USAF NEEDS/DIFFERENCES, CURRENT RESEARCH & IDENTIFIED KNOWLEDGE GAPS w/ FUTURE EVTOL SYSTEMS

Dr. Casey W. Pirnstill, AFRL/711th HPW/RHBFD
Biomedical Impact of Flight Branch - Biodynamics Section

Mr. Nathan Wright, AFLCMC/WNU
Aircrew Egress & Survival Branch

Brief Date: JAN-19-2021

Outline

I. USAF Research & Acquisition Areas of Interest

- Who We Are!
  - ✓ ***Research Focus & Unique Capabilities***

II. Re-evaluate Current Crash Environment For EVTOL Certification Development

- **Rotorcraft Crashworthiness**, Mishap History Summary (Military Aviation)
- Define **eVTOL** Design Configurations & How Systems Will Be Utilized (Mission Envelope)
- Understand **eVTOL** Crash Differences Compared W/ Legacy Aircraft (FAR 23)/Rotary (FAR 27) Mishaps
- **eVTOL** Operational Expectations & Crashworthiness Moving Forward
  - ✓ ***Evaluate AW*** Using Combo (Aircraft/Rotorcraft) Requirements

III. The Gaps: *Current USAF Airworthiness Certification Processes (Transport Aircrafts & Rotorcraft)*

IV. Differences In USAF & FAA AW Certification Process: *(Transport Aircrafts/Rotorcraft)*

- ***USAF AW*** Process Risk Based & ***FAA AW*** Process (Pass/Fail)
- Lack Injury Risk Curves, ***Pass/Fail*** Criteria For Most FAA Criteria Locations
- ***FAA*** Limited Anthro Range, Include, 50th% Hybrid III Aero/FAA/ES-II: *All 50th% Occupants*
  - ✓ ***Need valid injury risk curves, across full anthropometric range*** *(5th% Female thru 95th% Male)*

V. Examples Of Recent Seat AW Programs & Resulting Issues Based Existing STD Gaps

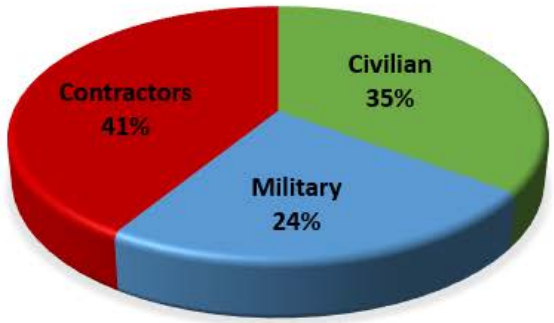
- **Military Rotorcraft Seating**
- **C-17/C-130**; Negative Pressure Conex/Conex Light (NPC/NPCL) Side-Facing Troop Seat

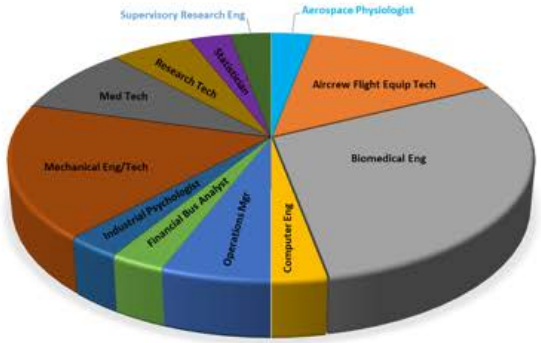
711TH HPW/RHB & AFLCMC/WN:
Who We Are!

As part of a research effort at the request of AMC & AFOTEC, Biodynamics Team conducted impact assessment of C-17 side-facing troop seats for integration into Negatively Pressurized Conex (NPC) model, which was developed to support COVID-19 relief efforts by transporting infectious, ambulatory & litter patients in global operations

Why AFRL *Aircrew Biodynamics & Protection Team?*

- **Expertise:**





- **Unique DoD Facility:**

Horizontal Impact Accelerator
Up to 120 G

Vertical Deceleration Tower
Up to 35 G

SIXMODE Vibration Table
Program any vibration signature

Vertical Impulse Accelerator

Man-Rated Acceleration/Vibration

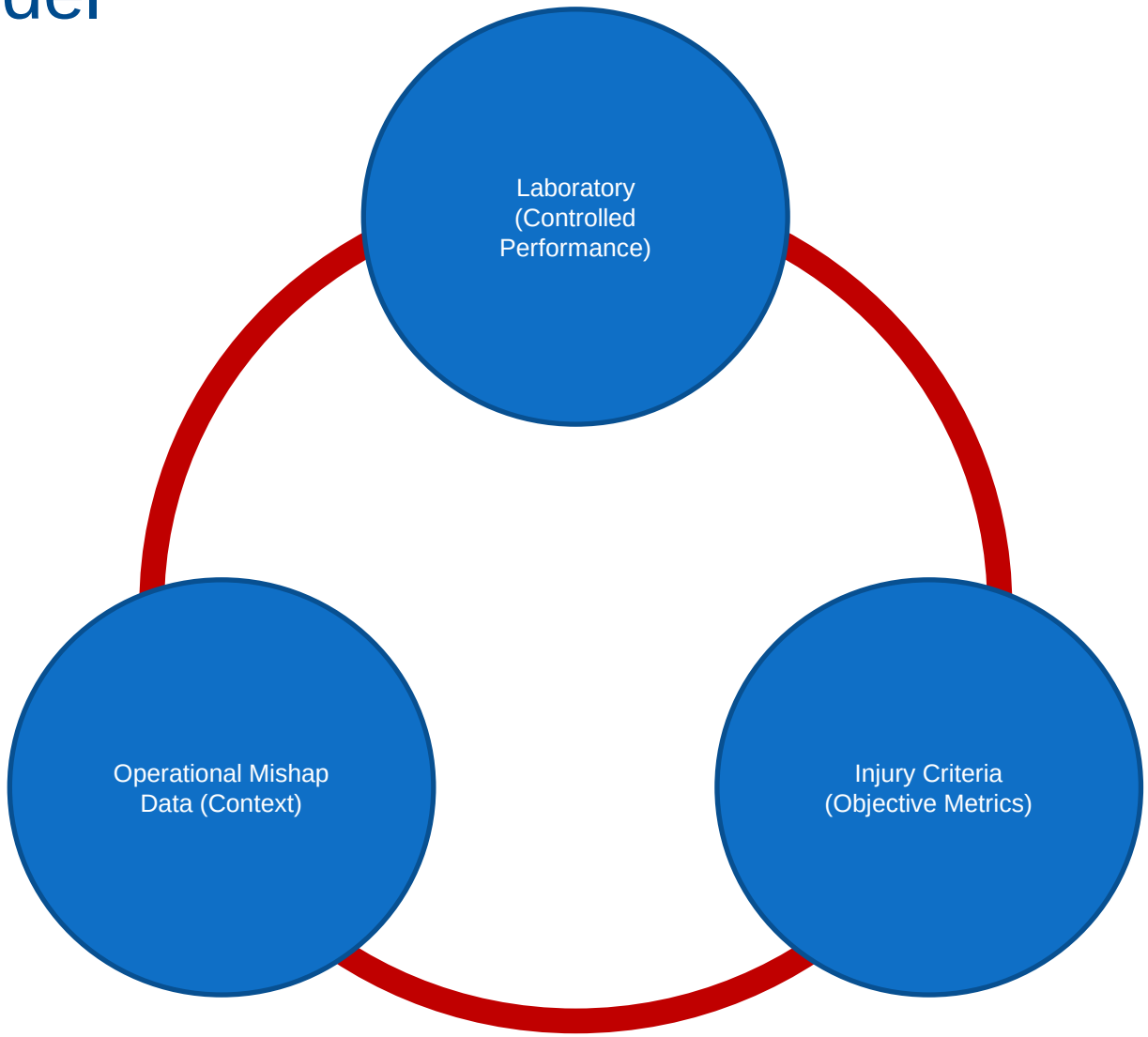
Resources

- *Civilians*: 12
- *Military*: 8
- *Contractors*: 15

Big Picture Questions:

