U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND – ARMAMENTS CENTER

Developments in Metal MEMS Latching, Setback Sensing Mechanisms

Kevin M. O'Connor Jr.

Mechanical Engineer

U.S. Army CCDC - Armaments Center, Fuze Division

04 AUG 2020

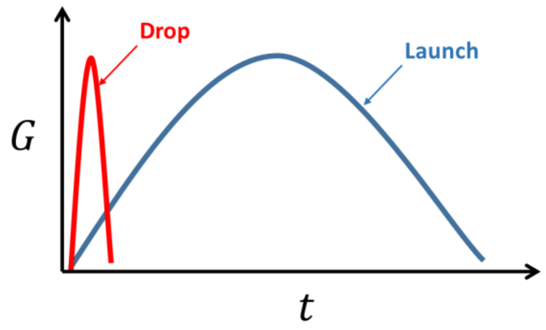
Project Background

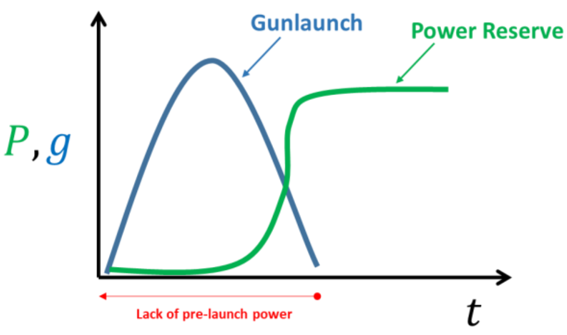
Fuze Community Need and MEMS Design Process

HISTORY

- **The Army fuzing community has a need for a high-G, un-powered latching sensor**
  - Distinguish between valid gun launch, and the vibration and mechanical shock exposures of the tactical environment

- **Electronic Safe and Arm Devices (ESAD)**
  - Need for a mechanical sensor within the fuze electronics that can record and report whether or not a true gun launch has occurred
  - There can be no powered launch-detecting sensors because the ESAD battery takes time to power up
  - What is needed is an unpowered mechanical switch that could detect launch (and reject handling drops) by latching during the no-power phase and that could then be queried later when the fuze circuit and ESAD wants to function

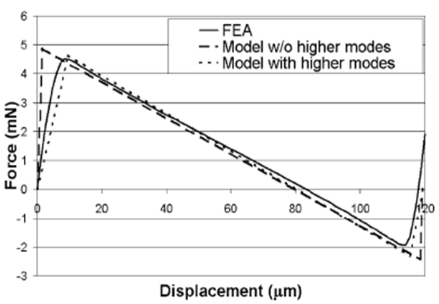




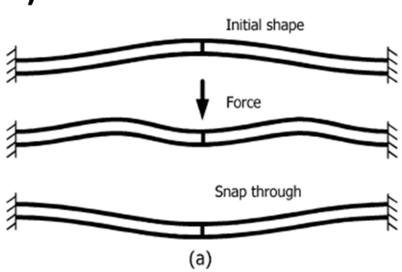
MEMS DESIGN

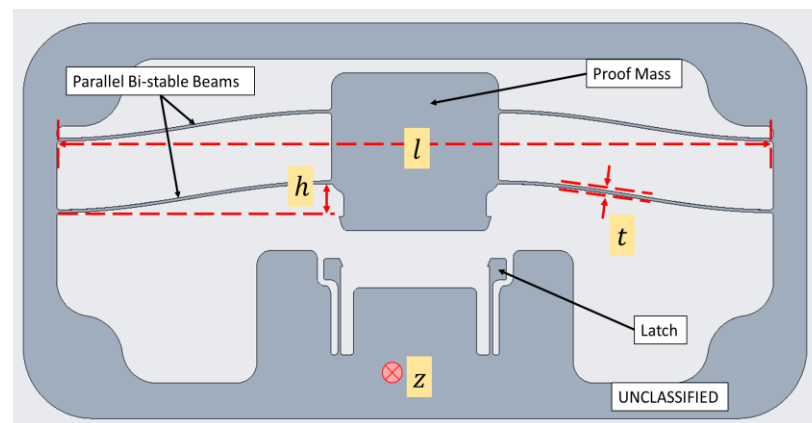
- **Bi-stable mechanism in a curved parallel beam design**
  - A minimum force threshold required to actuate a ‘snap-through’ effect. Forces greater than this threshold will result in an unrecoverable ‘snap-though’ of considerable distance
  - The force to actuate this mechanism can be estimated from: $F_{snap-thru} = C * \frac{Etz^3 h}{l^3}$
  - This design includes latching barbs to catch the proof mass

a)



b)

