- Task Description / Goals
- Schedule
- Hypothesis
- Results
- Conclusions and Future Work

Team Members

- PI: Warren Ostergren (NMT)
- Co-PI: Seokbin (Bin) Lim (NMT)
- Co-PI: Andrei Zagrai (NMT)

- Student: Antonio Garcia (NMT)
- Student: Steven Sweeney (NMT)
- Test Engineer: Meliton Flores (EMRTC)

- COE CST Program Manager: Ken Davidian (FAA)
- Technical Monitor: Yvonne Tran (FAA)
- Technical Monitor: Don Sargent (FAA)

Task Description / Goals

- Objectives
  - Develop an understanding of fragmentation hazards from composite tanks used for fuel/oxidizer storage
  - Construction of hypothesis and experimental validation of how cracks form in test samples

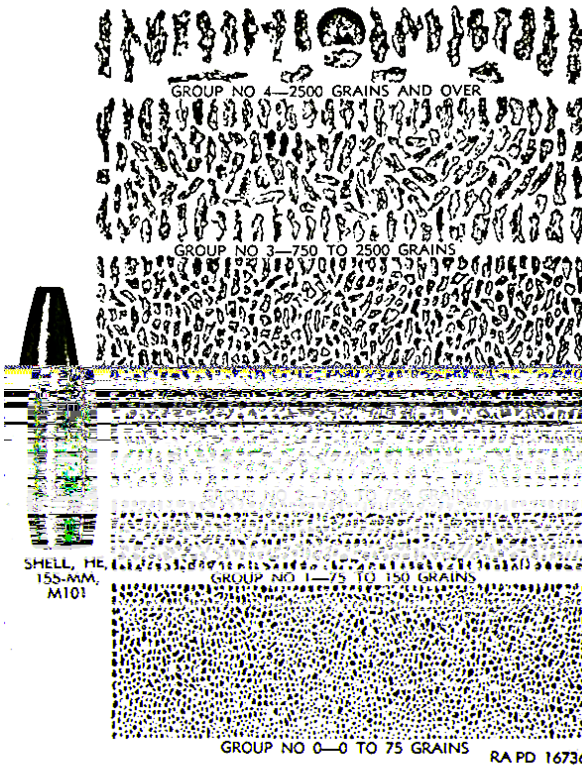
- Tasks
  - 5 tests each of Al 6061 & composite material tubes to understand the crack opening behavior (10 tests total)
  - Develop methods to predict crack opening behavior
  - Develop standard test procedures for composite materials under shock and high-rate loading
  - Numerical simulations to predict the fragmentation (in progress)

Schedule

- Determination of sample thickness (numerical simulation): Jan 2015-Mar 2015
- Design of test fixture: Mar 2015-May 2015
- New test fixture construction: May 2015-July 2015
- 1st aluminum tube test: Aug 19, 2015
- 2nd aluminum tube test: Sep 10, 2015
- 3rd aluminum tube test: Sep 10, 2015
- 4th aluminum tube test: Sep 23, 2015
- 5th aluminum tube test: Oct 7, 2015

- 5 more composite tube tests are scheduled in late 2015

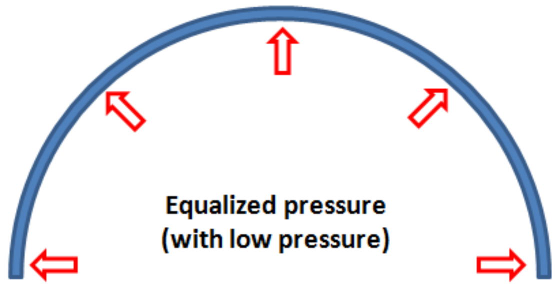
Hypothesis



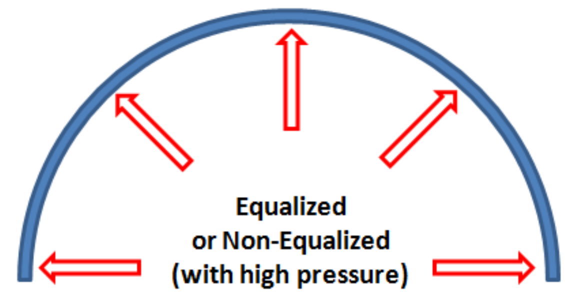
Static vs. Dynamic

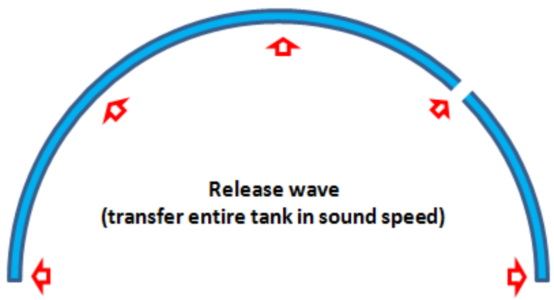
(Very slow loading Vs. Fast-Continuous loading)

Equilibrium
(low strain-rate)

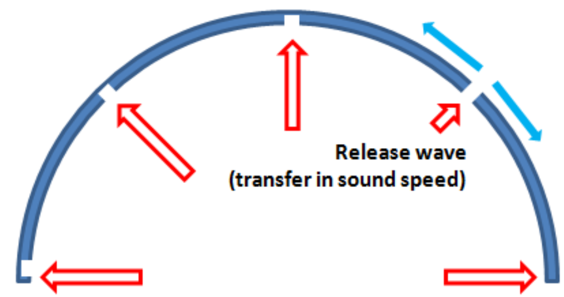


Non-equilibrium
(high strain-rate)





A weak point of the tank will be ruptured, and the subsequent release wave from the ruptured area will lower the stress in entire tank



A weak point of the tank will be ruptured initially, and the subsequent release wave forms but the speed of release wave is not fast enough to prevent extra initiations of ruptures nearby