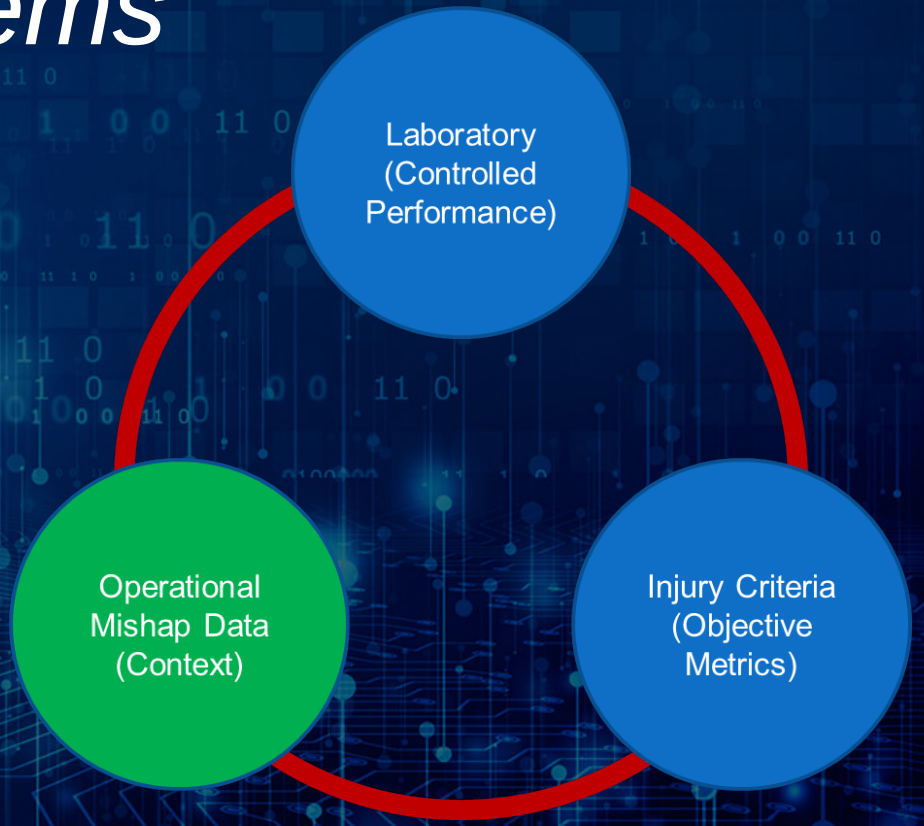
- Do current USAF injury risk requirements, identified in airworthiness standards, continue to improve occupant protection in Aircraft, Rotorcraft & VTOL seat design applications?
- How do we define considerations for survivable in USAF Operational Mishaps & is definition same across Gov't agencies?
- Is equivalent occupant protection expected in VTOL seating design certification processes, using existing requirements?
- What crash profiles should be use to assess VTOL occupant safety in seating platforms? *(combined rotorcraft/aircraft crash profiles)*
- How do we further improve mishap survivability for cabin occupants in future seating system designs?
- Do current USAF crash survivability requirements allow equivalent injury risk identification across expected occupant anthropometric ranges?

Overarching Model

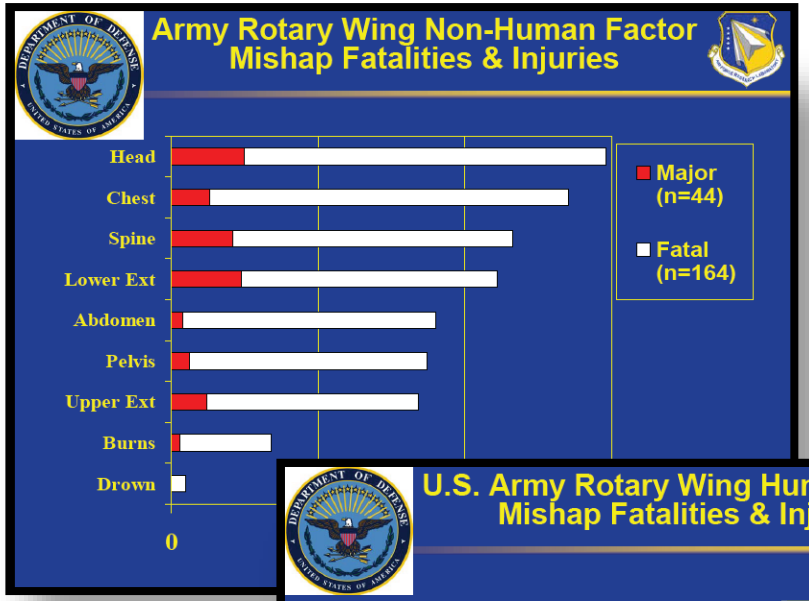


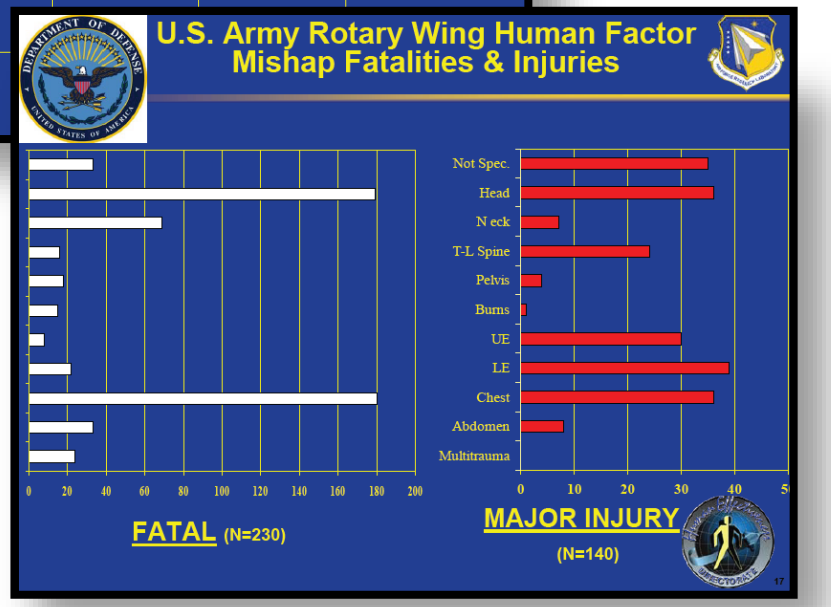
Evaluate Crash Safety Envelope:

Development Of Certification Requirements For VTOL Occupant Seating Systems



Rotary Wing (Army) Operational Mishap Data





TOP 10 MAJOR AND FATAL INJURIES:

