Materials and Structural Mechanics Task Group

AVT-174

Structural Design Criteria / Qualification Guidelines for Unmanned Military Air Vehicles

Linking UAV Categories to Risk and Safety

Presentation to
Kansas UAS Conference

C. Saff (USA), Chair,
Vice-Chair, E. Mennle (DEU)
Technical Editor, Jim Olsen (AFRL – Ret.)

Outline

- Content of Guidelines
- Content of Appendices
- Derivation of the Proposed Categories

Mission and Scope

- **Our mission is to develop structural guidelines for UAVs that can be tailored to the lethality of the vehicle and reduce the level of effort required:**
  - to achieve safety and reliability for these vehicles equivalent to manned aircraft levels;
  - reducing the testing requirements where rational;
  - commensurate with lethality to air and ground personnel; and
  - consistent with the value of the operational capability.

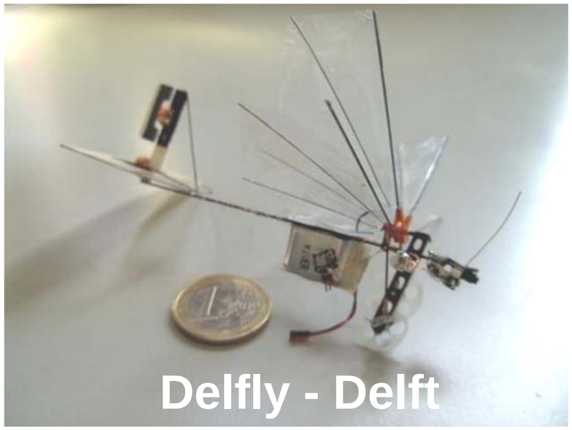
- **Our group supports the following military capabilities:**
  - Reconnaissance
  - Early strike

- **The scope/focus of our group:**
  - All military UAVs
  - Fixed and Rotary Wing Vehicles
  - Looking Toward Flight in International Airspace

Barracuda - EADS

History

- **Workshop held Spring of 2007**
- **Exploratory Team Began in Spring 2008 Learned that**
  - 350 different types of UAVs flying in NATO nations in 2007
  - 1,500 different types in 2013 via AIAA Worldwide UAV Roundup
  - STANAG 4671 did not cover the full range of existing UAVs
  - There was NATO interest in formulating rational set of guidelines from which criteria and requirements could be developed.
- **Formed AVT-174 in Spring 2009**
  - 13 Nations involved Spring and Fall Meetings
  - 5 major updates through the years
- **NATO Approved Guidelines for Publication**
  - Fall 2012


Delfly - Delft

Contributors

Topic	Sub-Topic	FRA	DEU	USA	ITA	GBR	NLD	POL	GRE	LVA	SPA	TUR
1. General UAV Design Requirements	Top Level Requirements Aircraft Type / Size Flight Control etc.. Agility	8	8	10	5	5	5					
2. Structural Design Criteria								5				
	Loads	10	8	8	5	1	1					
	Stiffness - Aeroelasticity	5	8	10	5	1	5					
	Static Strength – Factor of Safety – Re-evaluation for UAVs	8	10	8	8	5	1					
	Structural Health and Event Monitoring	1	10	8	8	8	1					
	Durability	8	8	8	10	5	1					
	Damage Tolerance	8	8	8	10	5	1					
	Fail Safety	5	8	10	5	1	1					
	Crashworthiness	5	5	10	8	1	1					
	Producibility	5	1	10	8	1	1					
	Maintainability – Repairability and Inspectability	5	5	8	8	10	1					
	Discreet Events	5	8	10	5	5	1					
3. Validation Approaches												
	Qualification by Analysis	8	10	8	8	5	1					
	Spiral Development as a New Design and Qualification Concept	8	8	10	5	1	1					
	Conventional Qualification	5	5	8	5	10	1					
	Hybrid Concepts	10	8	8	5	1	1					
	Dealing with Non-Conformance Issues	5	8	10	1	5	1					

No Contribution	0
Review	1
Small Contribution	5
Major Contribution	8
Leadership	10