Hypothesis

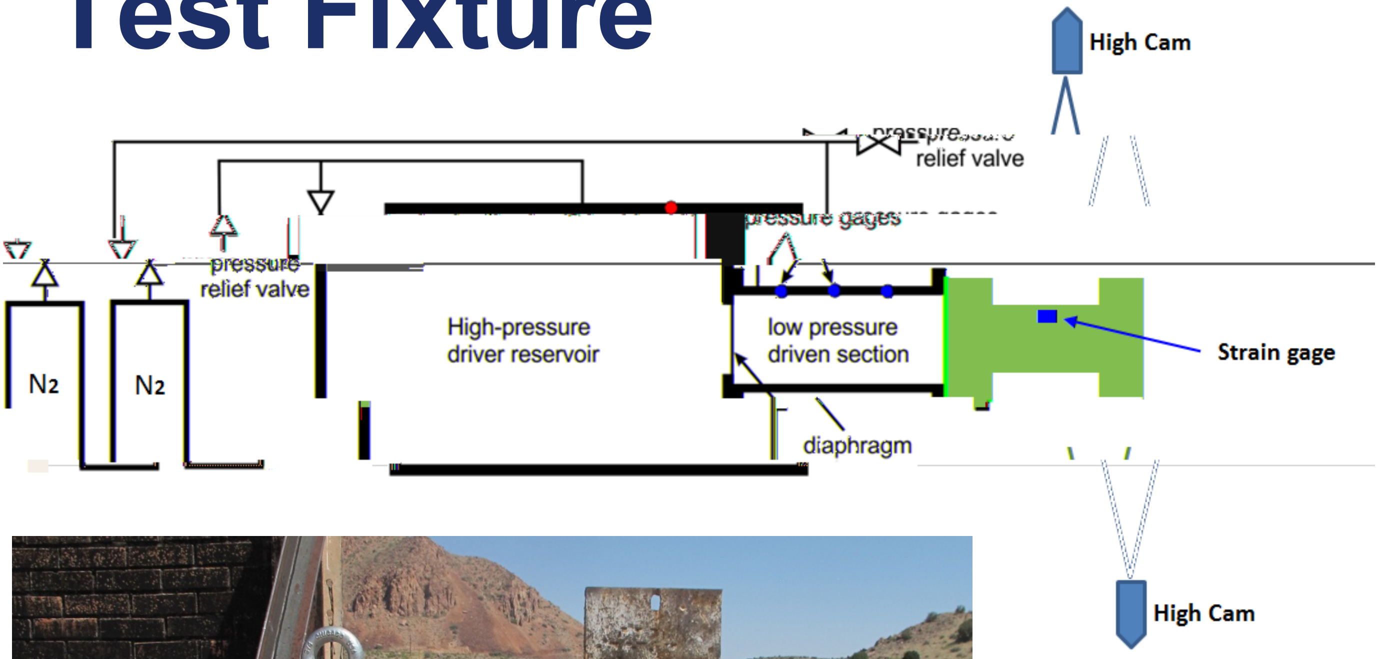
Expected damage/fracture patterns depending on the loading condition

	Equilibrium (low strain-rate)		Non-equilibrium (high strain-rate)	
	Non-brittle Material (Al)	Brittle Material (Composite)	Non-brittle Material (Al)	Brittle Material (Composite)
Plate test	Punching	Punching & Low fractures	Punching or High fractures	High fractures
Structural Tank Test (Tube)	Less number (or single) of opening	Less number (or single) of opening and fractures	Increased number of opening and shrapnel	Many number of opening and shrapnel

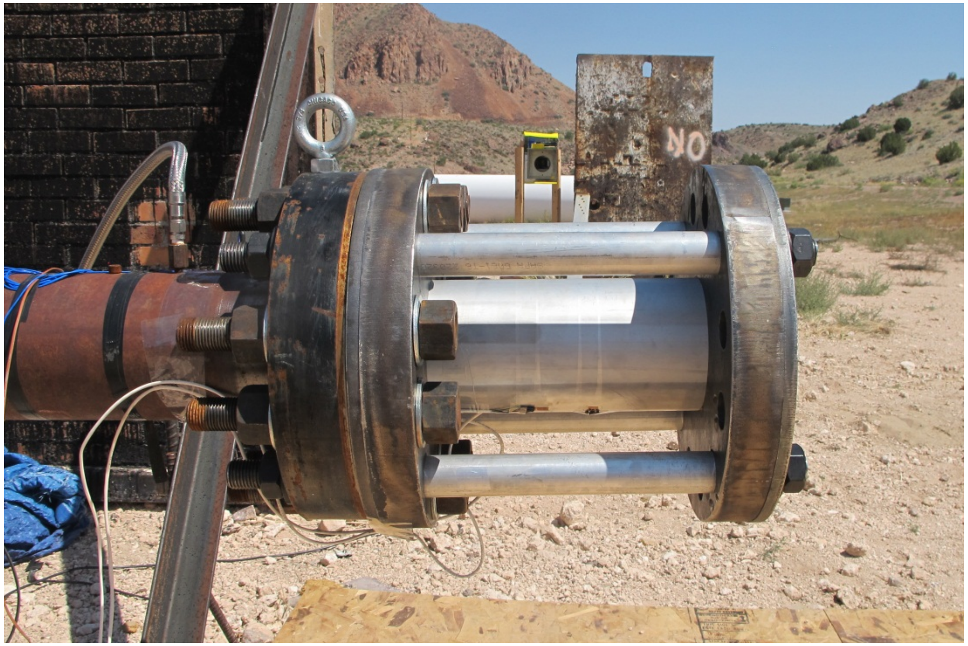
Pressure loading → **Opening** → **Secondary impact** → **Shrapnel**