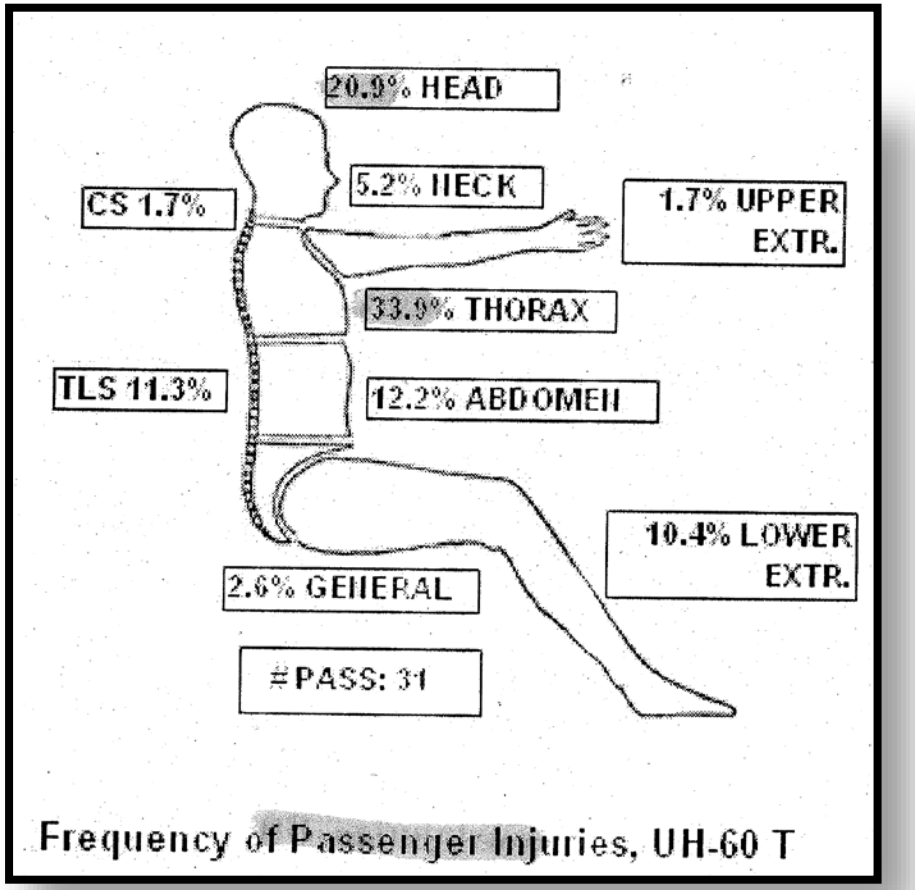
1. Head
2. Chest
3. Lower Extremities
4. Spine
5. Abdomen
6. Upper Extremities
7. Pelvis
8. Multi-trauma
9. Neck
10. Not Spec

*Potentially fixed w/5pt restraint

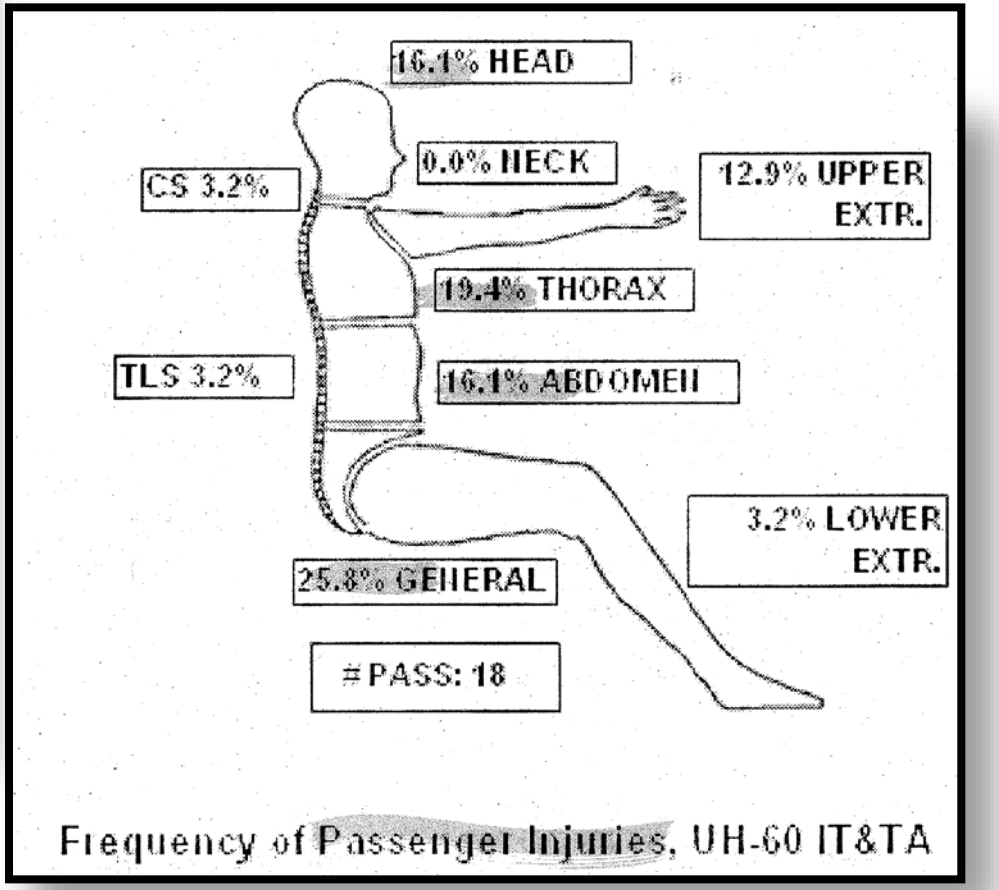
*** Rate of injury for cabin occupants significantly greater than pilot/copilot**

Mapes, P.B., Kent, R., Wood, R, "DoD Helicopter Mishaps FY 85-05: Findings and Recommendations", Defense Safety Oversight Council, OSD 09-S-1351, 2008.

Army UH-60 Operational Mishap Data



Labun, Lance, "Rotorcraft Crash Mishap Analysis", RDECOM TR 09-D-45, September 2009.



Eiband "Moderate" Injury Definition

"Moderate" contusions, lacerations, abrasions in any area(s) of the body. Sprains of the shoulders or principal articulations of the extremities. Uncomplicated, simple or green-stick fractures of extremities, jaw, or malar structures. Concussion as evidenced by loss of consciousness not exceeding 5 minutes, without evidence of other intracranial injury.

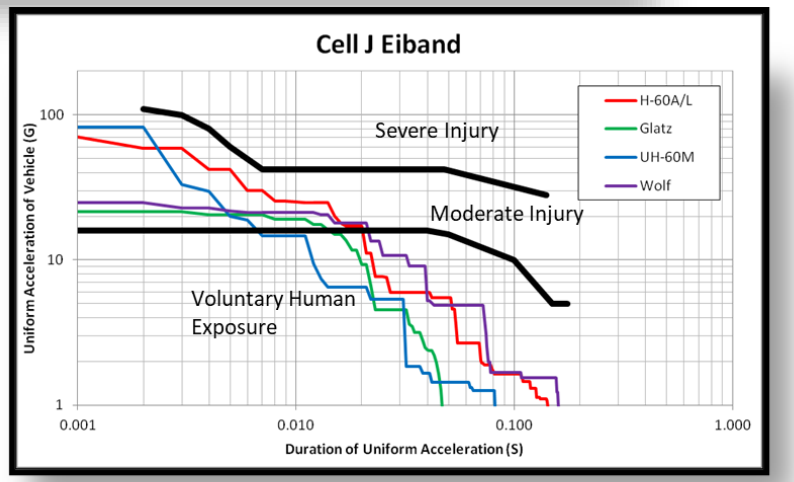
Compound or comminuted fractures

Simple fractures of vertebral bodies

Skull fracture

Loss of consciousness

Eiband results correlate w/ operational mishap injury types & severities



Airworthiness Process & Gaps In Seat Safety Design Requirements:

USAF Aircraft & Rotorcraft Occupant Seating Crashworthiness Survivability Standards

GAP - VTOL Crash Profile Vs. Historical Mishaps: *Aircraft & Rotorcraft (FAR 23, 25 & 27)*

- **Anticipated Difference In DoD Operational Mishap Data, Existing Injury Outcomes & Crashworthiness Criteria (Aircraft/Rotary) Vs. VTOL Application**
  - *Need to **Understand & Define** eVTOL operational expectations*
  - *Determine if existing crash scenarios & future VTOL applications are representative*
  - *Define crashworthiness criteria moving forward, accommodating VTOL occupant seat safety in addition to Aircraft & Rotorcraft Vehicles*

- **Develop New VTOL Seat Certification Process Requirement, Incorporating Existing Crash Scenarios (Aircraft & Rotorcraft) Defined In USAF/AW Process:** *Depends On Expected Mission Envelope For VTOL Aircraft*
  - Success of approach *dependent on similarity W/ defined & expected operational envelope in VTOL system as compared to historical Aircraft & Rotorcraft crash scenario defined based on operational mishap data & strong understanding of the crash profile*

GAP - FAA & USAF Crashworthiness Certification Processes

Do Measured Crash Events Match FAA & USAF eVTOL Expectations?