13 Nations are Involved

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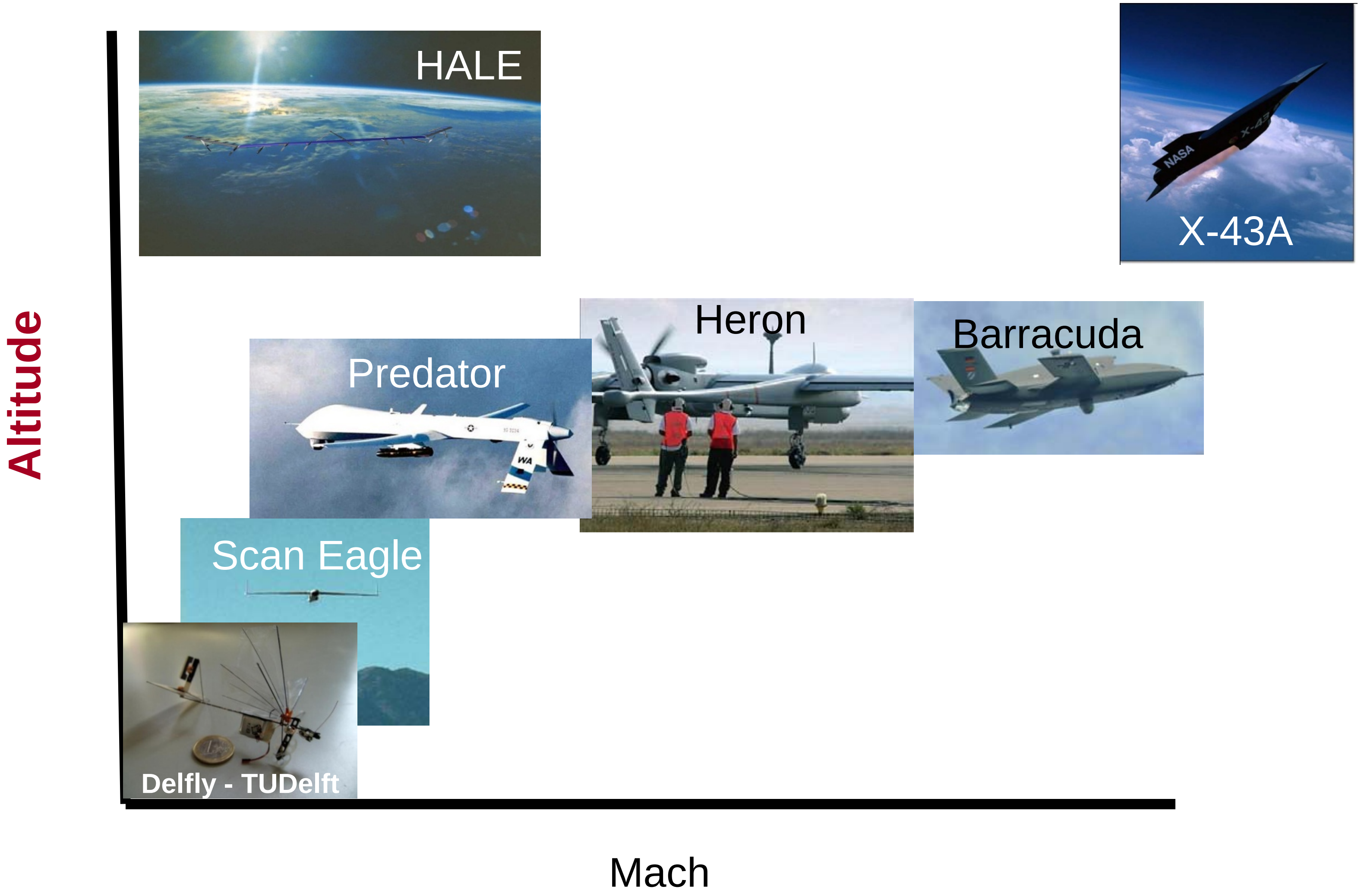
UAVs Cover a Broader Range of Flight Regimes than Manned Aircraft