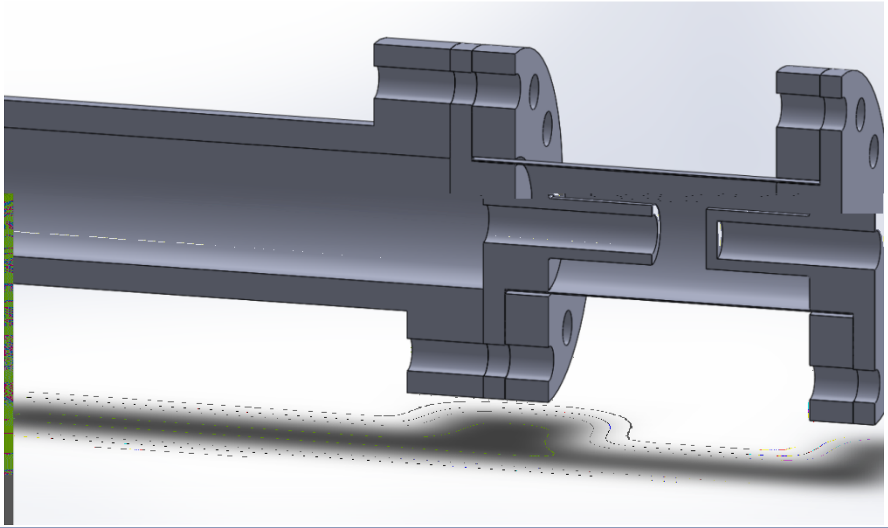
Current stage

Test Fixture

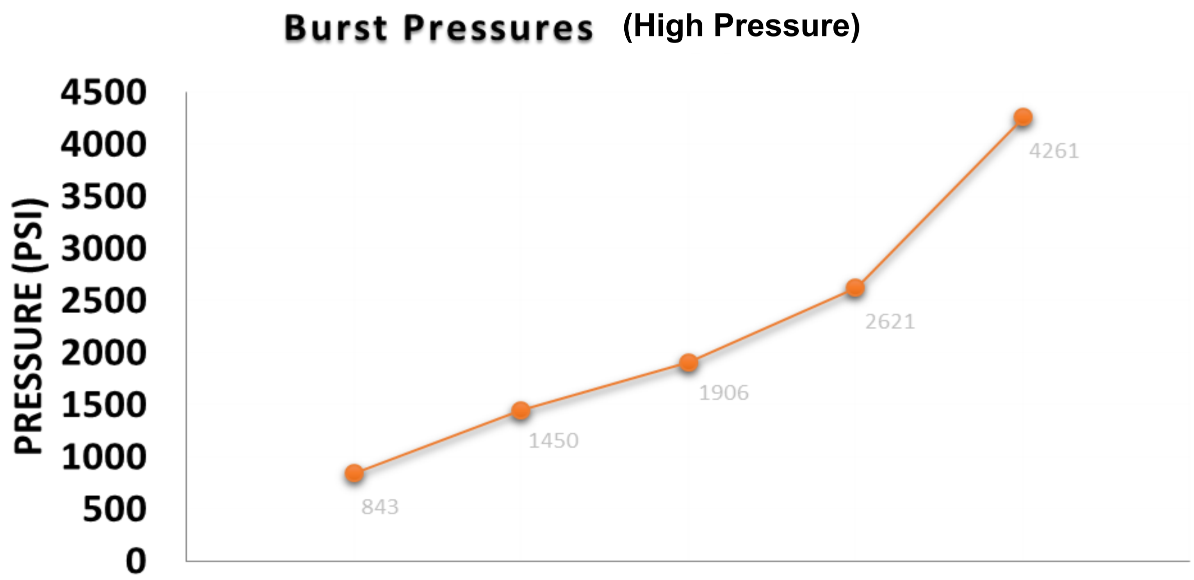


1/16 in. Wall thickness,
12 in. Long,
6 in. Diameter,
6061 Al Tube
Weight of tube: 1.65 lbs

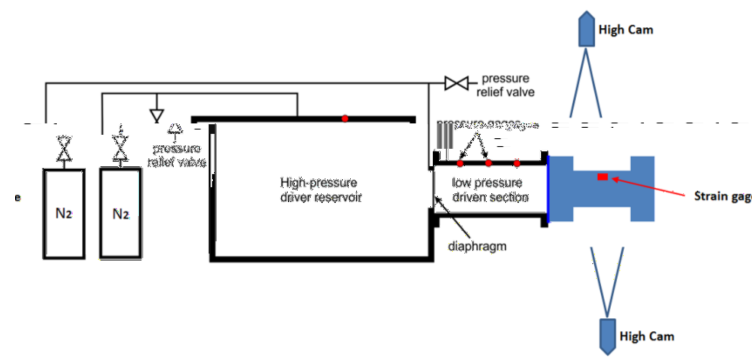




Test Matrix

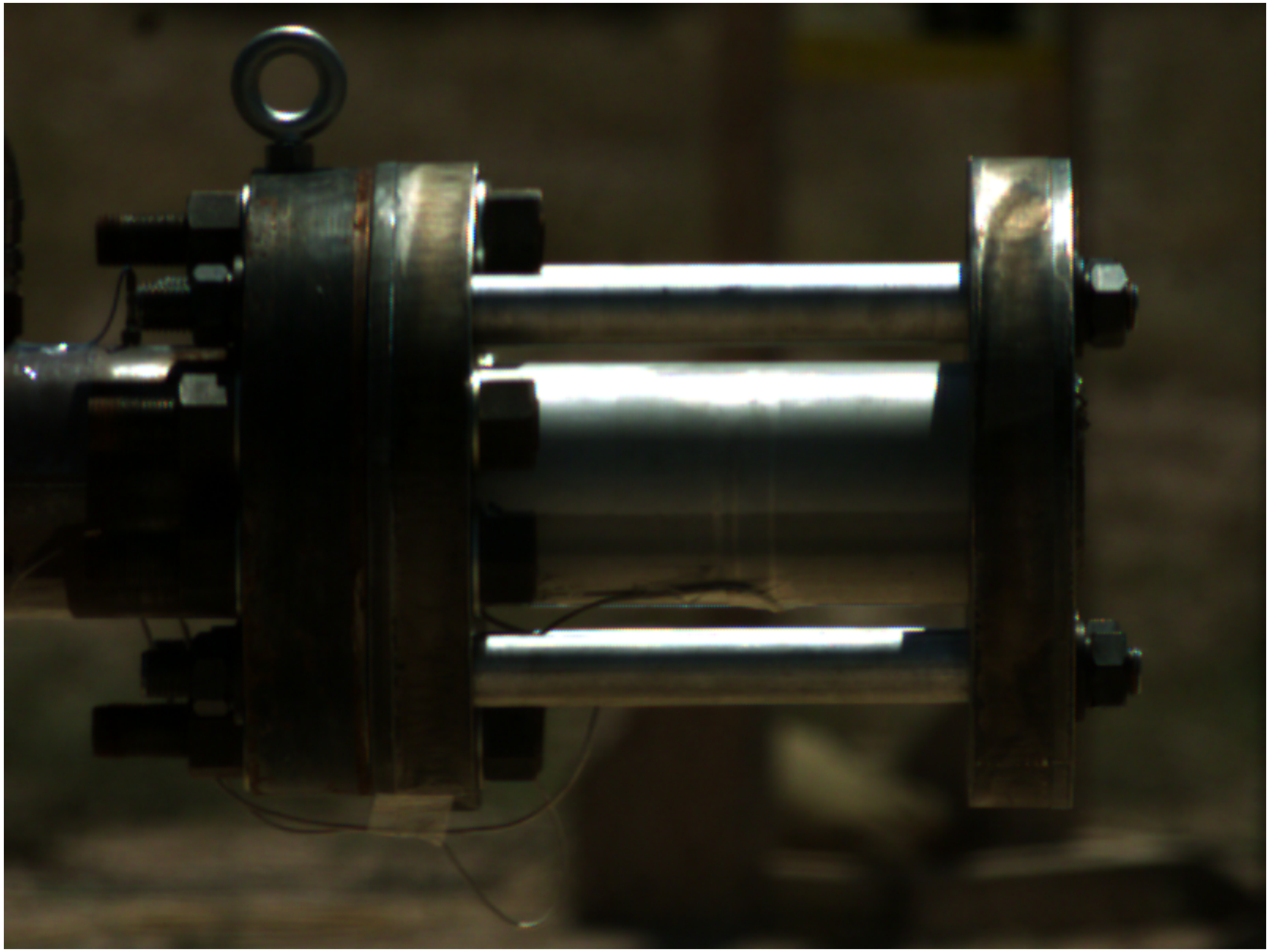


Test #	High	Low	Differential	Diaphragm	Sample
1	2621	692	1929	2008	Al tube
2	1906	699	1207	1195	Al tube
3	843	843	0	N/A	Al tube
4	4261	720	3541	3515	Al tube
5	1450	306	1144	1195	Al tube



Test Results (Shot #1)