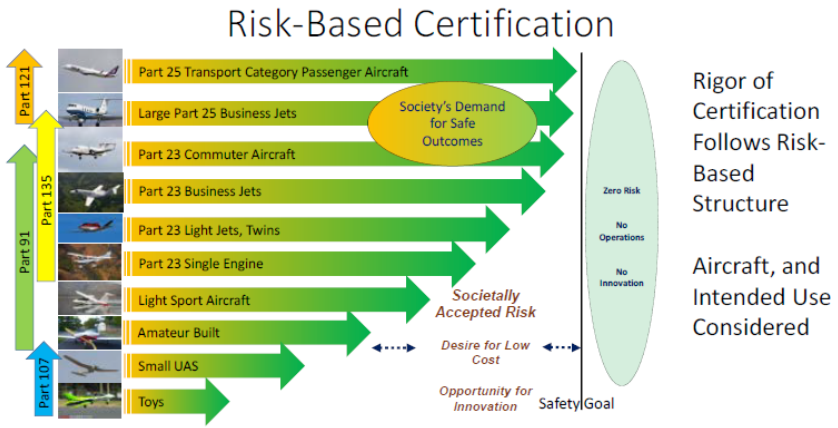
- **Transport Aircraft Seating:**
  - **FAR 25.562:** *Emergency Landing Dynamics Conditions*
  - **FAR 25.785:** *Seats, Berths, Safety Belts & Harnesses*
  - **FAA PS-ANM-25-03-R1:** *Technical Criteria Approving Side-Facing Seats*
  - ***FAR 49.*571.208** & **49.571.214**: *Criteria Crash Protection*
  - ***FAR 49.*572**: *ATDs*

- **Rotorcraft Seating:**
  - **FAR 27/FAR 29 (Normal/Transport):** *AW Standards*
    - *27.561, 27.785 & 27.1413*
    - *29.561, 29.785 & 29.1413*
  - **FAR 23:** 23.561, 23.785 & 23.1413
  - **FAR 91:** 91.107 & 91.203

Do Existing Requirements & STDs Reflect eVTOL Crashes Sufficiently?

- **Transport Aircraft & Rotorcraft Seating:**
  - **MIL-HDBK-516C**
    - *SAE Standard* ***AS8049 w/expanded population***

- **Rotorcraft Seating:**
  - **MIL-STD-85510(AS)**
  - **MIL-S-58095(AS)**
  - **JSSG-2010-7**



GAP - Current FAA & USAF Crashworthiness Differences:

Should VTOL injury be assessed as Rotorcraft or Transport Aircraft?

FAA Airworthiness Process *(Pass/Fail)*

- **FAA:** Most injury locations lack risk curves ***(Pass/Fail)***
- Structural Assessment **(Pass/Fail)**
- Lap Belt remains on pelvis? **(Pass/Fail)**
- Torso rotation remains <40^0? **(Pass/Fail)**
- Upper restraint remains on shoulders? **(Pass/Fail)**
- Occupant motion sufficiently restrained? **(Pass/Fail)**

FAA Criteria	Limit
Pelvis / Lumbar Loads (lbs)	1,500
Head Injury Criteria (HIC)	700
Resultant Shoulder Load (lbs)	1,850
L/R Shoulder Strap Loads (lbs)	1,750
Left / right femur bending angle	< 35°
Seat must remain attached to structure	P/F
If seat is damaged, it must not impede egress	P/S

USAF Airworthiness Process *(Risk Based)*

- Hard landing/crash AIS ≥2 % injury risk @ associated injury mechanism/location
- Combined total occupant injury risk (effect on EGRESS)
- Assess structure against 95th% male ATD (~245lb), LARD

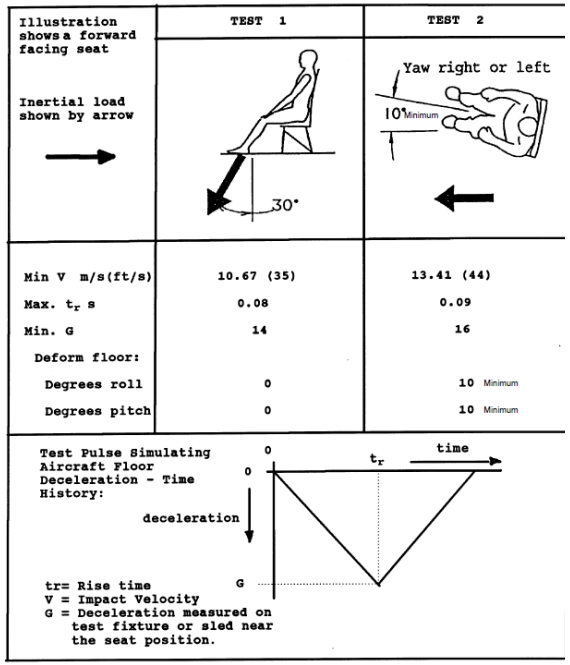


Figure 6 - Type A-T seat/restraint system dynamic tests

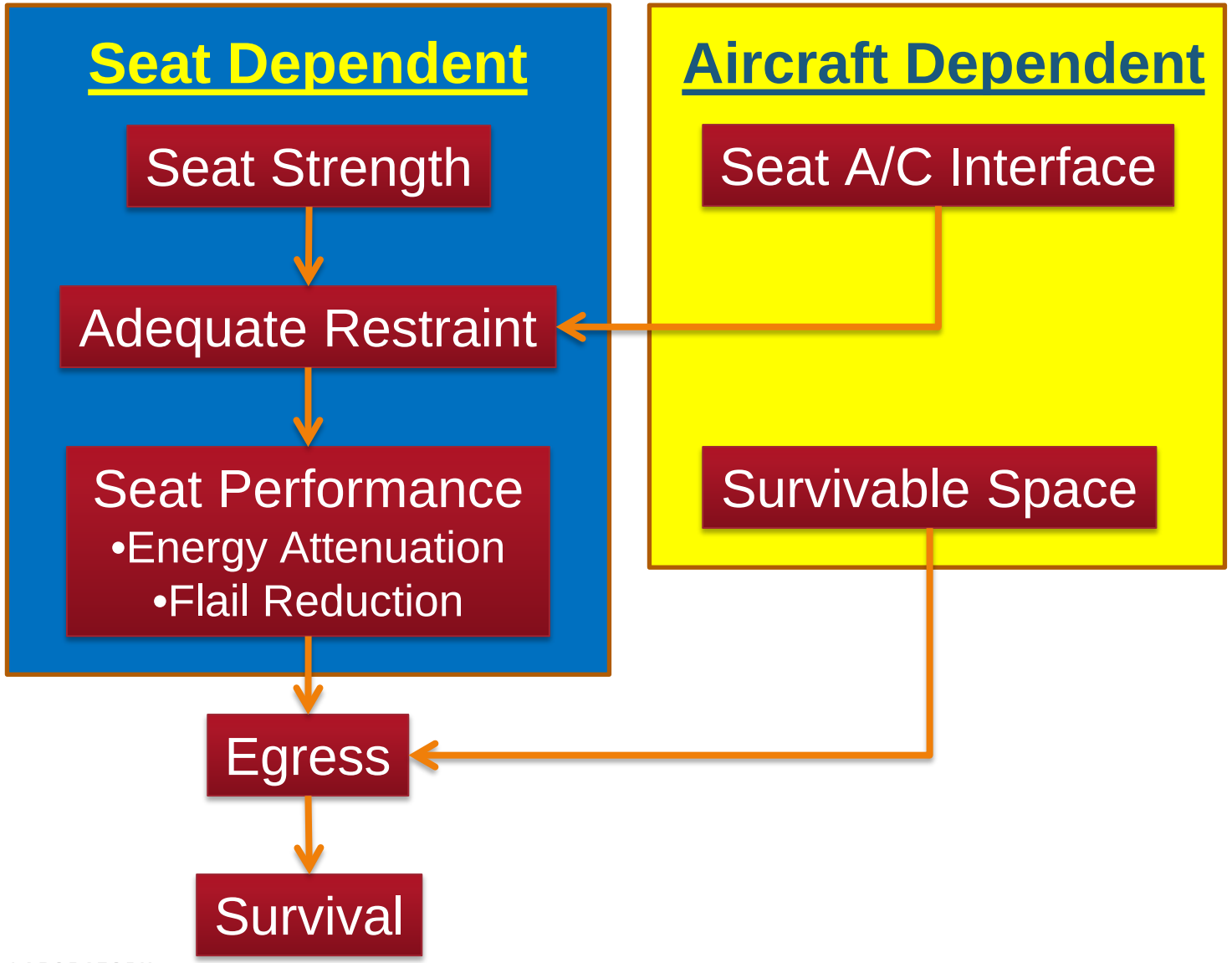
GAP - Limited ATD Range: *Male 50th percentile (Hybrid III AERO, FAA Straight Spine & ES-II ATDs)*