Proposed Categories

Vehicle Type	Existing Regulatory Guidance (Reference Only)	General Guidance	International Airspace	National Airspace	DoD Airspace		
		Max Energy mv^2	Sovereign	FAA Class A, B, C, D, E, G	Non-Expendable UAV Restricted to Combat Zones	Restricted Areas & Combat Zones	Expendable/ Prototype UAV Restricted to Range
Med/Large Fixed Wing	STANAG 4671 JSSG 2006	mv^2>(1320 lbs) (200 kts)^2 mv^2>(600 kg) (370 km/h)^2	1	1	1	1R	1P
Med/Large Rotary Wing	Part 27, 29		1	1	1	1R	1P
Light, F/W & R/W	AC 23-19A	mv^2<(1320 lbs) (200 kts)^2 mv^2<(600 kg) (370 km/h)^2	2	2	2	2R	2P
Small / Mini / Micro F/W & R/W	Association of Model Aeronautics (AMA)	mv^2<(20 lbs) (120 kts)^2 mv^2<(9 kg) (190 km/h)^2	3	3	3	3	3

Used JSSG As a Pattern
STANAG for Content

Overview and Technical Basis for the Guidelines

Appendix 1

Category 1
Qualification
Basically
STANAG
4671
With
Revisions

Category 1R
Restricted
Flight
Qualification
Limited Testing

Category 1P
Prototype
Qualification
Proof Testing

Appendix 2

Category 2
Qualification
Based on
Light Aircraft
Analysis and
Test
Guidelines

Category 2R
Restricted
Flight
Qualification
Limited Testing

Category 2P
Prototype
Qualification
Proof Testing

Appendix 3

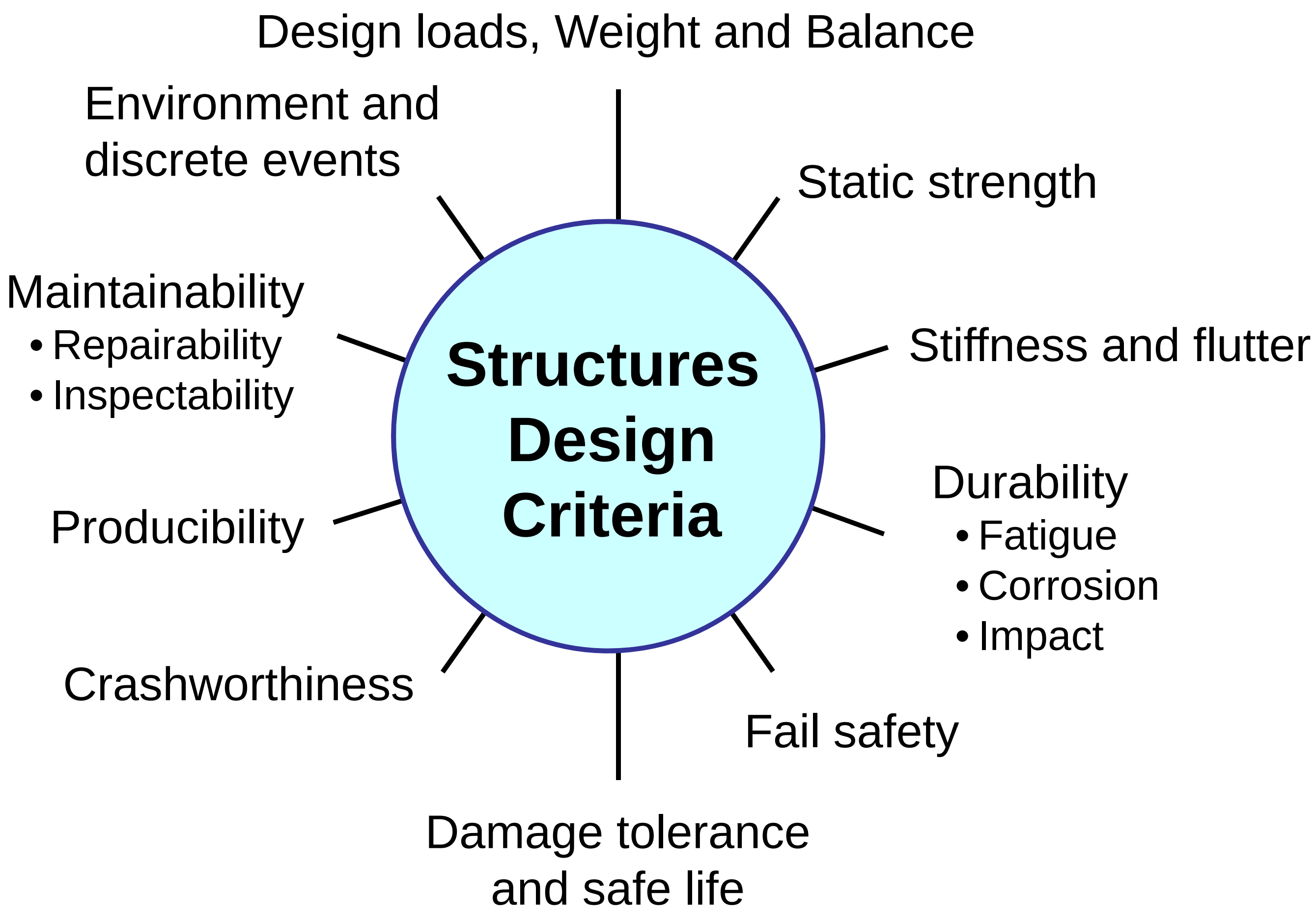
Category 3
Qualification
Analysis &
Flight Testing

