Reducing Blast Distant Focused Overpressure Effects

International Explosives Safety Symposium and Exposition
San Diego, CA
August 6-9, 2018

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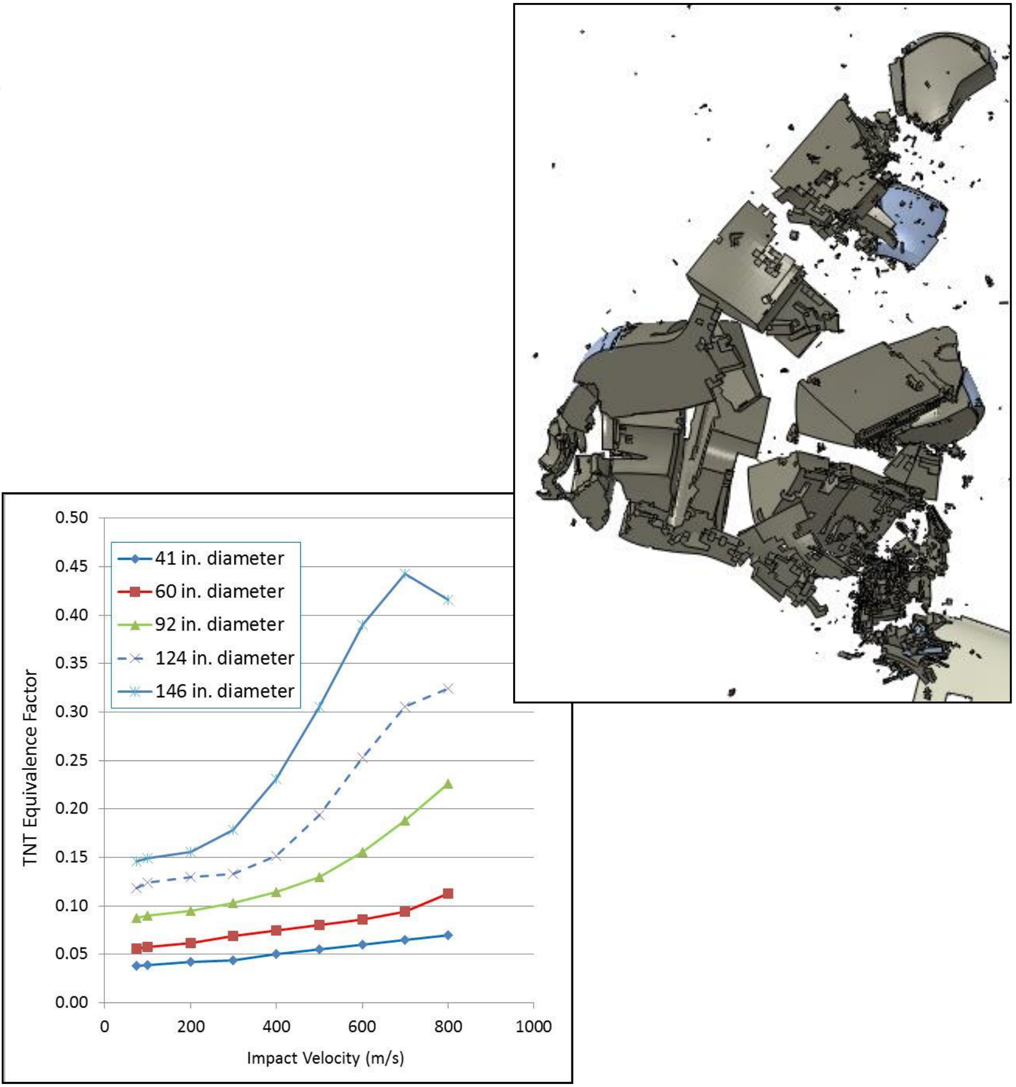
Northrop Grumman Innovation Systems

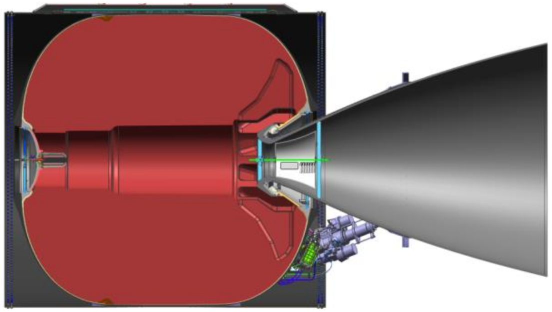
Outline

- Background/problem statement
- Drivers for blast DFO
- Mitigation approach
- Analysis and validation testing
- Comparative DFO analysis
- Summary and conclusions