Valid Injury Probability Criteria Over Full Anthro Range: *Female 5th% Through 95th% Male*

- **Current FAA Approved ATDs In FWD/AFT Facing Rotorcraft & Transport Airplane Seats Include:** *Hybrid III 50th Aero ATD & FAA Straight Spine 50th ATD*
- **Current FAA Approved ATDs In Side-Facing Rotorcraft & Transport Airplane Seats Include:** *ES-II 50th Percentile Male ATD*
- **USAF Requires Injury Criteria Valid Across Full Anthro Range (LOIS - LARD) W/ Injury Probability Curves In Future VTOL Applications**
  - Initially, combine Transport/Rotorcraft airworthiness standards into new operational case, *unless VTOL crash profiles expected to drastically vary from Aircraft/Rotorcraft cases*
- **USAF AW Certification Process Based On ID Of Occupant Injury Risks & Evaluating Tradeoffs In Probability Of Injury & Risk Acceptance Toward Airworthiness Approval**
  - AF requires injury risk probability estimates @ relevant anatomic locations for all anticipated injury methods
  - FAA Crashworthiness Certification Criteria historically imposes (Pass/Fail) test limits which must not be exceeded for acceptability: *Specified acceptable safety metrics do not have associated injury risk probability estimates assigned during required crash test loading scenarios*

Examples For Crashworthiness Assessments of Occupant Seat Survivability

Personnel Survival Chain



Side-Facing Seats

CV-22 Seat

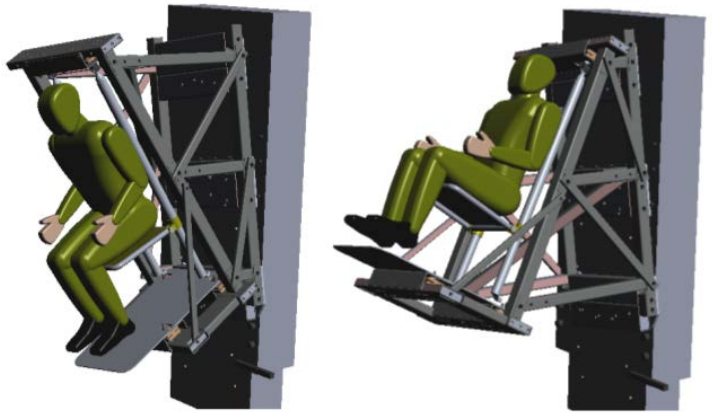
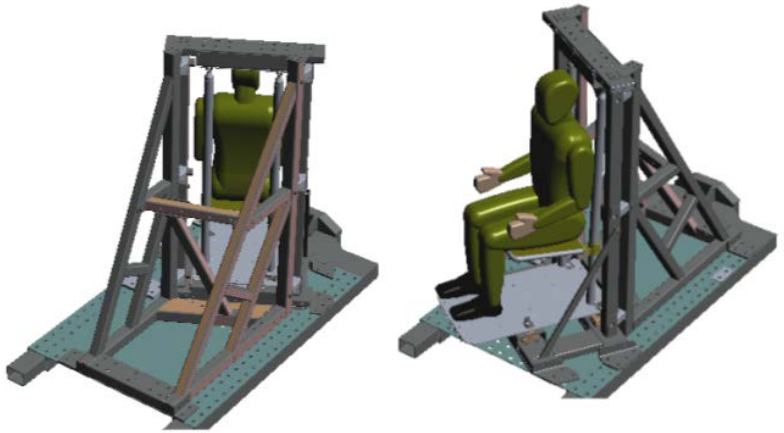
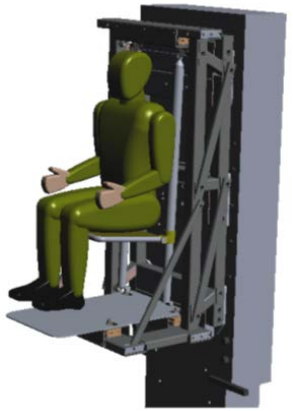
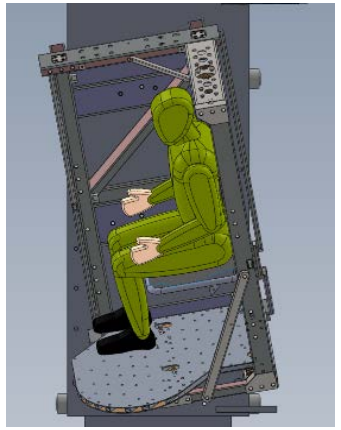
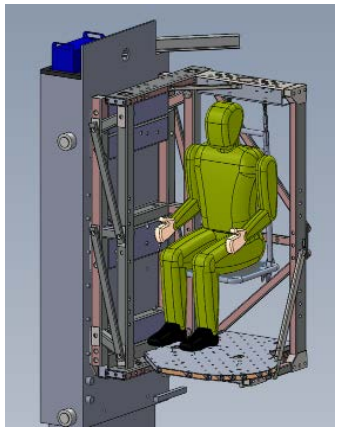
C-17 Seat

Example 1: *Military Rotorcraft Seating*

Background

- Purpose to evaluate current and prototype rotorcraft seat survivability across USAF anthro population
- Testing Partially Based On **MIL-STD-85510(AS)** & Legacy Seat Testing
- Impact Testing Using AFRL Horizontal Impact Accelerator (HIA) & Vertical Deceleration Tower (VDT)
- Seats from H-60,V-22, CH-53, and prototypes tested

Orientations

	Combined Vertical (CV)	Combined Horizontal (CH)	Pure Vertical (PV)
Fore/Aft-facing seats			
Side-facing seats			

Orientations, accel levels based on ~1960s mishap data (Crash Survival Design Guide)

Instrumentation

- **Lightest Occupant In Service (LOIS) 5th% Female (~107lb)**
- **Large Anthropomorphic Research Device (LARD) 98th% Male (~245lb)**
- **Manikin Instrumentation:**
  - *Head accelerations (linear & angular)*
  - *Upper/Neck forces & moments*
  - *Lumbar/Chest accelerations*
  - *Lumbar forces & moments*
- **Seat Mount Forces**
- **Seat Acceleration**

	LOIS (lb)	LARD (lb)
Upper Torso		
Manikin	45.3	108.8
Instrumentation	1.8	1.6
Cables	1.4	1.8
Lower Torso		
Manikin w/Abdomen	47	118.6
Instrumentation	1.4	1.4
AFE	10.6	15.6
Total	107.5	247.8