Two openings

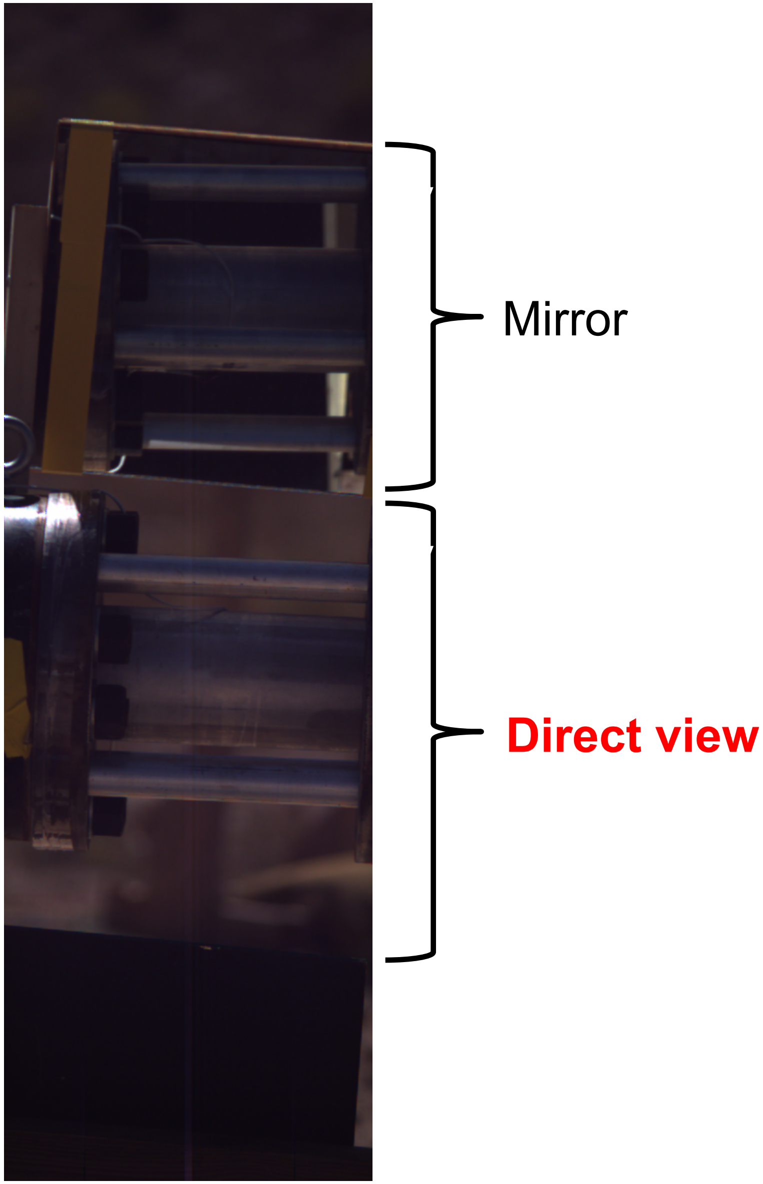


Test Results (Shot #3: static test)

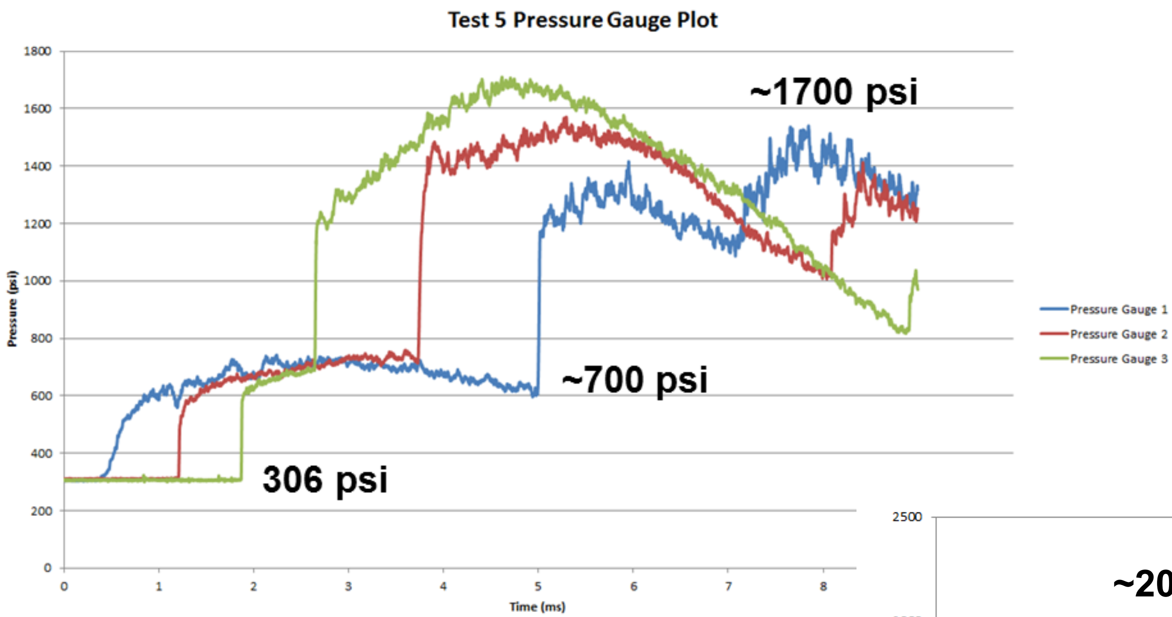
Single opening

Test Results (Shot #4)