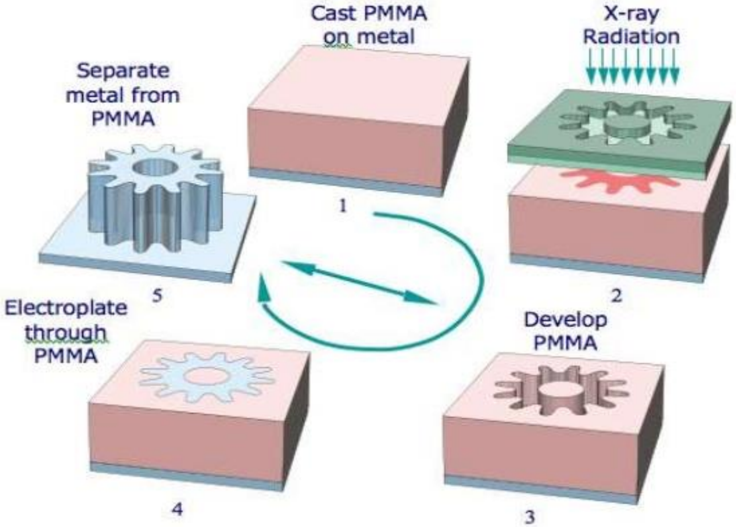




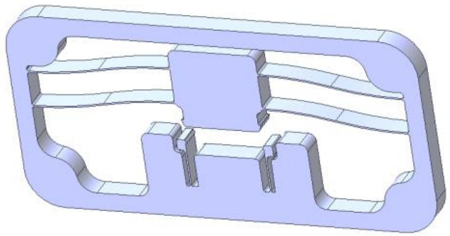
- Design size is roughly 3mm x 6mm, with a thickness of less than 0.5mm

LIGA FABRICATION PROCESS

- **Precise lithography**
  - A sensitive polymer is bonded to an electrically conductive substrate
  - Allows dimensional control of micro-sized geometrical features
  - Ability to fine tune the geometry to the appropriate 'snap-through' force
- **HT MicroAnalytical**
  - Fabricated 5 variant wafers of the MEMS switch design.
  - Used a LIGA MEMS foundry with an electroplated Nickel alloy material