*Side-facing program

General Test Matrix (From Side-facing study)

Cell	Orientation	Acceleration (G)	Delta V (ft/s)	Rise Time (ms)	Manikin
A	CV	24	40	30	LOIS
B	CV	30	48	26	LOIS
C	CV	24	40	30	LARD
D	CV	30	48	25	LARD
E	CH	18	46	78	LARD
F	CH	24	53	62	LARD
G	PV	15	32	35	LOIS
H	PV	34	46	26	LOIS
I	PV	15	32	35	LARD
J	PV	34	46	26	LARD

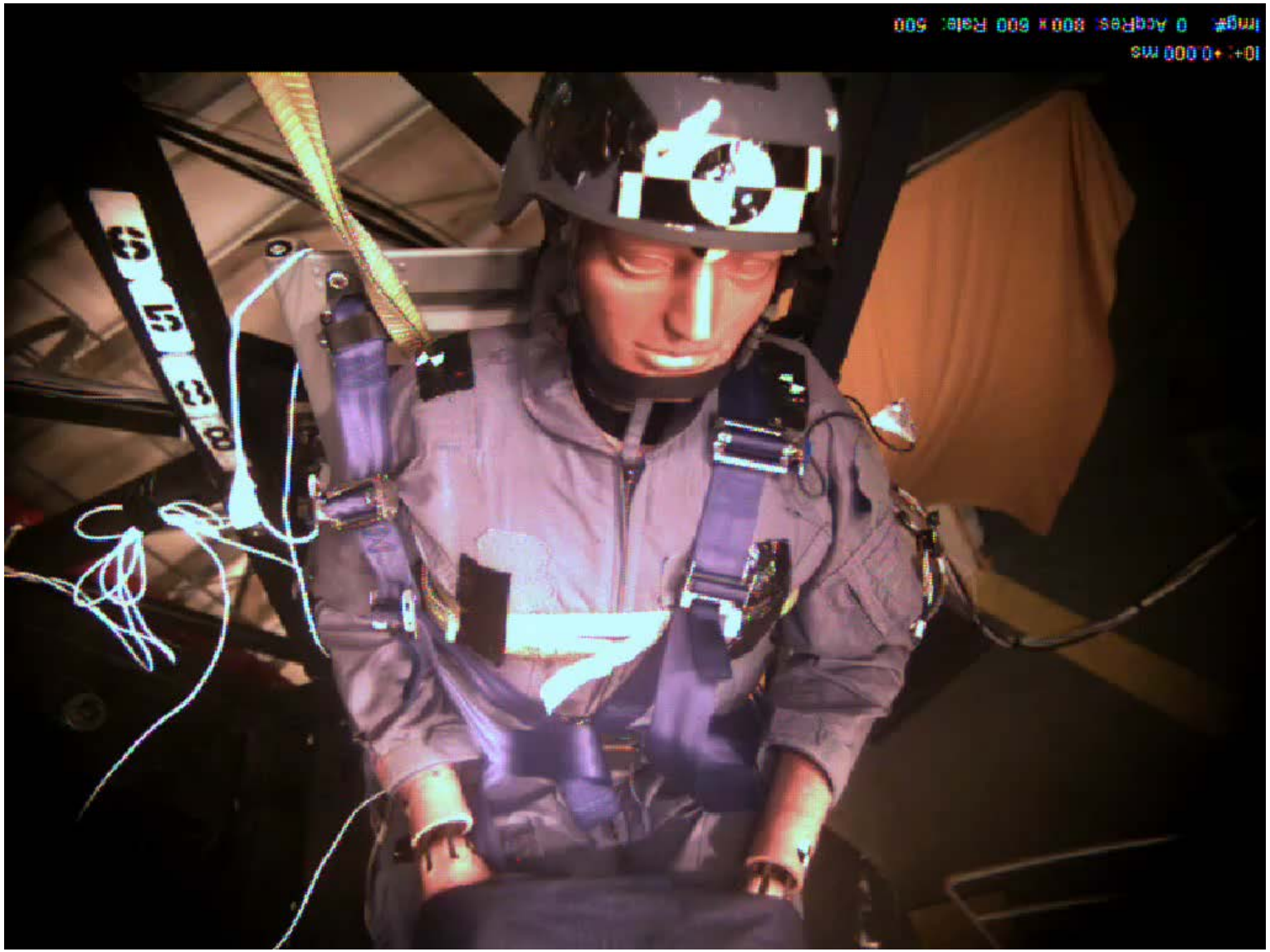
*Orientations/levels based on MIL-S-85510(AS) & H-60A/L acceptance testing, though do not strictly adhere to standards

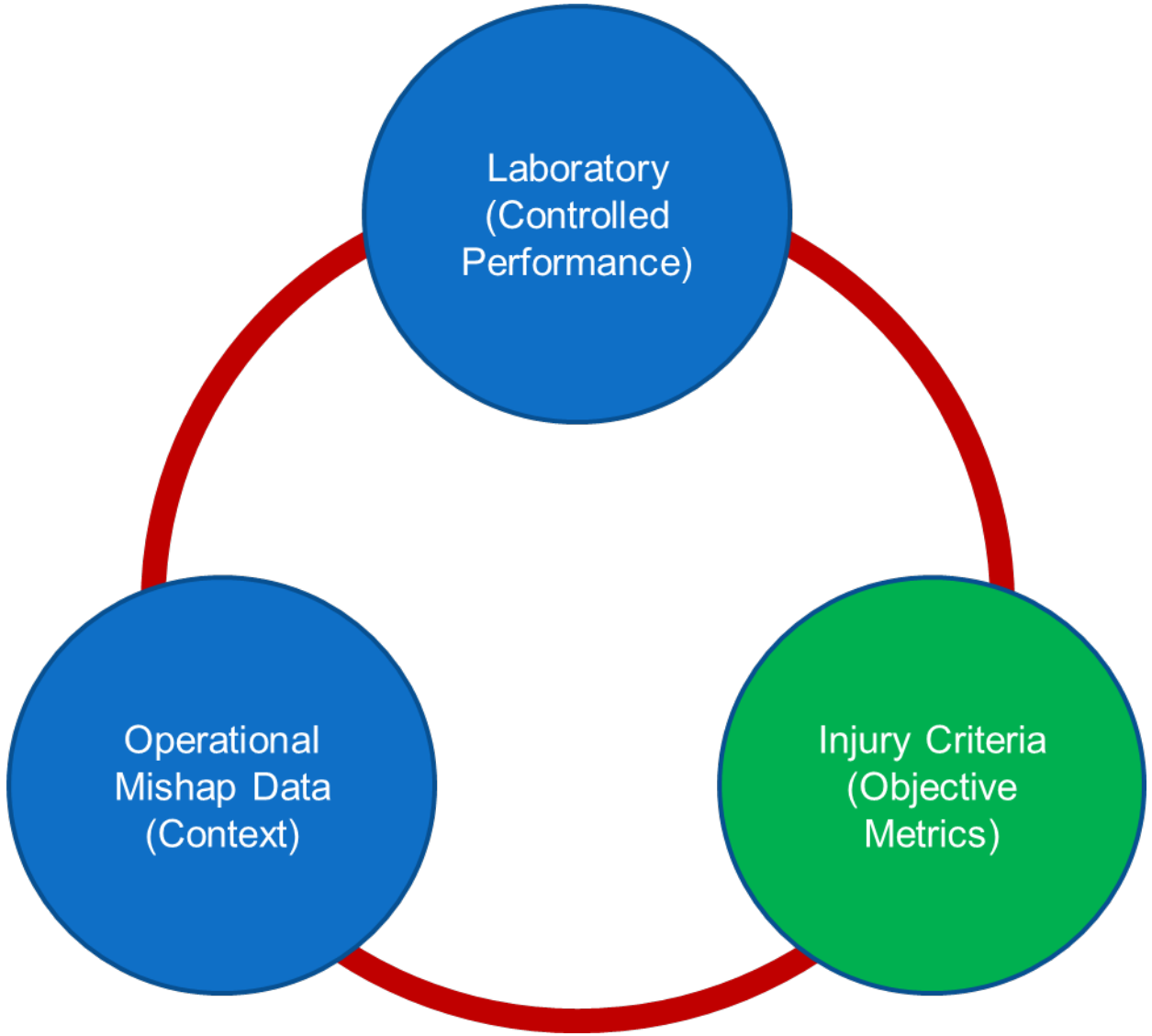
Vertical Tower Tests

Horizontal Track Tests

Combined Horizontal Video: *CV-22 Seat, LARD, 24.36G, 53.02ft/s, 62.3ms Rise Time*