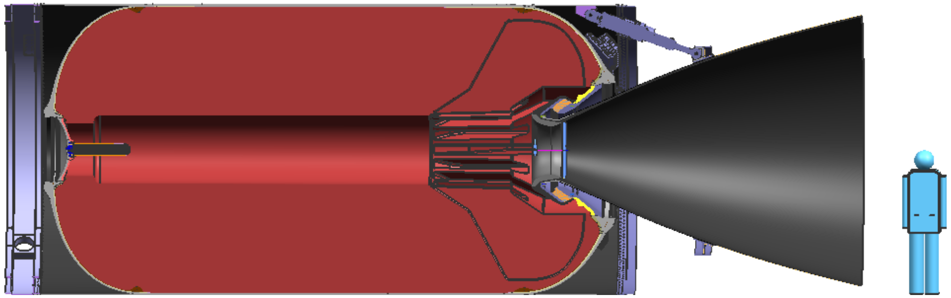


Background Problem Statement

- If large SRM launch vehicles fail during early stages of launch, their subsequent impact with the earth can generate substantial overpressure
- The overpressure and resulting distant focused overpressure (DFO) can negatively impact launch availability
- Issue appears particularly challenging when large unignited upper stages are incorporated into the vehicle design

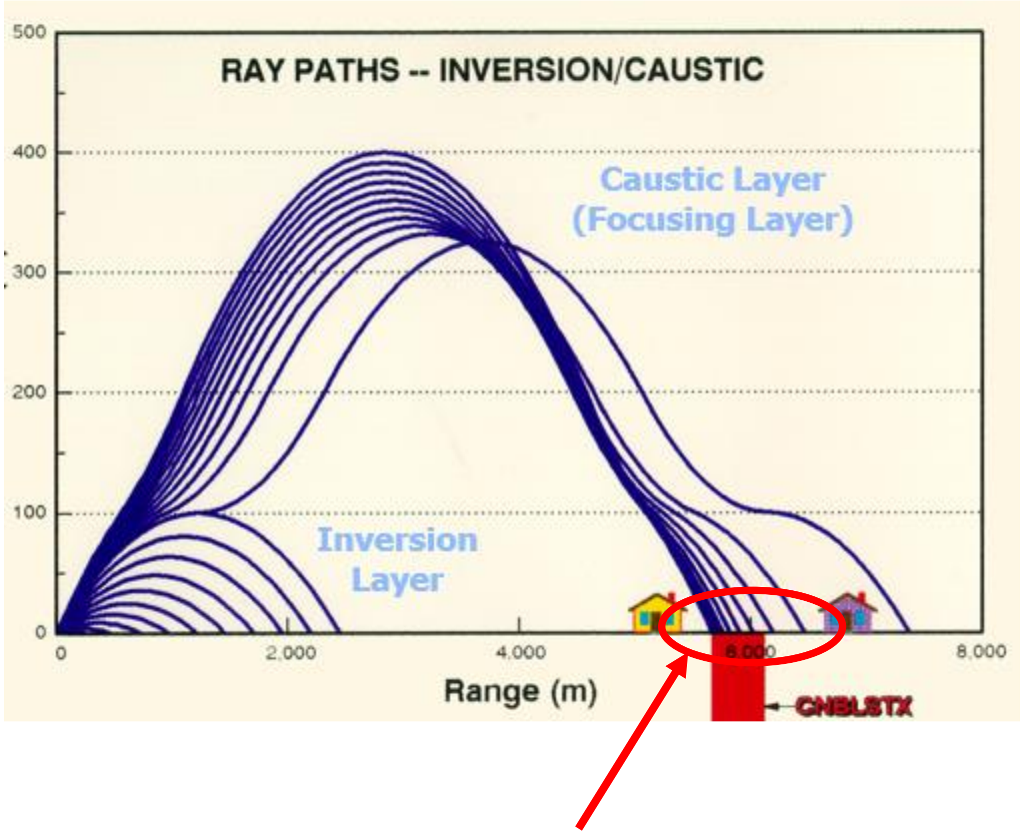


Typical Launch Vehicle Propellant Wt. (lb)	
First Stage	≥ 225,000
Second Stage	≥ 225,000
Upper Stages	≥ 40,000
Goal: no propellant chunks larger than 40,000 lbs after destruct	



Distant Focused Overpressure (DFO)

- DFO hazard is flying glass shards from broken windows
- TNT yield at explosion site initiates shock wave expansion
- At larger distances from explosion source shock front becomes sonic
- Shock front expansion modeled by ray tracing
- Adverse (caustic) atmospheric conditions bend sonic rays back toward the ground
- Overpressures above standard attenuation occur in regions where sonic rays are focused
- Significant DFO factors:
  - **TNT yield**
  - **Focusing overpressure gain**