Two openings and many secondary fragments

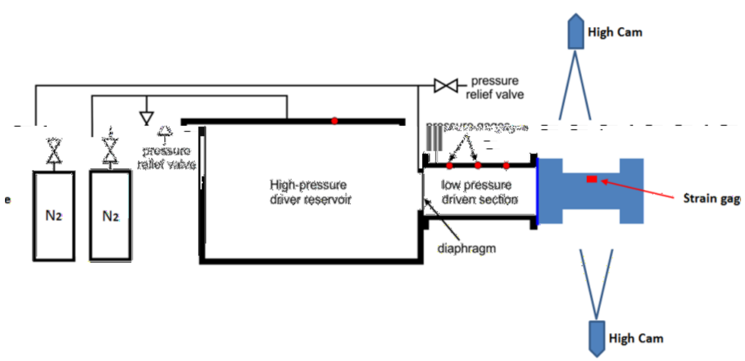


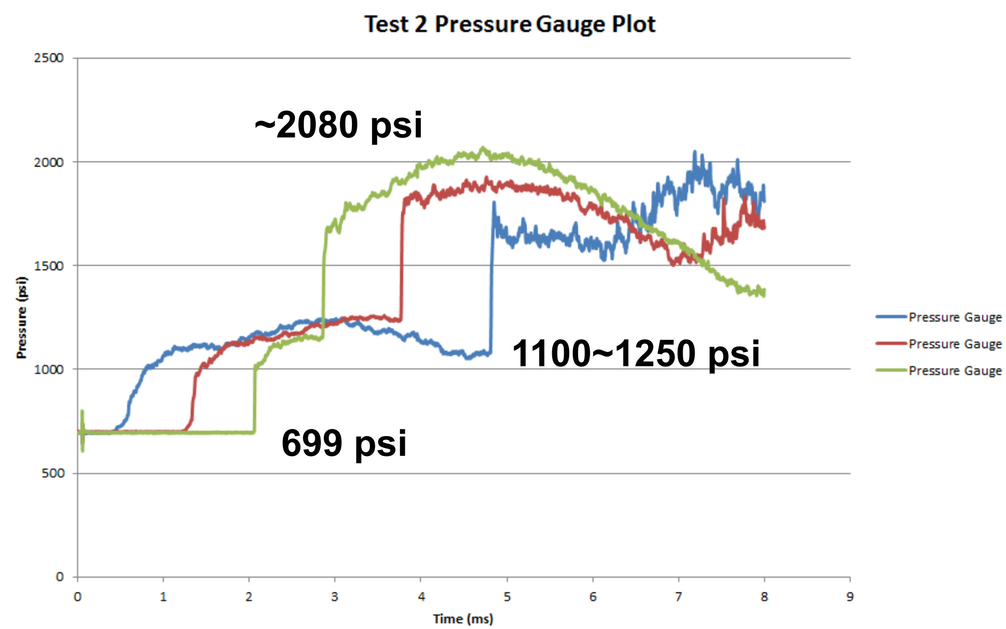
Results



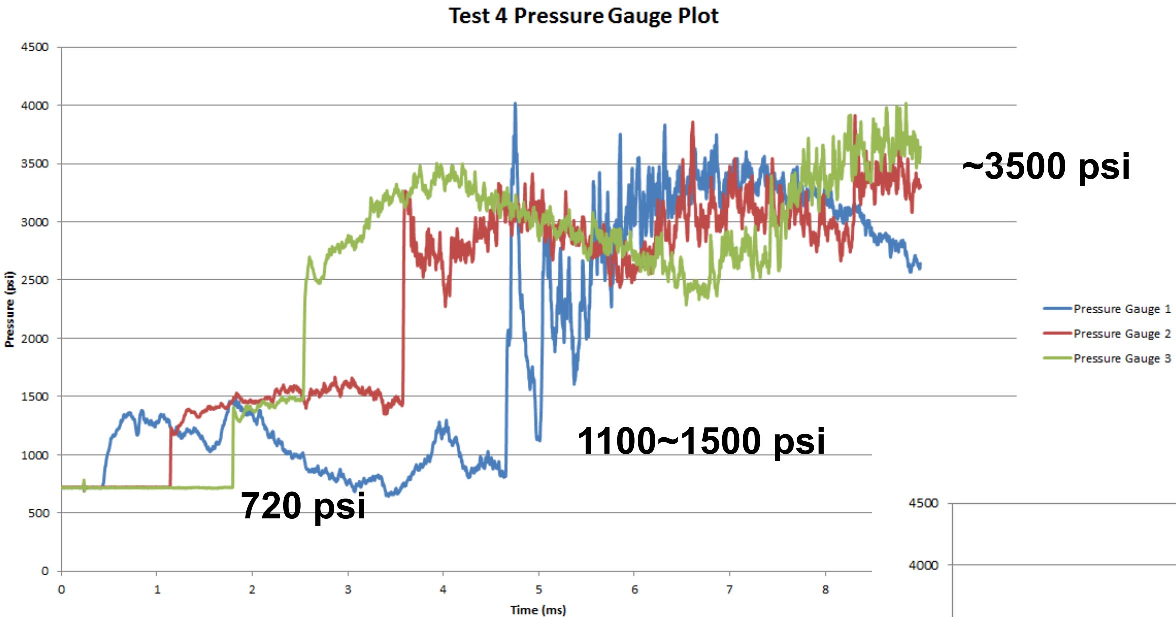
Test #	High (psi)	Low (psi)	Differential (psi)	# of opening
2	1906	699	1207	1
5	1450	306	1144	1

Single opening



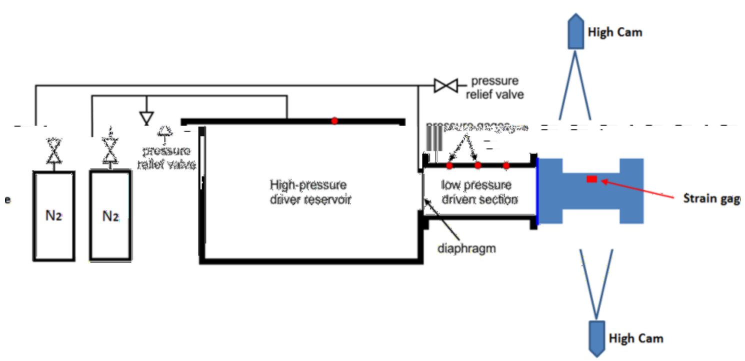


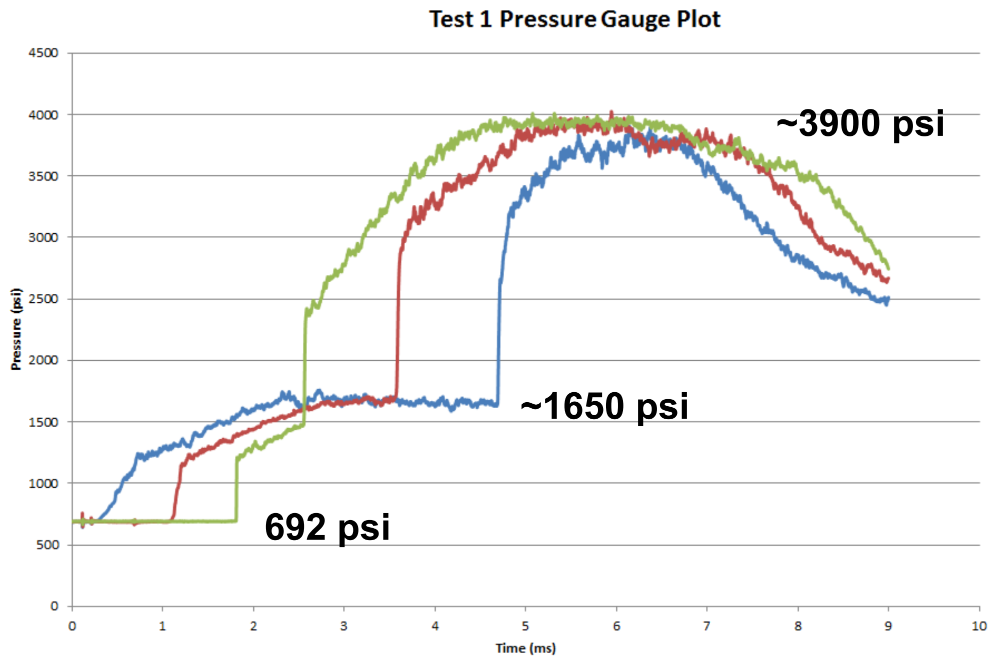
Results



Test #	High (psi)	Low (psi)	Differential (psi)	# of opening
1	2621	692	1929	2
4	4261	720	3541	2