Combined Vertical Video: *CV-22 Seat, LARD, 29.71G, 48.93ft/s, 18.4ms*





Data Analysis

- **Seat Structural Strength**
- **Injury Criteria Primarily From Full Spectrum Crashworthiness Report (2011); Other Historical Criteria Used For Comparison**

	Recommended by FSC	Criteria Used	CV	PV	CH
Head	HIC				
Neck	Nij	Nij	X	X	X
Chest	Belt Loads	Chest Accel and Belt Loads	X	X	
Lumbar	Peak Loads	Peak Loads and DRIz	X	X	
Whole Body		Eiband 85510		X	

Example 2: *Negatively Pressurized Conex/Conex Light (NPC/NPCL)*

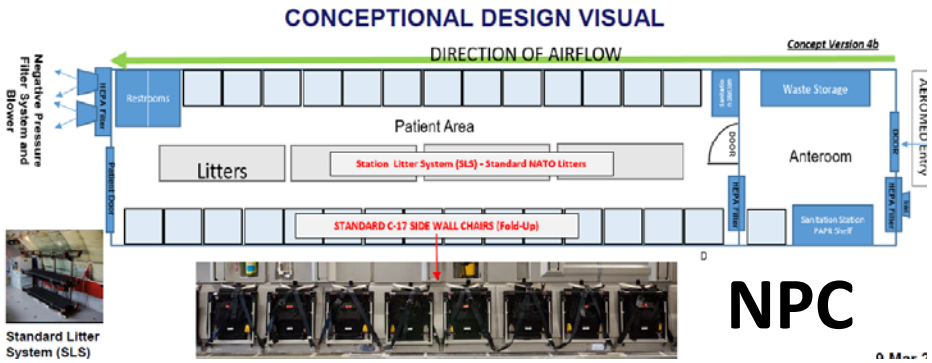
Assessment Of Side-Facing Troop Seat: *Negatively Pressurized Conex/Conex Light (NPC/NPCL)*

PLAN:

- *NPC leveraged Other Transactional Authority (OTA) agreement to rapidly procure prototype NPC system. Design based upon concept of modified 40-foot ISO container (Conex) w/ negative pressure system to provide max possible capacity on C-17 to transport diagnosed/symptomatic passengers & patients, while also mitigating risk to aircrew & aeromedical evacuations specialists*

HOW:

- *NPC designed to be safe-to-fly on C-17, maximize passenger capability w/ a configurable interior (ambulatory & litter) & meet requirements of USTRANSCOM JUON "Need for High Capacity Airlift of COVID-19 Infected Passengers" & NPCL designed to be safe-to-fly on C-130's & smaller cargo aircrafts*
- *Part of OUE is impact assessment of proposed seat, to be used by medical crew while in NPC*

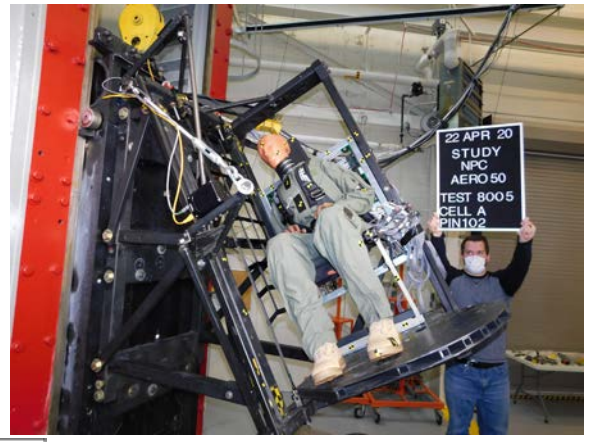


NPC has two areas, anteroom & patient area, separated by steel door. Patients loaded into NPC through patient doors & remain in patient area, outfitted w/ two restrooms, for duration of flight. Aeromedical crew enter & exit through anteroom, where they can doff & decon-equipment. At rear of Conex is redundant blower, creating negative pressure environment, driving laminar flow from anteroom into patient area. Design considerations incorporate communications, power, back-up, aeromedical requirements, transportability, modularity, configurability & more

Assessment Of Side-Facing Troop Seat: *Negatively Pressurized Conex & Conex Light (NPC/NPCL)*

HOW:

- ***AS8049*** *requirement for vertical impact conducted on AFRL Vertical Deceleration Tower (VDT)*
- *Vertical Impact Requirements:*
  - Seat Upright Side-Facing W/ Aircraft Rearward Pitch Angle Of **30°**
  - Peak Impact Acceleration **≥ 14 G**
  - Time-To-Peak Acceleration **≤ 80 ms**
  - Velocity Change **≥ 35 ft/s**
- *VDT facility successfully met required impact conditions*
- ***AS8049*** *Impact Requirements/Results:*



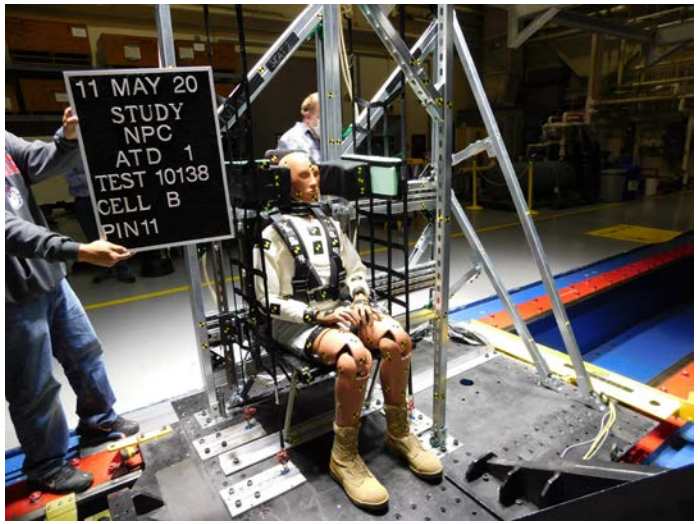
Criteria (50th Percentile Hybrid III Aero) Side-Facing	Limit	Max	Prob. Inj. AIS2+ (%)
Structural Analysis Seat-Pan Structure Broke, resulting in ATD pressed downward stuck inside Seat-Pan Frame: FAA	Pass/Fail	Fail	N/A
Velocity (ft/sec):	>35	35	N/A
Acceleration (G):	>14	15.9	
Lumbar Load (Lb):	1,350	1,025	N/A
Head Injury Criteria (HIC15):	700	85	
Femur Load (lbs):	2,250	0	
Neck Injury Criteria (Nij):	0.5	0.1623	13.50%
Resultant Shoulder Load (lbs):	1,850	458	N/A
Mil-Std 516C (50th Hybrid III Aero)	**Limit**	**Max**	**Prob. Inj. AIS2+ (%)**
UNMIx:	0.5	0.1339	N/A
UNMIz:	0.5	0.2764	
Multi-Axial Neck Injury Criteria (MANICxz):	0.56	0.20	0.01%
Multi-Axial Neck Injury Criteria (MANICy):	0.48	0.34	2.10%