Appendix A

Linking UAV
Categories to
Safety and Risk
for
Structural Design
Guidelines

Appendix B
Excerpts from
AVT-028 Report
on Design Loads
for Future Air
Vehicles

Principal Structural Design Requirements and Criteria Consist of 10 Core Elements



Structures Design Criteria

Design loads, Weight and Balance

Static strength

Stiffness and flutter

Durability
- Fatigue
- Corrosion
- Impact

Fail safety

Damage tolerance and safe life

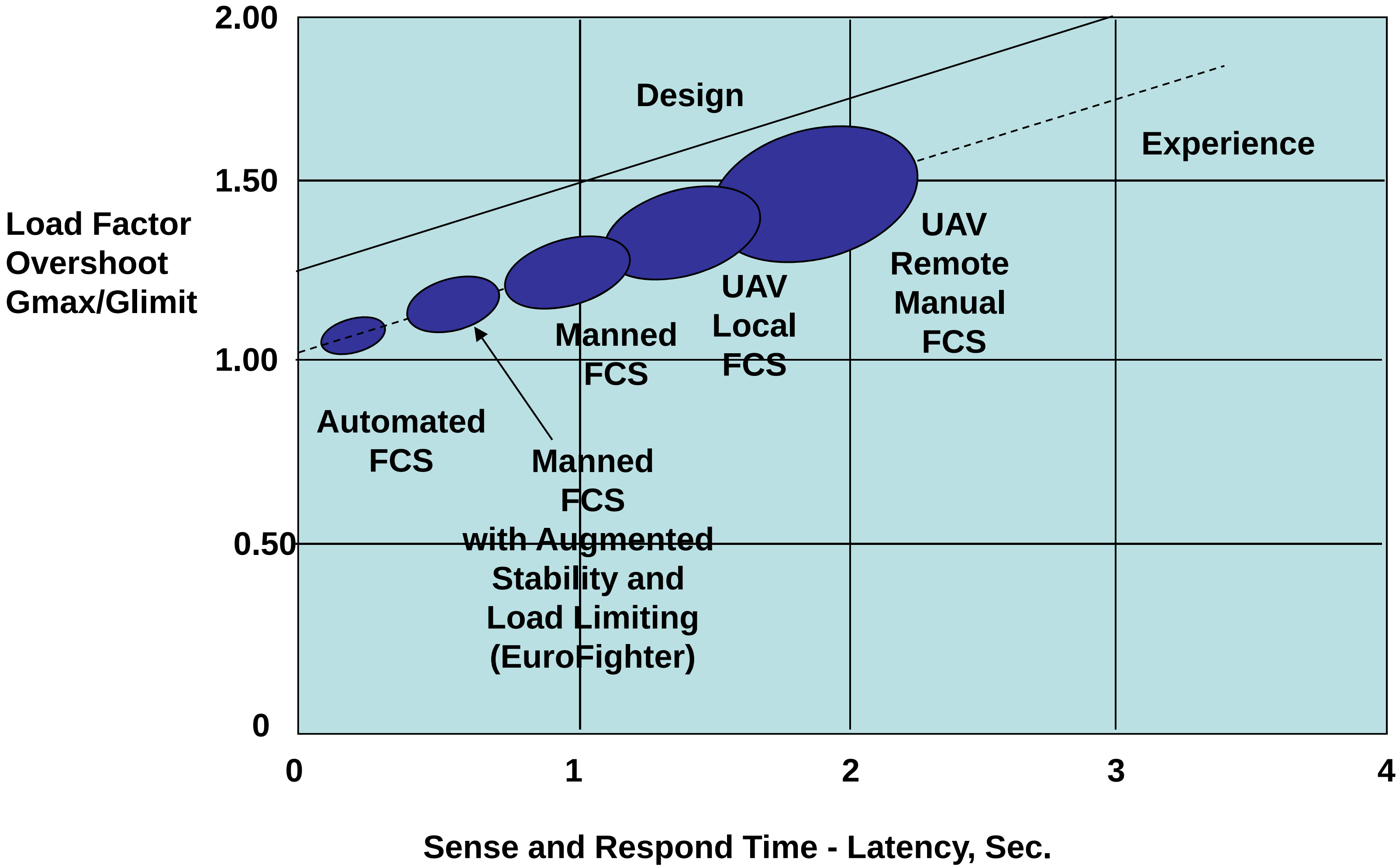
Crashworthiness

Producibility

Maintainability
- Repairability
- Inspectability

Environment and discrete events

Response Time Affects Overloads



Many Factors Affect Factors of Safety

	Configuration	Flight Control / Loads	Environment	Manufacturing	Materials	Technology	Development Maturity
-0.25	Conventional Design Well Within Design Space Established by 5 Generations of Like Configurations	0.01 Sec Lag (automated flight and stability control)	Environment included in Ground Certification Tests	NA	5+ Applications of Material System and 5+ years of In-Service Use	5+ Applications of Technology and 5+ years of In-Service Use	NA
-0.125	Conventional Design Well Within Design Space Established by 3 Generations of Like Configurations	0.1 Sec. Lag (Man Augmented by Stability and Load Control)	Environment Well Understood or Considerable Design Margin Demonstrated by Ground Test	Tooling and Process Controls Used for Multiple Current Production Applications	2-3 Applications of Material System and 2-3 Years of In-Service Use	2-3 Applications of Technology and 2-3 Years of In-Service Use	Conventional Engineering/Mfg. Development With Increased Analysis and/or Testing