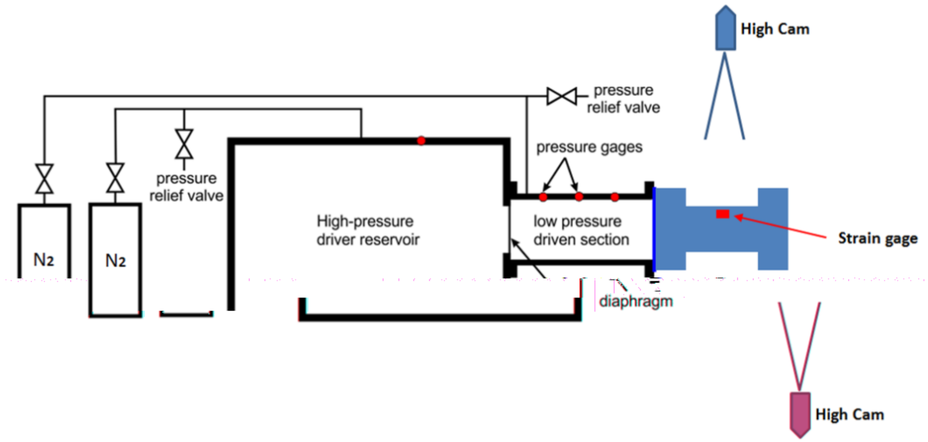
Two openings



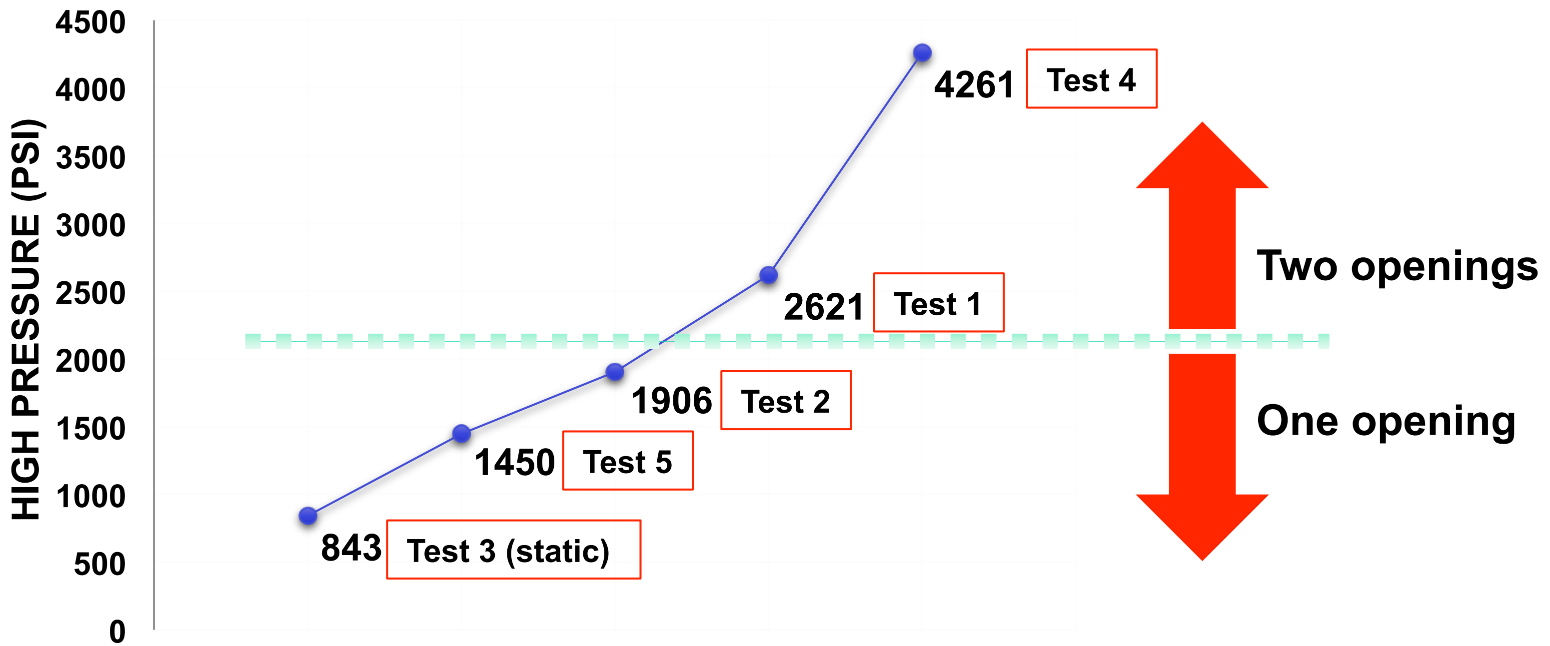


Results

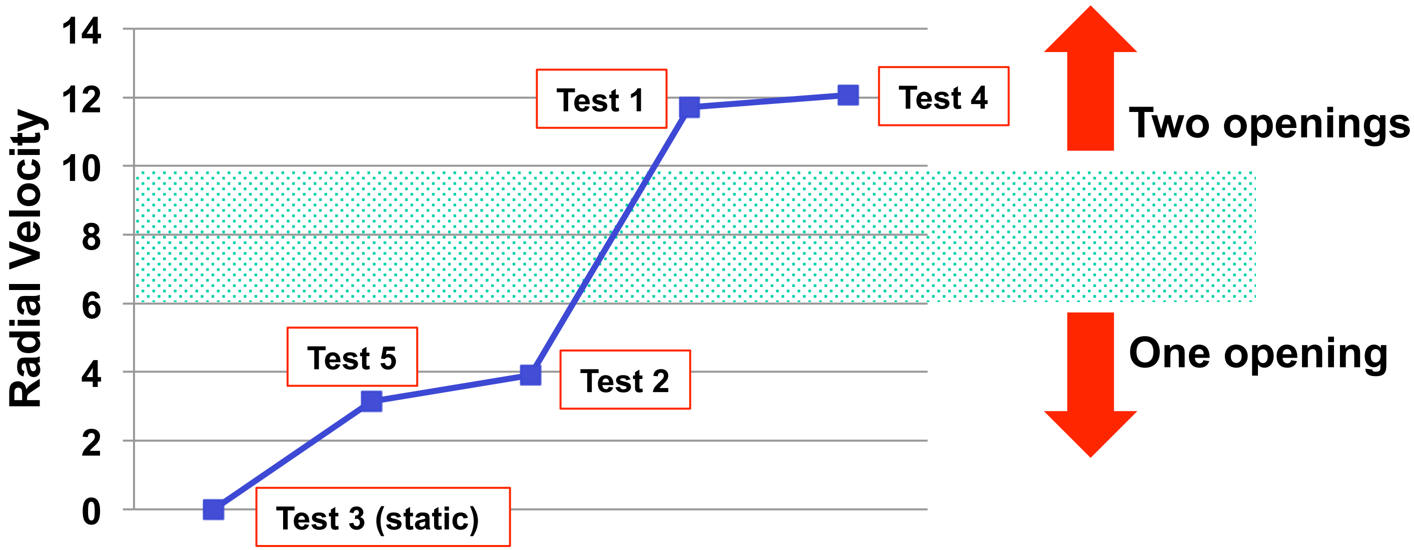
Test # (by date)	High (psi)	Low (psi)	Differential (psi)	Diaphragm (psi)	Radial vel. (m/s)	Circf. elong. vel. (m/s)	Radial strain rate (s^{-1})	# of opening	# of fragments
3	843	843	0	N/A	Too low	Too low	Too low	1	One large
5	1450	306	1144	1195	3.92	33.67	0.035	1	One large & small frags
2	1906	699	1207	1195	3.15	32.24	0.043	1	One large & small frags
1	2621	692	1929	2008	11.70	73.56	0.154	2	Approx. 20
4	4261	720	3541	3515	12.06	75.80	0.159	2	Many