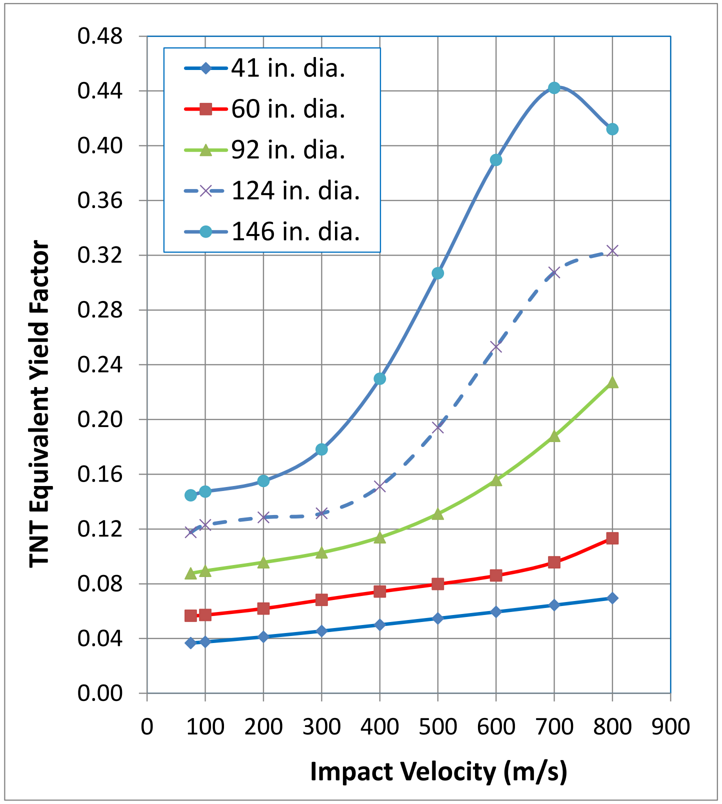


Focusing Region Affecting a Population Center

Drivers for Blast DFO

- Large solid rocket motor launch vehicles manufactured in the United States use HC 1.3 rocket propellant for their primary stages

- Testing shows HC 1.3 propellants do not detonate during rocket motor fallback
  - However, these propellants can release substantial amounts of energy
- Effective yield increases with motor diameter
  - Vehicles with unignited upper stages have the potential to create large shock waves
- Analyses indicated breaking motors into smaller pieces was the key to reducing blast during a fallback event
  - Solution must work for ignited and unignited stages