LIGA Processess

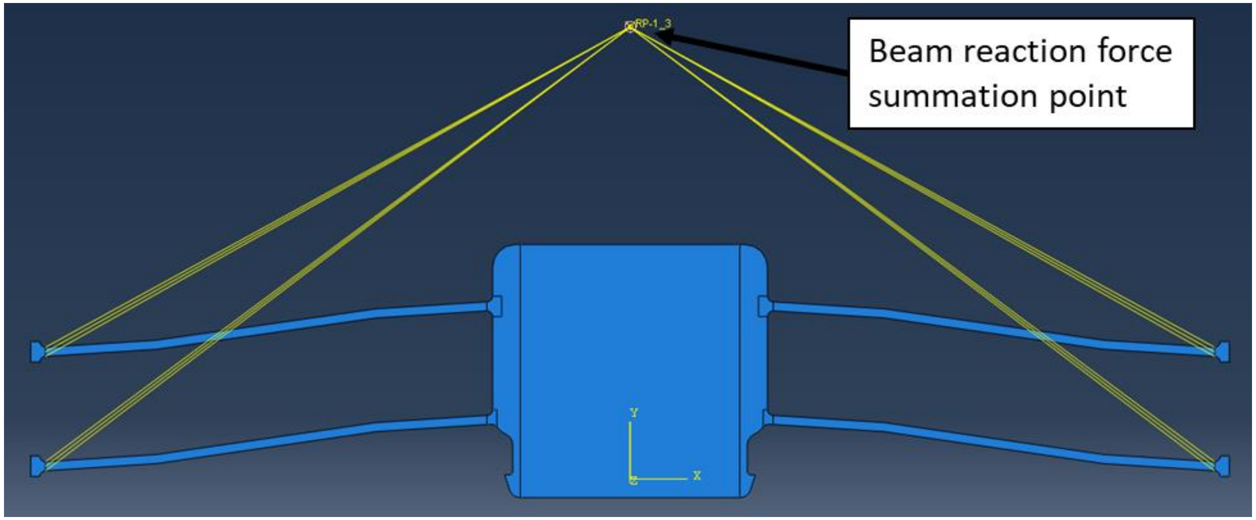


Mechanical Characterization

Numerical, Analytical & Experimental Testing

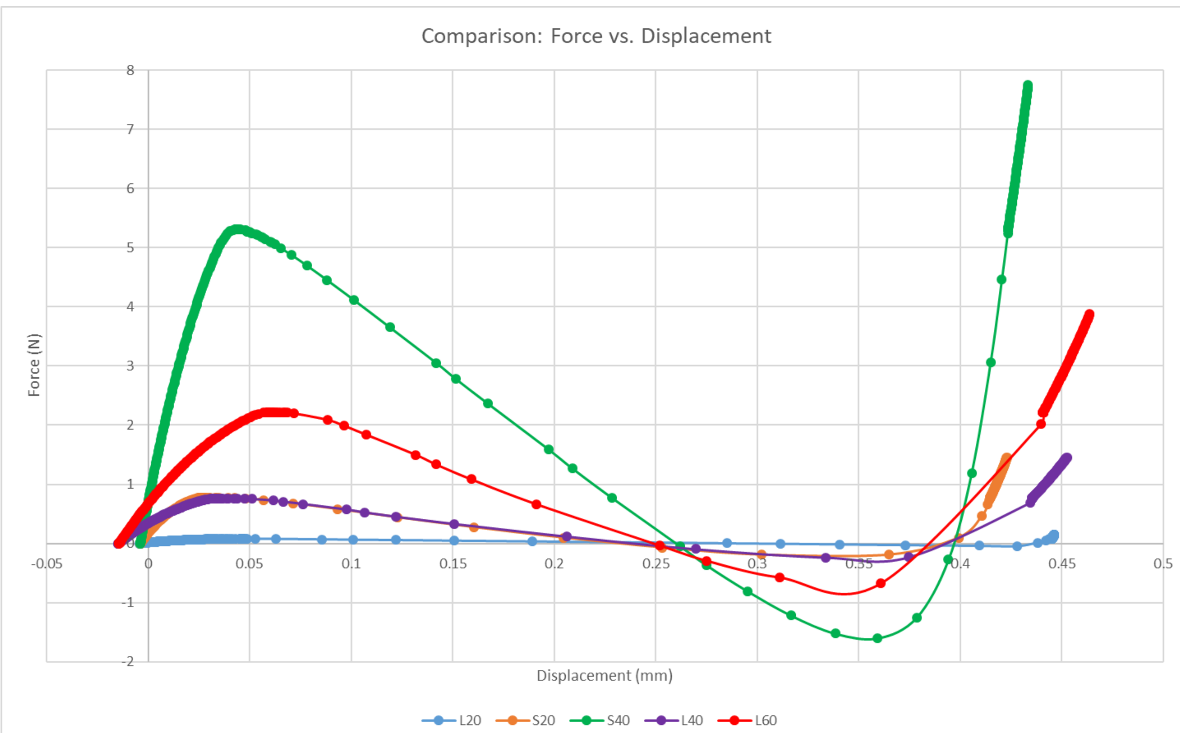
FINITE ELEMENT ANALYSIS - SETUP

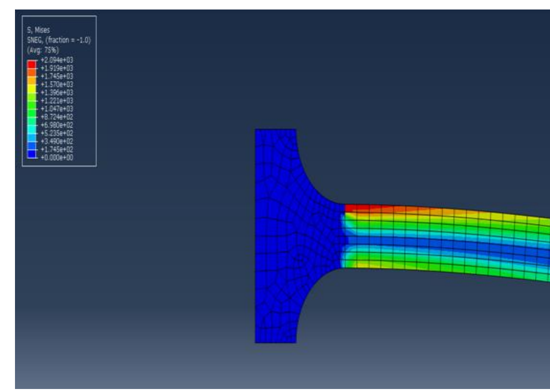
- **Abaqus 2018 was used to extract the static closure force of the five switch variants**
  - Symmetry of the switches in the z-direction, a homogeneous shell section was utilized
  - To extract the total reaction force from the system into a graph, a reference point was created above the switch and was coupled to the ends of the four beams
  - The displacement of a single node at the bottom of the switch mass was also extracted into a graph
  - The applied shell edge load varies between each design; Static, elastic analysis



FINITE ELEMENT ANALYSIS - RESULTS

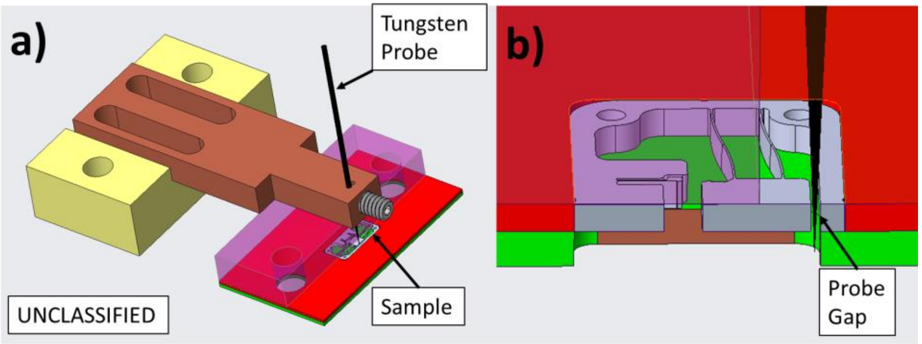
- **Switch variant comparison**
  - Combining the two curves from the history output allows the creation of the Force vs. Displacement graph for each switch design
  - The location of the max von Mises stress for each design is shown to be located at the top surface of the beam's edge furthest from the central mass