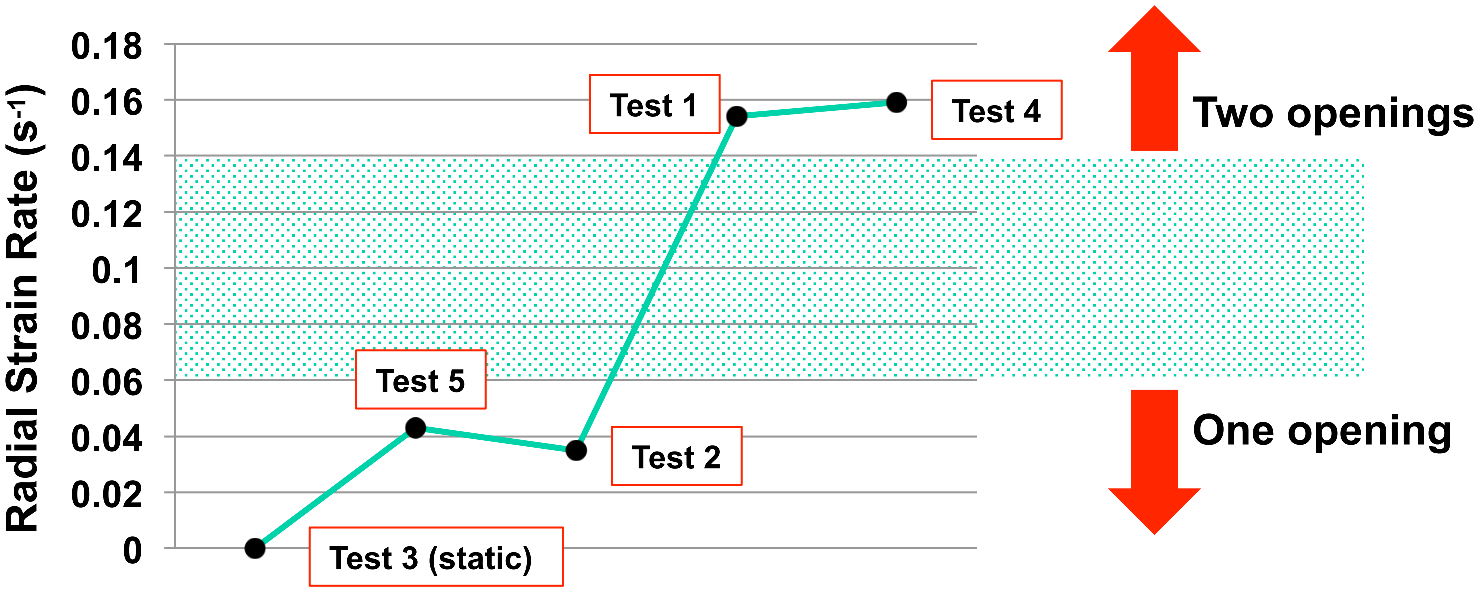


Results


HIGH PRESSURE (PSI)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
4261
Test 4
2621
Test 1
1906
Test 2
1450
Test 5
843
Test 3 (static)
Two openings
One opening

Results


Radial Velocity
14
12
10
8
6
4
2
0
Test 1
Test 4
Test 5
Test 2
Test 3 (static)
Two openings
One opening


Radial Strain Rate (s-1)
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Test 1
Test 4
Test 5
Test 2
Test 3 (static)
Two openings
One opening

Conclusions

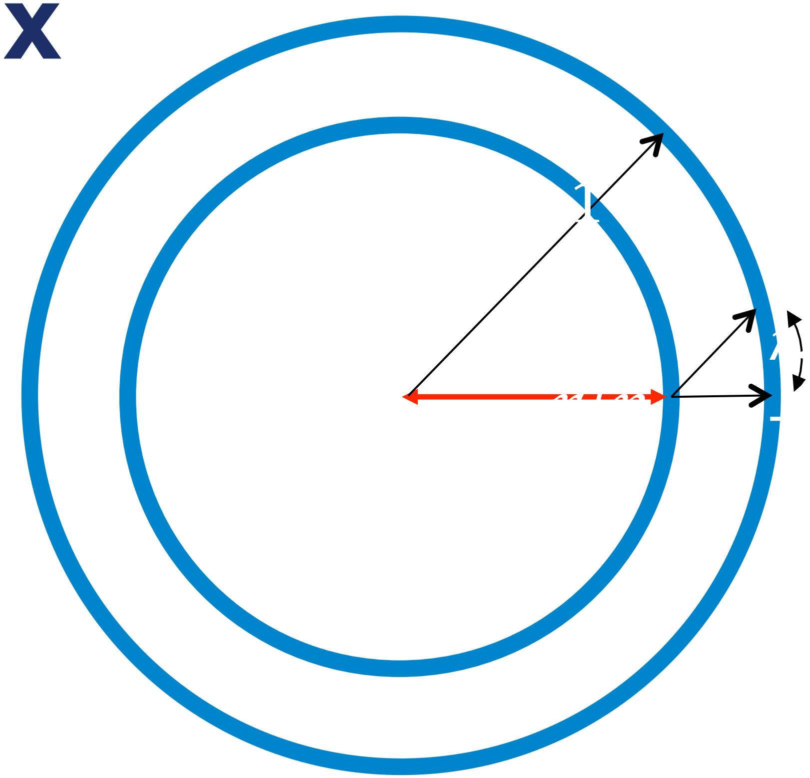
- Pressure tests on aluminum tubes show a clear tendency for the number of openings to be dependent on the input pressure
- The input pressure causes a similar trend in important deformation criteria: radial velocity, circumferential velocity, and strain rate
- The formation of small shrapnel in the aluminum is from secondary impact in the test structure
- The crack opening characteristic helps to predict the shrapnel kinetics (velocity, size, direction, etc.)