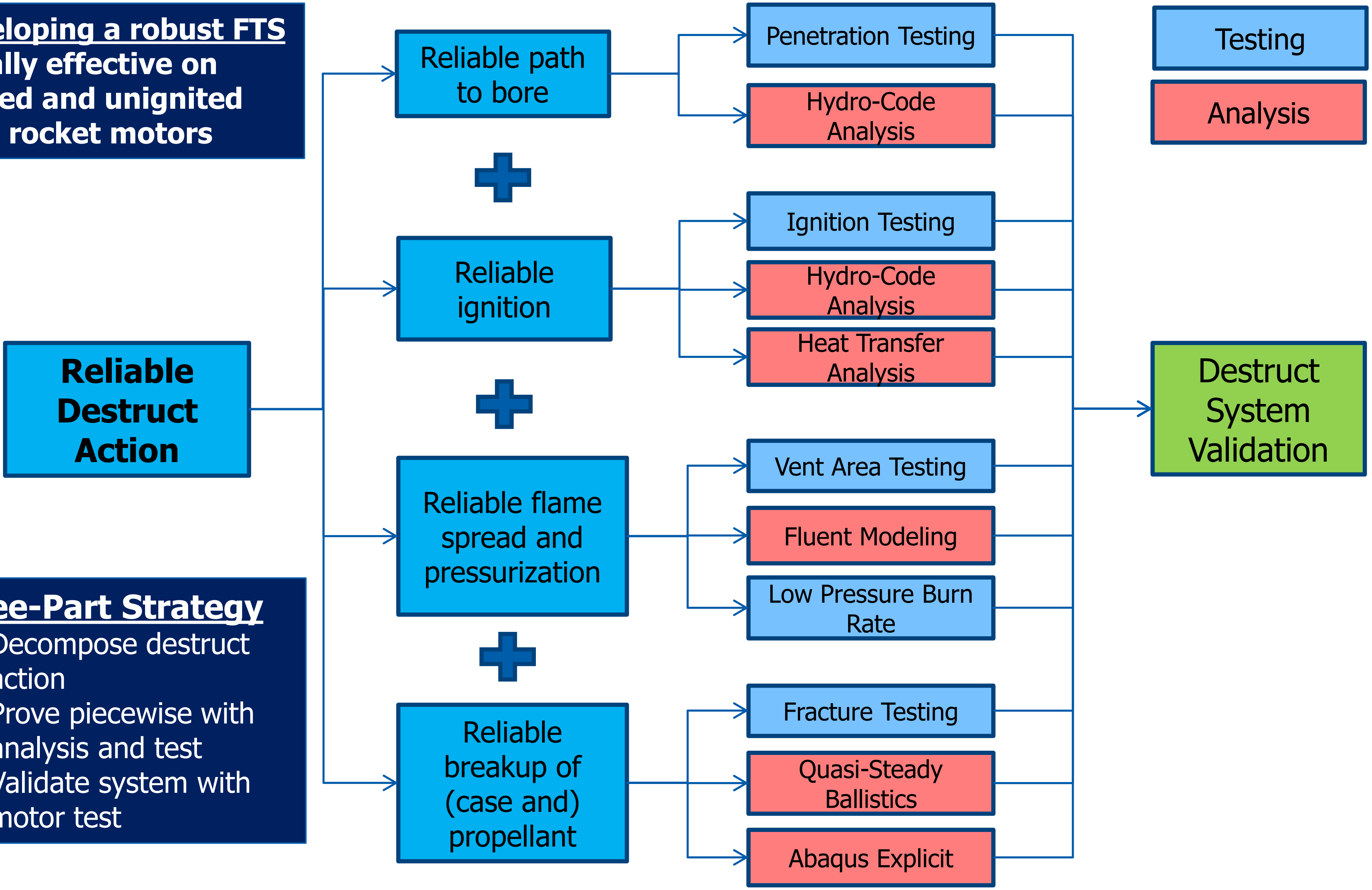
Destruct Design Elements

Analysis and Test for Every Destruct Element

Developing a robust FTS
Equally effective on ignited and unignited solid rocket motors

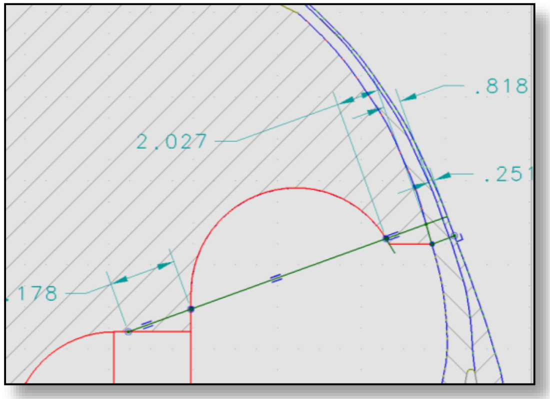
Three-Part Strategy

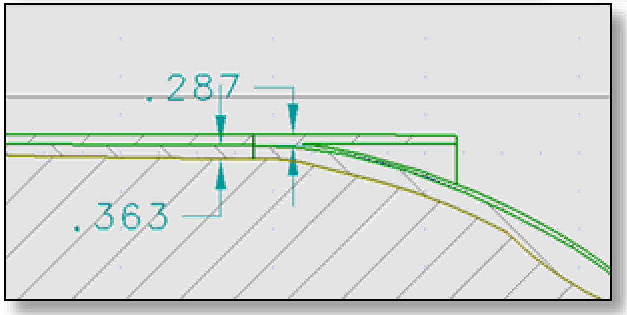
1) Decompose destruct action
2) Prove piecewise with analysis and test
3) Validate system with motor test