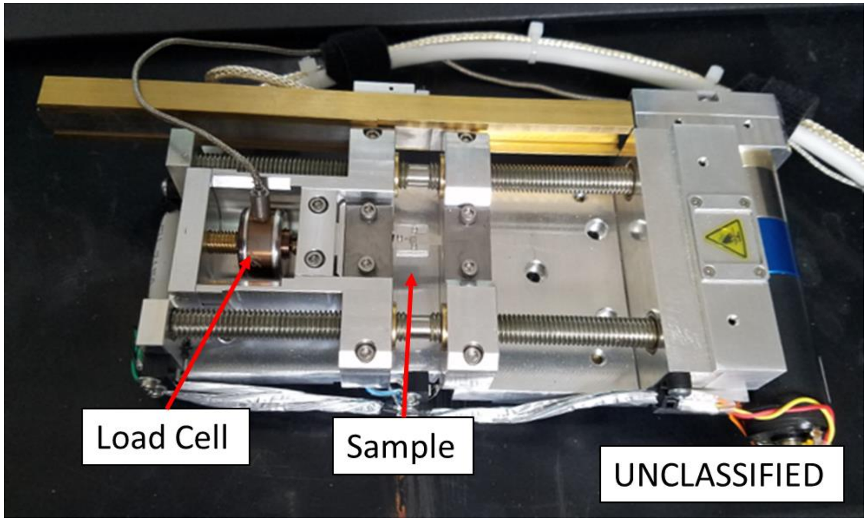




TENSILE TEST - SETUP

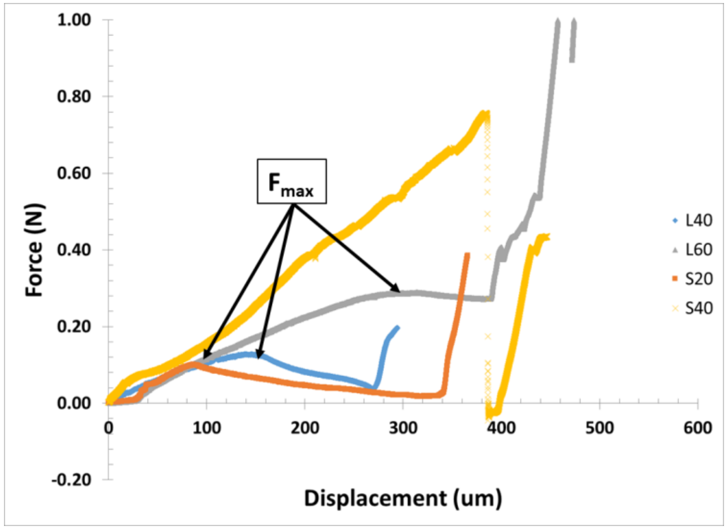
- **Displacement-controlled miniature tensile test apparatus (MTIfullam SEMtester)**
  - A sub-mm tungsten probe was used to engage and actuate the proof mass of the latching switch
  - After the probe made contact with the sample proof mass and the load was zeroed, the test apparatus was operated at 25.4 µm/s until the test was stopped. The load cell recorded the force at 1000 Hz
  - The overall system spring constant of the parallel beam structure, K, can be extracted from the linear region of the F vs displacement slope before the snap-thru actuation has occurred