Future work

- Finalize quantification of the crack opening characteristics
- Investigation of the composite tube opening behavior
- Characterize the secondary impact and creation of small shrapnel (fragments)
- Understand the kinetics of the fragments

Questions?

Appendix



Circumferential elongation velocity

Radial expansion velocity

Test	Cam	frame	size	size	surface a	surface a	speed measurem	speed measurem	speed measurem	speed measurem	speed measurem	speed measurem	avg speed	average spe
1	N	33	0.0554	0.0449	0.36	2.31	44.15	47.06	56.14	61.49	63.1		54.39	24.31
1	N	61	0.162	0.1772	4.13	26.67	88.49	77.95	78.42	76.68			80.39	35.94
1	N	63	0.0654	0.1024	0.96	6.22	145.63	137.337	136.94				139.97	62.57
1	S	24	0.2	0.1731	4.99	32.16	635	544.21					589.61	263.58
2	N	83	0.3394	0.1267	6.19	39.95	568.75	524.93	512.01	520.14			531.46	237.58
2	N	89	0.128	0.0527	0.97	6.27	359.92	401.64	395.96				385.84	172.49
2	N	88	0.1312	0.2443	4.62	29.78	204.13	200.05					202.09	90.34
2	N	98	0.3419	0.1517	7.47	48.19	159.32	160.27	159.86				159.82	71.44
2	S	78	0.1079	0.1015	1.58	10.17	167.99	165.24	160.64				164.62	73.59
2	S	71	0.0535	0.0433	0.33	2.15	93.02	96.8	107.88	115.29			103.25	46.16
2	S	86	0.1741	0.0779	1.95	12.60	532.12	547.32	558.79				546.08	244.12
2	S	72	0.1276	0.0605	1.11	7.17	132.91	136.45	140.89	141.96	144		139.24	62.25
2	S	74	0.043	0.0239	0.15	0.95	147.19	152.9	160.13	164.32	166.71		158.25	70.74
2	S	75	0.1861	0.0545	1.46	9.42	382.42	323.4	308.51	323.56	310.56		329.69	147.38
2	S	76	0.121	0.0348	0.61	3.91	359.93	384.14	374.54				372.87	166.69
2	S	72	0.1157	0.134	2.23	14.40	106.29	106.14	106.68	101.9	101.87		104.58	46.75
2	S	72	0.1581	0.0592	1.35	8.70	241.36	244.81	248.93	250.1984	255.05		248.07	110.90
2	S	72	0.1211	0.0624	1.09	7.02	62.47	64.51	74.19	74.89	81.41	85.66	73.86	33.02
2	S	79	0.0879	0.0508	0.64	4.15	393.74	366.79	370.32				376.95	168.51
2	S	73	0.0717	0.0492	0.51	3.28	125.7	128.95	133.73				129.46	57.87
3	N	-129	0.1155	0.0454	0.76	4.87	375.51	110.06	101.21	92.25			169.76	75.89
3	N	-130	0.1389	0.075	1.50	9.68	89.09	70.84	66.06				75.33	33.68
3	N	-99	0.0651	0.0601	0.56	3.63	117.35	90.79	82.14	79.87			92.54	41.37
3	S	-115	0.2331	0.1267	4.25	27.44	140.06	124.72	127.5	131.46	138.6		132.47	59.22
3	S	-77	0.2125	0.1314	4.02	25.94	225.76	242.12	250.72				239.53	107.08
3	S	-91	0.2081	0.1201	3.60	23.22	176.43	177.78	179.08	180.79	179.12		178.64	79.86
3	S	-24	0.238	0.2473	8.48	54.68								
3	S	-82	0.0853	0.2	2.46	15.85	85.97	88.93					87.45	39.09
3	S	-75	0.2363	0.2571	8.75	56.44								
3	S	-52	0.0894	0.052	0.67	4.32	104.06	109.22	107.87				107.05	47.86
4	N	92	0.1791	0.0543	1.40	9.03	248.22	245.73	247.41				247.12	110.47
4	N	108	0.4499	0.3145	20.38	131.45	163.38	163.38	157.6	160.44	162		161.36	72.13
4	N	103	0.1713	0.0455	1.12	7.24	151.8	150.16	148.4				150.12	67.11
4	N	86	0.0984	0.0785	1.11	7.18	341.27	288.83					315.05	140.84
4	N	122	0.1823	0.0895	2.35	15.16	193.27	176.83	184.56	185.65			185.08	82.74
4	N	97	0.0516	0.0552	0.41	2.65	319.99	315.84	320.19	319.34	318.92		318.86	142.54
4	N	198	0.1542	0.328	7.28	46.99	141.8	121.23	119.84				127.62	57.05
4	N	248	0.1223	0.1344	2.37	15.27	23.42	26.97	30.21	33.06	32.72		29.28	13.09
4	N	204	0.1315	0.0734	1.39	8.97	63.57	58.78	60.33	59.61	58.22		60.10	26.87
4	S	69	0.0336	0.062	0.30	1.94	354.35	313.25					333.80	149.22
4	S	69	0.1306	0.1614	3.04	19.58	408.04	406.99	415.96	406.69			409.42	183.03
4	S	68	0.064	0.064	0.59	3.81	190.43	216.15					203.29	90.88
4	S	80	0.3283	0.1835	8.67	55.97	126.69	142.67	139.9				136.42	60.99
4	S	103	0.0904	0.0407	0.53	3.42	35.06	36.48					35.77	15.99
4	S	106	0.1343	0.0593	1.15	7.40	28.1	56.08	68.04	73.24			56.37	25.20
4	S	173	0.1678	0.1007	2.43	15.70	76.1	84.04	92.67				84.27	37.67
5	N	69	0.1208	0.0614	1.07	6.89	244.82	254.64	258.9	258.68			254.26	113.66
5	N	70	0.2768	0.0427	1.70	10.98	362.63	257.5	255	256.35	255.99		277.494	124.05
5	N	66	0.0702	0.1073	1.08	7.00	432.29	419.75	433.09				428.37667	191.50
5	S	119	0.4565	0.1787	11.75	75.79	67.05	58.23	66.14	66.16	72		65.916	29.47
5	S	111	0.2791	0.102	4.10	26.45	126.12	166.2	181.11	190			165.8575	74.14
5	S	125	0.1806	0.1354	3.52	22.72	267.43	271.04	274.49	272.72			271.42	121.34
5	S	137	0.5183	0.1051	7.84	50.61	175.98	174.9	177.91	182.17			177.74	79.46
5	S	135	0.1426	0.0514	1.06	6.81	100.14	97.94	99.53	97.68	98.37	100.5	99.026667	44.27