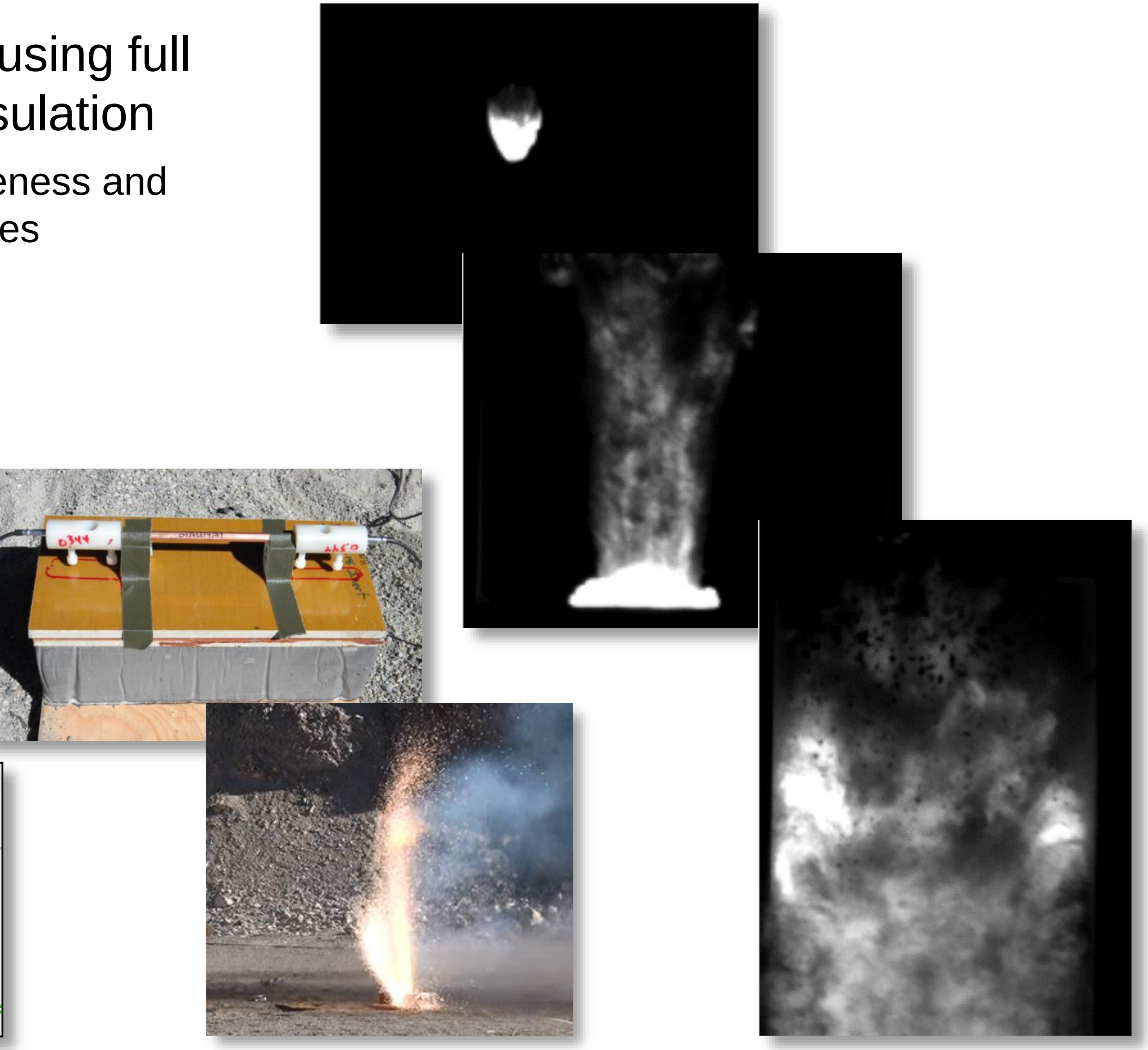


Piecewise Full-scale Testing Anchors Models

- LSC and CSC testing using full thickness case and insulation
  - Demonstrated effectiveness and selected shaped charges
  - Demonstrated ignition
  - Established timing



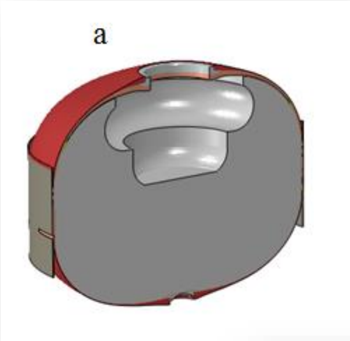




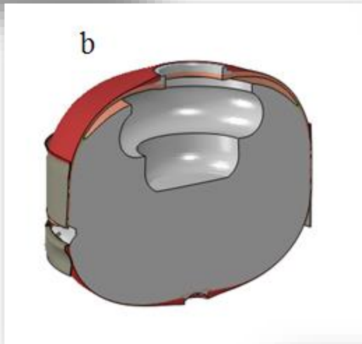
Real-Time Video Documents Motor Destruction

High-Speed Video of Test Confirms Analysis

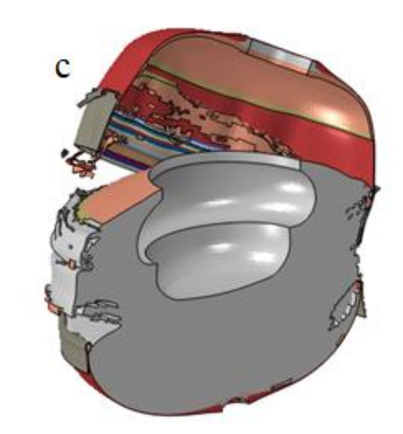
Structural Analysis & Modeling Match Actual Rocket Motor Destruct Test




Shaped charges fire




Circumferential crack propagates




Dome separates

Evaluation of Multi-Stage Launch Vehicle

- A feasibility evaluation study was performed for Northrop Grumman by ACTA to assess the blast DFO risks associated with an all solid propellant launch vehicle
  - Analysis was performed with and without improved destruct system
  - Sized for a current United States launch site

- Four-stage vehicle
  - First stage: CASTOR® 260
  - Second stage: CASTOR 260
  - Third stage: CASTOR 130
  - Fourth stage: CASTOR 30XL

- Total solid rocket propellant weight is in excess for 500,000 lb.