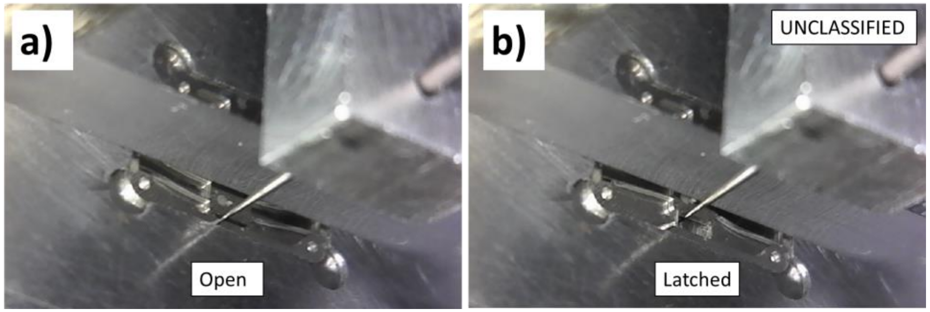




TENSILE TEST - RESULTS

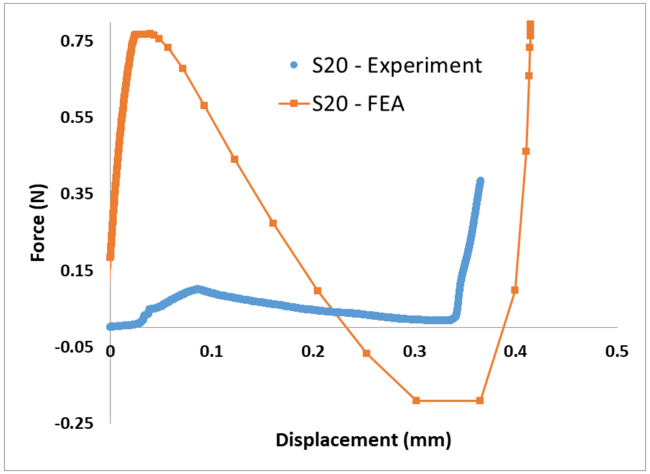
- **Four of the five designs (S20, S40, L40, and L60) were evaluated with the MTS tensile test apparatus**
  - The Force vs. Displacement plot includes key features such as the linear ramp up of force to F_{max} at which point the force "snaps-thru" and decreases to a force minimum
  - The S40 switch had a larger strength than the bending stiffness of the tungsten probe and the probe was bent or curled before the snap-thru event

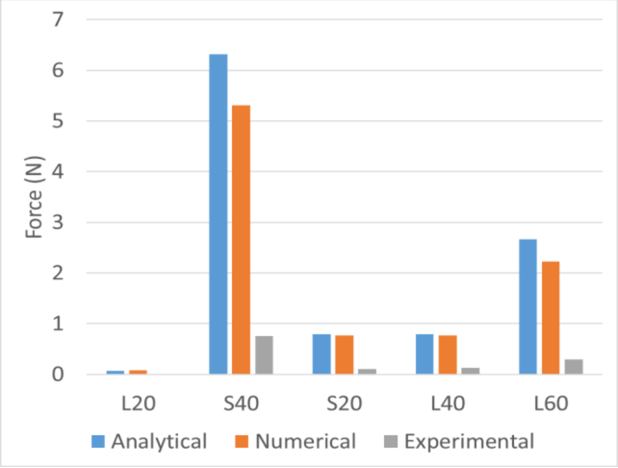




ANALYSIS RESULTS COMPARISON

- **The bi-stable nature of the MEMS switches was observed in both experiment and simulation**
  - The numerical analysis (FEA) matches quite closely with the analytical analysis. The experimental response is systematically lower in all cases
  - There was visual evidence that during tensile tests the bi-stable latches did not rapidly snap-thru as expected but simply tracked the motion of the tungsten pin as the force was applied
  - Doubling the beam width (t) of the switch increased the force to snap-thru. Halving the beam length (l) resulted in a similar increase