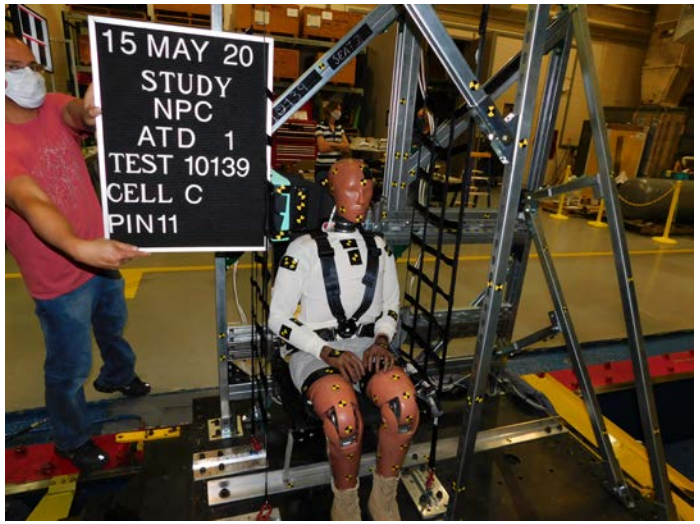
Pass
Fail
Marginal
Cannot Assess

Assessment Of Side-Facing Troop Seat: *Negatively Pressurized Conex/Conex Light (NPC/NPCL)*

HOW:

- ***AS8049*** *requirement for horizontal impact conducted on AFRL Horizontal Impulse Accelerator (HIA)*
- *Horizontal Impact Requirements:*
  - Seat Upright W/ Yaw Angle Of **0°**
  - Peak Impact Acceleration **≥ 16 G**
  - Time-To-Peak Acceleration **≤ 90 ms**
  - Velocity Change **≥ 44 ft/s**
- *HIA facility successfully met required impact conditions*
- ***AS8049*** *Impact Requirements/Results:*





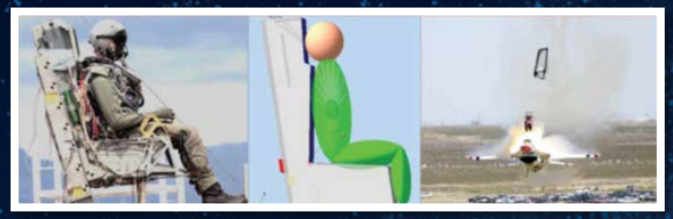
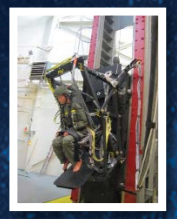
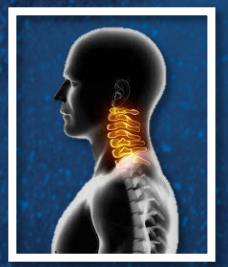
Pass
Fail
Marginal
Cannot Assess

Criteria (50th Percentile Hybrid III Aero) Side-Facing	Limit	Max	Prob. Inj. AIS2+ (%)
Pelvic Excursion (Load Bearing Portion ATD pelvis must not translate beyond edge seat's bottom structure): FAA	Pass/Fail	Fail	N/A
Upper-Torso Support (Lateral flexion of ATD torso must not exceed 40 degrees from normal upright position): FAA	<40°	Fail	
Occupant Retention (Pelvic Restraint must remain on ATD pelvis during impact & rebound phases): FAA	Pass/Fail	Fail	
Occupant Retention (Upper-Torso Restraints must remain on ATD shoulder during impact & rebound phases): FAA	Pass/Fail	Fail	
Velocity (ft/sec): FAA	>44	52.43	N/A
Acceleration (G): FAA	>16	16.25	
Lumbar Load (Lb): FAA	1,350	135.70	N/A
Head Injury Criteria (HIC15): NHTSA	700	253.01	
Neck Injury Criteria (Nij): NHTSA	0.50	0.52	19%
Resultant Shoulder Load (lbs): FAA	1,850	1,456	N/A
Compression Femur Injury, Left (lbs): NHTSA	2,250	4	0.31%
Femur Bending Fracture, sqrt(Mx^2+My^2), Left (in*lb): NHTSA	3,009	2,352	1.65%
Tibia Injury, Left (RTI): NHTSA	0.8	0.94	27.63%
Compression Femur Injury, Right (lbs): NHTSA	2,250	130	0.22%
Femur Bending Fracture, sqrt(Mx^2+My^2), Right (in*lb): NHTSA	3,009	3,558	55.33%
Tibia Injury, Right (RTI): NHTSA	1.3	1.35	55.57%
Left/Right, Femur Bending Angle: FAA	<35°	Fail	N/A
Mil-Std 516C (50th Hybrid III Aero)			
	Limit	Max	Prob. Inj. AIS2+ (%)
UNMlx:	0.5	0.27	N/A
UNMlz:	0.5	0.19	
Multi-Axial Neck Injury Criteria (MANICxz):	0.56	0.58	5.35%
Multi-Axial Neck Injury Criteria (MANICy):	0.48	0.59	10.42%

Criteria (50th Percentile Hybrid III Aero) Side-Facing	Limit	Max	Prob. Inj. AIS2+ (%)
Pelvic Excursion (Load Bearing Portion ATD pelvis must not translate beyond edge seat's bottom structure): FAA	Pass/Fail	Fail	N/A
Upper-Torso Support (Lateral flexion of ATD torso must not exceed 40 degrees from normal upright position): FAA	<40°	Pass	
Occupant Retention (Pelvic Restraint must remain on ATD pelvis during impact & rebound phases): FAA	Pass/Fail	Pass	
Occupant Retention (Upper-Torso Restraints must remain on ATD shoulder during impact & rebound phases): FAA	Pass/Fail	Pass	
Velocity (ft/sec): FAA	>44	51.32	N/A
Acceleration (G): FAA	>16	16.22	
Lumbar Load (Lb): FAA	1,350	422	N/A
Head Injury Criteria (HIC15): NHTSA	700	217.90	
Neck Injury Criteria (Nij): NHTSA	0.50	0.31	16%
Resultant Shoulder Load (lbs): FAA	1,850	1,472	N/A
Compression Femur Injury, Left (lbs): NHTSA	2,250	1.9	0.30%
Femur Bending Fracture, sqrt(Mx^2+My^2), Left (in*lb): NHTSA	3,009	1,976	0.32%
Tibia Injury, Left (RTI): NHTSA	0.8	0.63	8.03%
Compression Femur Injury, Right (lbs): NHTSA	2,250	3.42	0.31%
Femur Bending Fracture, sqrt(Mx^2+My^2), Right (in*lb): NHTSA	3,009	4,155	96.79%
Tibia Injury, Right (RTI): NHTSA	1.3	1.97	98.97%
Left/Right, Femur Bending Angle: FAA	<35°	Fail	N/A
Mil-Std 516C (50th Hybrid III Aero)			
	Limit	Max	Prob. Inj. AIS2+ (%)
UNMlx:	0.5	0.46	N/A
UNMlz:	0.5	0.26	
Multi-Axial Neck Injury Criteria (MANICxz):	0.56	0.43	2.92%
Multi-Axial Neck Injury Criteria (MANICy):	0.48	0.48	5.28%

Recommendations:

- **Recognized Gaps:**
  - **VTOL Crash Profile Vs. Historical Mishaps**
  - **FAA & USAF Crashworthiness Certification Processes**
  - **Current FAA & USAF Crashworthiness Differences**
  - **Limited ATD Range**
- **Define eVTOL operational crash profiles. "How will we crash?"**
- **Develop definitive injury criteria for MIL ATDs**
- **Better align FAA and MIL crashworthiness criteria**
  - **Define appropriate injury metrics for operational crash environment**
  - **Establish acceptable injury severity level probability during a mishap**





Questions?