Original Blast DFO Risk Analysis

- Objective: Evaluate potential DFO risk associated with a proposed launch of an all-solid propellant vehicle at a US launch site
  - Contract with subject matter experts at ACTA, Inc. to perform the analysis
- Issues:
  - Nearest off-base population centers are within **3 km** of launch pad
  - Large solid rocket motors potentially have high TNT yields
  - No breakup of unpressurized upper stages
  - Proper treatment of explosive yield for intact impact of entire vehicle
    - Treat all HD 1.3 propellant treated as one source? (Conservative)
    - Treat each stage as an independent explosive source? (Optimal)
      - Considered more likely given orientation of vehicle stack at impact

Original Blast DFO Risk Analysis

- Analysis Approach
  - Model vehicle failure modes and resultant vehicle breakup conditions
  - Calculate explosive yield based on largest fragment size and impact velocity
    - Use PIRAT curves
    - Consider land versus water impacts
  - Construct TNT yield and probability pairs and develop a yield histogram
  - Perform blast DFO Monte Carlo simulations for 9,000 archived launch site weather balloon soundings and compare predicted risk with launch “Go” threshold of 80 x 10^{-6}
    - Perform uncertainty sampling on weather covariance
    - Loop over all yields
    - Loop over discrete azimuth directions

Original Blast DFO Risk Analysis Result

- **Average Launch Availability = 8.1% - UNACCEPTABLE**

Explosive Yield [LBM TNT]	Relative Probability
4000	3.92E-01
10000	8.98E-02
15000	7.99E-02
20000	6.42E-02
25000	3.17E-02
30000	6.51E-02
35000	9.36E-02
40000	1.13E-01
45000	2.74E-02
50000	1.33E-02
55000	9.53E-03
60000	8.33E-03
65000	4.24E-03
70000	3.42E-03
75000	2.24E-03
80000	1.42E-03
85000	4.52E-04
90000	2.03E-04
95000	2.28E-04
101250	7.31E-05
108750	4.31E-05
116250	2.32E-05
123750	4.65E-06
131250	6.68E-08

						OffBase	**OffBase**	**Launch**
Case	**Pop**	**#Cases**	**#Red**	**#Grey**	**#Green**	**Max Ec**	**Median Ec**	**Availability**
						x10^{-6}	**x10^{-6}**	
JanDay	Winter	428	170	197	61	1845	218	**14.25%**
JanNit	Winter	243	60	137	46	998	124	**18.93%**
FebDay	Winter	502	214	229	59	4578	231	**11.75%**
FebNit	Winter	231	49	132	50	1712	143	**21.65%**
MarDay	Winter	551	288	212	51	3333	321	**9.26%**
MarNit	Winter	252	61	149	42	813	154	**16.67%**
AprDay	Winter	535	259	230	46	2143	290	**8.60%**
AprNit	Winter	228	58	139	31	971	189	**13.60%**
MayDay	Winter	548	270	249	29	2043	295	**5.29%**
MayNit	Winter	248	54	177	17	921	178	**6.85%**
JunDay	Summer	542	403	133	6	4202	582	**1.11%**
JunNit	Summer	231	13	203	15	1020	126	**6.49%**
JulDay	Summer	529	423	105	1	3114	648	**0.19%**
JulNit	Summer	223	21	195	7	720	127	**3.14%**
AugDay	Summer	327	275	52	0	4823	847	**0.00%**
AugNit	Summer	252	38	204	10	787	138	**3.97%**
SepDay	Winter	553	357	188	8	14412	438	**1.45%**
SepNit	Winter	256	66	179	11	1148	199	**4.30%**
OctDay	Winter	521	305	189	27	2437	376	**5.18%**
OctNit	Winter	282	85	173	24	934	183	**8.51%**
NovDay	Winter	496	262	193	41	1844	329	**8.27%**
NovNit	Winter	260	81	153	26	980	201	**10.00%**
DecDay	Winter	522	234	204	84	1748	251	**16.09%**
DecNit	Winter	276	91	144	41	7332	183	**14.86%**