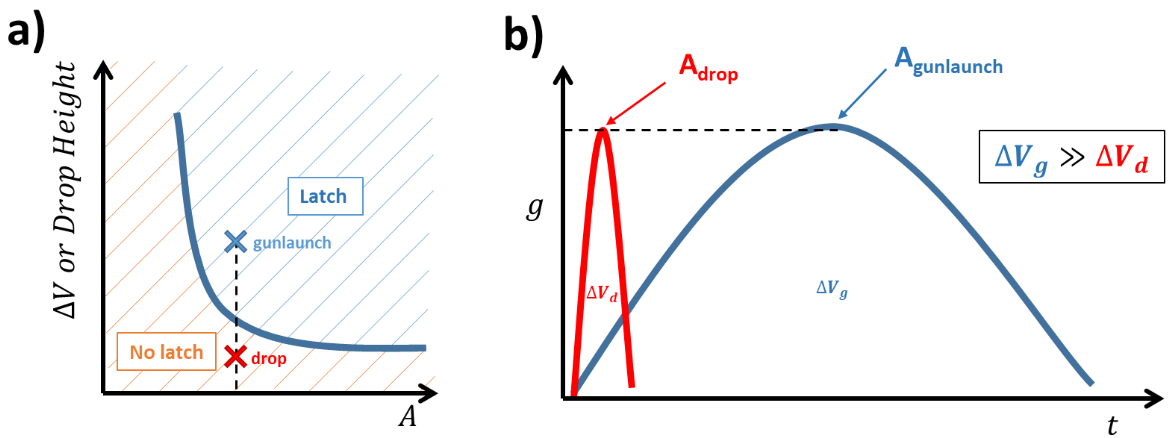


Sensitivity Characterization

Drop Environment & Airgun Testing

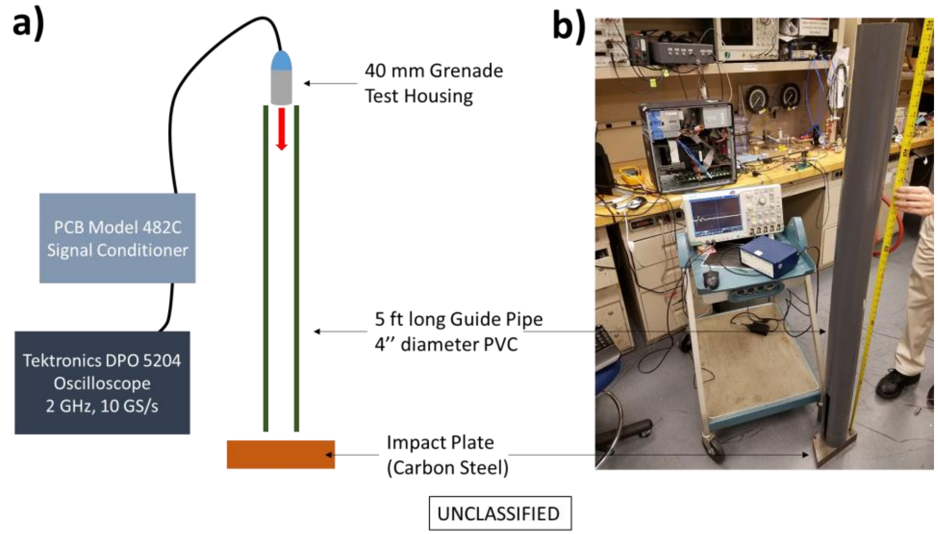
SENSITIVITY GRAPHS

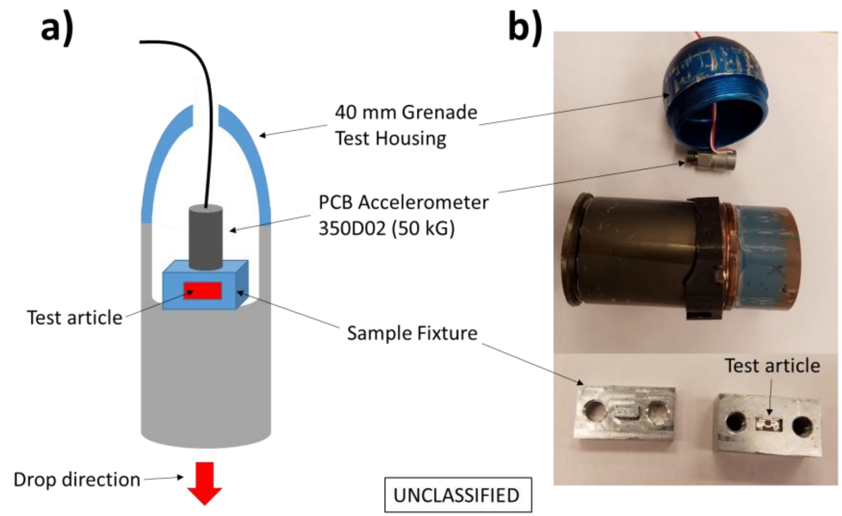
- **Show thresholds for drop height or corresponding change in velocity (ΔV) for a munition that impacts a surface base down**
  - This sensitivity curve predicts whether a spring-mass system will latch or not latch for a given acceleration amplitude (A) of known pulse duration
  - The geometric variations in each design determine the shape and location of the sensitivity curve



DROP TESTING - SETUP

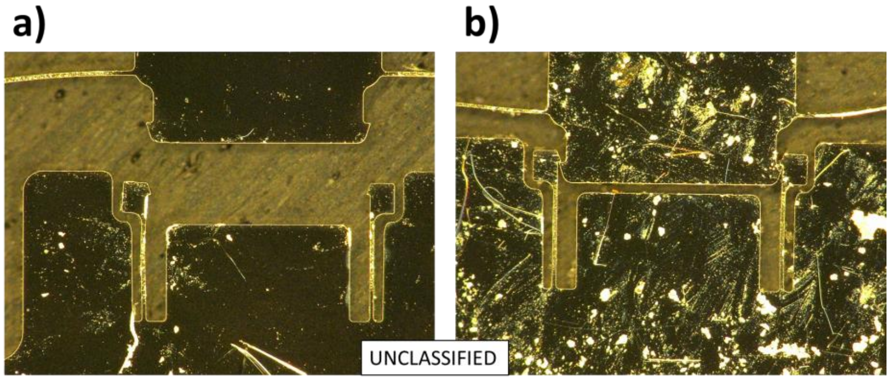
- **Design**
  - 4 inch diameter, 5 foot long PVC tube was used to guide drop fixture onto the impact surface
  - 40 mm grenade drop fixture
  - 2 inch thick steel plate was used as the impacting surface
  - a 9 foot drop was used to evaluate stiffer spring design iterations
  - oscilloscope was triggered to measure and record the first few hundred microseconds following impact





DROP TESTING - RESULTS

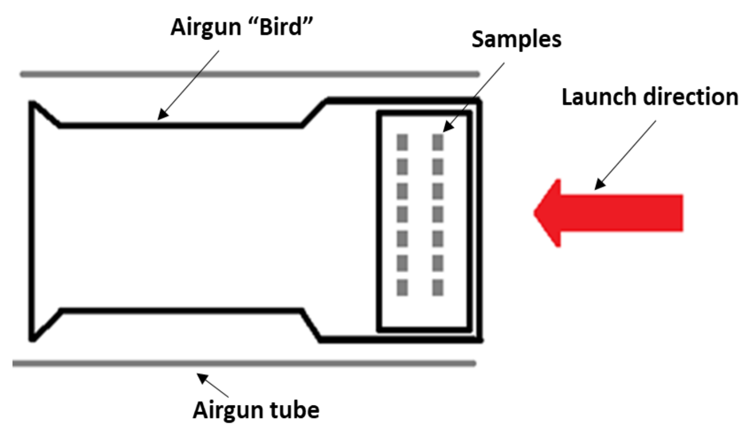
- **Component Testing**
  - The average peak acceleration experienced under 5 foot drop is calculated to be 14,720 g's for the test setup.
  - After each drop, the test fixture was carefully disassembled to inspect the latching status of the LIGA MEMS mechanism
  - L20 was found to frequently latch under a 5 foot drop
  - Other designs did not latch in a 5 foot drop and were then subjected to a more severe drop environment of 9 feet



Drop Height (feet)	Version	Average Half Sine Peak Duration (s)	Average Max g's	Latched	%
5	L20	8.2E-05	16,680	6/9	66.7%
9	S40	7.7E-05	22,760	0/4	0%
9	S20	8.3E-05	21,150	0/4	0%
9	L40	8.6E-05	12,480	0/8	0%
9	L60	7.8E-05	16,980	0/4	0%

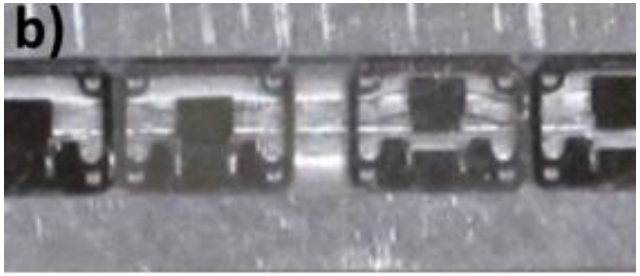
AIRGUN TESTING - SETUP

- **155mm air cannon**
  - Switch fixture was oriented so that the setback from the airgun was the only force acting on the switches
  - Fixture housed 4 variants of the switch design
  - The bird itself with the fixture weighed a total of 24 lbs and was launched at a pressure of 18,150 psi



AIRGUN TESTING - RESULTS

- **The bird experienced a max of 15,100 g's**
  - All four of the L40 switches latched while three of the four S20 switches latched. The S40 and L60 switches remained unlatched
  - After the airgun test was completed, the test fixture was carefully disassembled to inspect the latching status of each switch



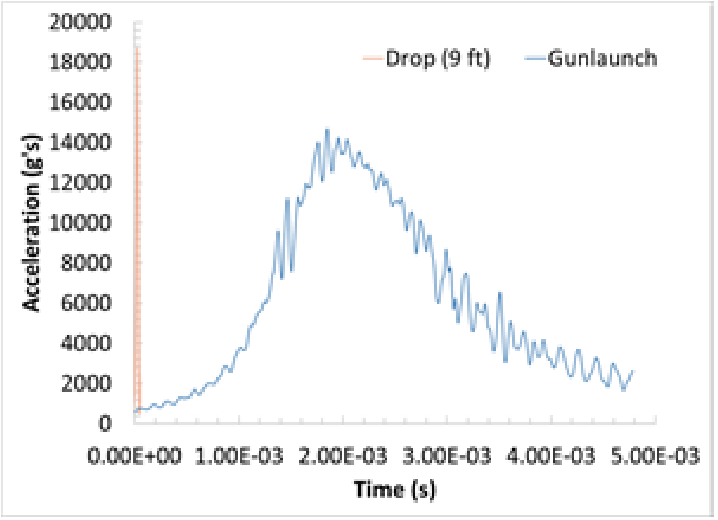
Airgun Peak Pressure (psi)	Version	Half Sine Peak Duration (s)	Max g's	Latched	%
-	L20	-	-	-	-
18,150	S40	3.7E-03	15,120	0/3	0%
18,150	S20	3.7E-03	15,120	3/4	75%
18,150	L40	3.7E-03	15,120	4/4	100%
18,150	L60	3.7E-03	15,120	0/3	0%