Enhanced FTS Breakup Blast DFO Risk Analysis

NORTHROP GRUMMAN

- Adverse results of baseline study were driven by intact stage 2 impacts following FTS or aerodynamic breakup
  - Stage 2 propellant weight is over 200,000 lb.
- Enhanced FTS breakup of stages 2 and 3 is estimated to reduce largest fragments to approximately 35,000 lb.
- Only concerned with largest fragments for DFO purposes

Mass	Number	Volume	Cube Dimension	Area	Beta	Delta-V	Grp Wt	Stage
[lbm]		[in^2]	[in]	[ft^2]	[lb/ft^2)	[ft/s]	[lbm]	
35,087	1	551,185	81.99	68.53	602	36	35,087	2
33,964	1	533,544	81.11	66.34	602	112	33,964	3
24,548	8	385,627	72.79	47.95	602	36	196,384	2
7320	1	114,991	48.63	14.30	602	187	7,320	3
4894	14	76,880	42.52	12.56	519	112	68,516	3
1329	2	20,877	27.54	5.27	336	185	2,658	2

Enhanced FTS Blast DFO Risk Analysis

NORTHROP GRUMMAN

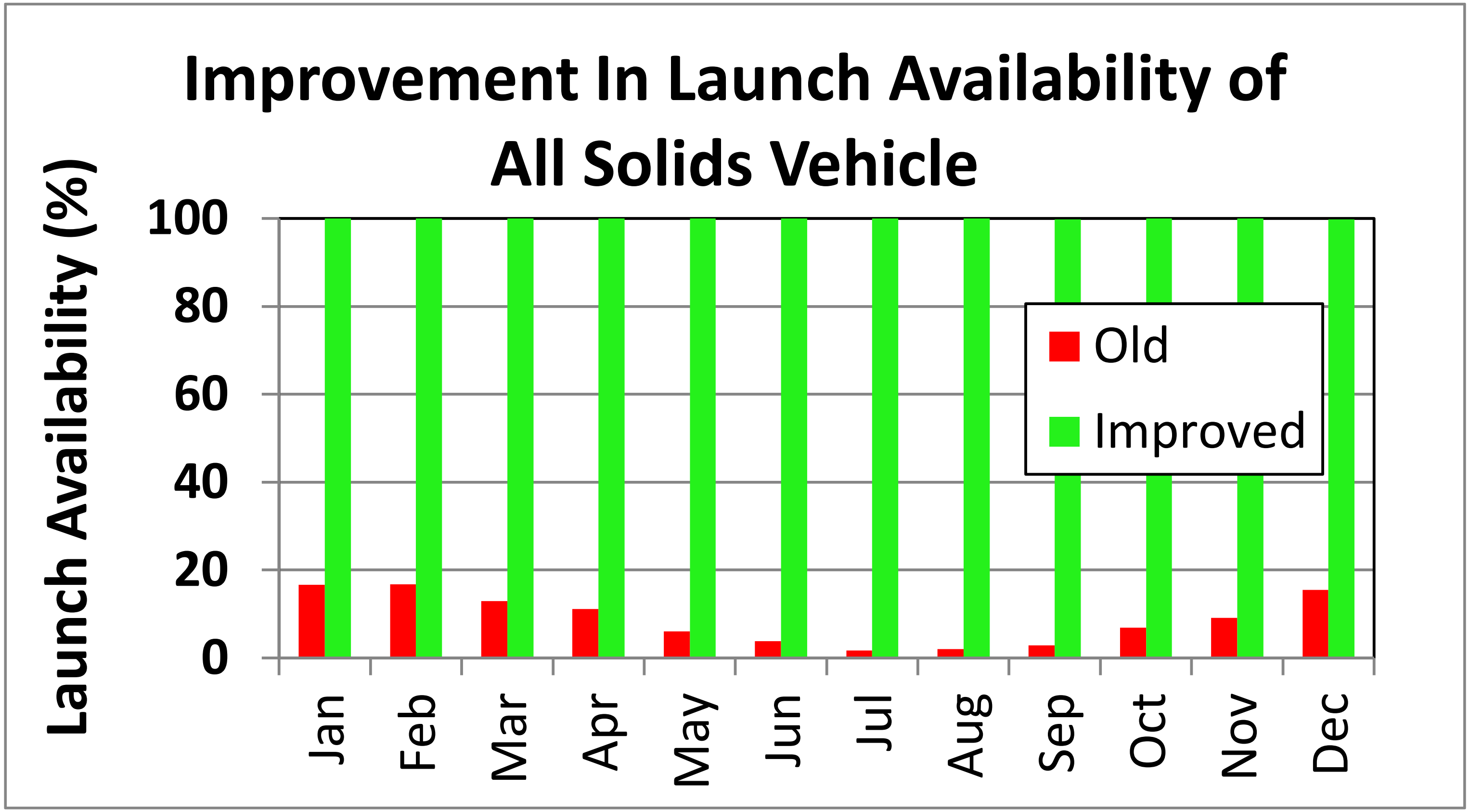
- Enhanced Breakup Results (**Average Launch Availability = 100%**)

Explosive Yield [LBM TNT]	Relative Probability
1000	4.15E-01
2000	9.95E-02
4000	3.24E-01
6000	1.24E-01
8000	3.73E-02
11000	8.08E-05
15000	0.00E+00
20000	0.00E+00
25000	0.00E+00
30000	1.45E-04
35000	3.25E-04
40000	9.65E-05

						OffBase	OffBase	Launch
Case	**Pop**	**#Cases**	**#Red**	**#Grey**	**#Green**	**Max Ec**	**Median Ec**	**Availability**
						x10^{-6}	**x10^{-6}**	
JanDay	Winter	428	0	0	428	5.6	0.7	100.00%
JanNit	Winter	243	0	0	243	3.6	0.5	100.00%
FebDay	Winter	502	0	0	502	18.5	0.7	100.00%
FebNit	Winter	231	0	0	231	5.9	0.5	100.00%
MarDay	Winter	551	0	0	551	9.0	0.9	100.00%
MarNit	Winter	252	0	0	252	3.4	0.5	100.00%
AprDay	Winter	535	0	0	535	5.6	0.8	100.00%
AprNit	Winter	228	0	0	228	3.2	0.6	100.00%
MayDay	Winter	548	0	0	548	5.9	0.8	100.00%
MayNit	Winter	248	0	0	248	3.4	0.6	100.00%
JunDay	Summer	542	0	0	542	9.1	1.3	100.00%
JunNit	Summer	231	0	0	231	3.8	0.4	100.00%
JulDay	Summer	529	0	0	529	7.2	1.4	100.00%
JulNit	Summer	223	0	0	223	2.8	0.4	100.00%
AugDay	Summer	327	0	0	327	9.8	1.9	100.00%
AugNit	Summer	252	0	0	252	3.0	0.5	100.00%
SepDay	Winter	553	0	2	551	125.8	1.3	99.64%
SepNit	Winter	256	0	0	256	4.3	0.7	100.00%
OctDay	Winter	521	0	0	521	6.7	1.1	100.00%
OctNit	Winter	282	0	0	282	3.0	0.7	100.00%
NovDay	Winter	496	0	0	496	5.2	1.0	100.00%
NovNit	Winter	260	0	0	260	3.9	0.7	100.00%
DecDay	Winter	522	0	0	522	5.4	0.7	100.00%
DecNit	Winter	276	0	1	275	50.0	0.6	99.64%

Launch Availability Comparison

- Benefits of using new FTS system is obvious



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Enhanced FTS Breakup Blast DFO Risk Analysis

- Fragmentation uncertainty evaluation
  - Arbitrarily increased size of largest fragments by 50% (52,600 lb.)
    - No change in yield histogram
    - TNT yields dominated by fourth stage (55,000 lb.)
  - Arbitrarily increased size of largest fragments by 100% (70,000 lb.)
    - No change in yield histogram if fragments defined as annular segments or cubes
    - TNT yields dominated by fourth stage (55,000 lb.)
- Effect of changing fragment shape designation
  - Treated large fragments (70,000 lb.) as full cylindrical segments
  - Segments have higher TNT yield than cubes or annular segments of the same weight
  - Yield histogram increased yields in 15,000 to 25,000 lbs. range
  - Launch availability drops to around 80%

Explosive Yield [LBM TNT]	Relative Probability
1,000	2.80E-01
2,000	9.27E-02
4,000	1.70E-01
6,000	4.33E-02
8,000	1.10E-01
11,000	2.21E-01
15,000	**6.53E-02**
20,000	**1.61E-02**
25,000	**7.17E-04**
30,000	1.77E-04
35,000	3.25E-04
40,000	9.65E-05

Conclusions

- Launch of a large solid propellant vehicle from some sites can be hampered by potential glass breakage hazards associated with explosion of large upper stages

- Blast DFO launch availability analyses indicate very restricted launch availability at 8% with an intact upper stage weighing over 200,000 pounds

- Analysis indicates that reducing the size of propellant fragments mitigates blast DFO risk

- Northrop Grumman demonstrated the capability of an enhanced FTS to break up an unpressurized upper stage propellant grain

- When advanced FTS technology was applied to this example, launch availability increases to nearly 100%

Acknowledgements

- This work was internally funded
- Randy Lyman and Ron Lambert of ACTA, Inc. for their excellent and timely analysis
- Helpful discussions with range safety officers from multiple launch sites
- Numerous Northrop Grumman team members who contributed to this work