TESTING COMPARISON

- **Drop vs. Airgun**
  - Demonstrated that certain designs of the bi-stable latching mechanism would latch in airgun environments would not latch in 9-ft drop environments
  - The acceleration amplitude ratio (drop:gunlaunch) is typically 1:1 while the pulse duration ratio can be as much as 1:45

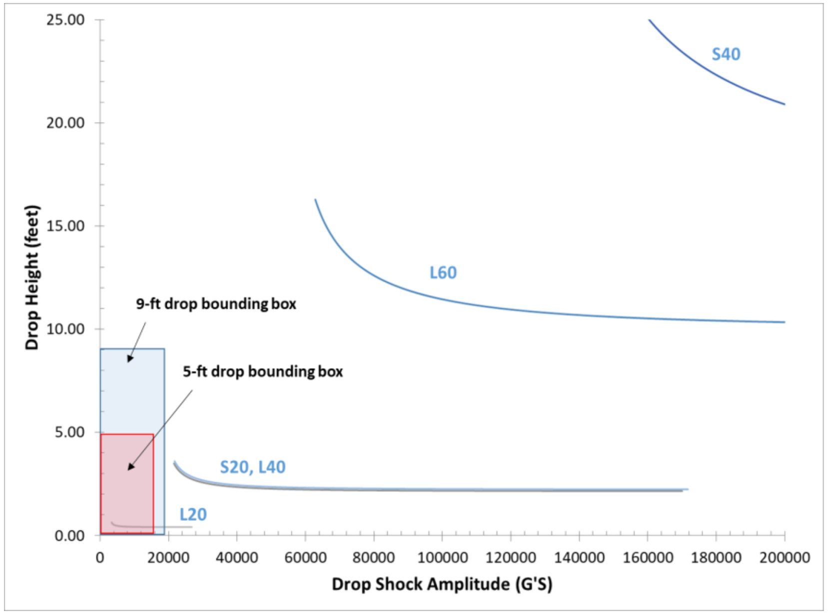
Version	5-ft drop	9-ft drop	Airgun
L20	67%	-	-
S40	-	0%	0%
S20	-	0%	75%
L40	-	0%	100%
L60	-	0%	0%

a)



CONCLUSIONS

- **Resultant Sensitivity Curves**
  - The S20 and L40 sensitivity curves predict that these designs are on the marginal edge of latching in 9-ft drop environments.
  - The L60 and S40 designs are sufficiently stronger and would require a much larger amplitude shock and pulse duration to latch
  - The implications of this work are that these bi-stable mechanisms may be useful in munitions packages that have higher g-level acceleration profiles



PATH FORWARD

- **DTIC Reports Currently in Review Process**
  - "Analysis of LIGA MEMS Parallel Beam, Bi-stable Latching Metallic Mechanisms - Part 1 - Mechanical Characterization (in preparation)," DTIC, Picatinny Arsenal, 2019. J. R. Smyth, K. M. O'Connor and A. DeSantis
  - "Analysis of LIGA MEMS Parallel Beam, Bi-stable Latching Metallic Mechanisms - Part 2 - Sensitivity Characterization (in preparation)," DTIC, Picatinny Arsenal, 2019. J. R. Smyth, A. Warne, K. M. O'Connor, A. DeSantis and S. Genberg

- **Joint Fuze Technology Program (JFTP) - Project**
  - 21-G-035 6.2 Time Integrating Miniature Setback Switch (TIMSS)
    - Time-integrating features (like a ZigZag) would enable functioning in a less high-g sensitivity range
    - Similar testing of designs using three different manufacturing methods:
      - MEMS-based planar technique
      - micro-Electric Discharge Machining (μ-EDM) planar technique
      - micro additive manufacturing (AM, 3D printer) three dimensional technique

Questions?

REFERENCES

- **J. R. Smyth, K. M. O'Connor and A. DeSantis, "Analysis of LIGA MEMS Parallel Beam, Bi-stable Latching Metallic Mechanisms - Part 1 - Mechanical Characterization (in preparation)," DTIC, Picatinny Arsenal, 2020.**

- **J. R. Smyth, A. Warne, K. M. O'Connor, A. DeSantis and S. Genberg, "Analysis of LIGA MEMS Parallel Beam, Bi-stable Latching Metallic Mechanisms - Part 2 - Sensitivity Characterization (in preparation)," DTIC, Picatinny Arsenal, 2020.**