0	Generally Conventional Design With 1-2 Unique Features That Drive Technical Risk	1 Sec. Lag (Manned Aircraft)	Combination of Environment Definition and Assoc'd Design Margin Similar to Past Development Programs	Tooling and Process Controls Well Established and Used on 1 or More Production Applications	A and B-Basis Allowables Documented	Comprehensive Development of Technology to Support Fleet Production and Operational Use	Conventional Engineering/Mfg. Development to Support Fleet Production and Operational Use
0.125	Conventional Design With Multiple Unique Features That Drive Technical Risk	1.5 Sec. Lag (Remotely Piloted Locally from Control Station)	Environment Not Well Understood or Considerable Design Margin Not Demonstrated by Ground Test	Tooling or Process Controls Require Maturation	B-Basis Allowables Internally Documented	Prototyping of Technology With Reduced Ground Testing	Prototyping Environment With Reduced Ground Testing
0.25	Un-Conventional Design With Multiple, Highly Features That Drive Technical Risk	2.0 Sec. Lag (Remotely Piloted from Ground w/o Control Station or from Transcontinental Control Station)	Environment Not Well Understood and Considerable Design Margin Not Demonstrated by Ground Test	First Application of Tooling or Process Controls	Design Values Determined by Minimum Test Plan	Rapid Prototyping of Technology With Little/No Ground Testing	Rapid Prototyping Environment With Little/No Ground Testing

Appendices 1-3
Cover Category 1-3 UAVs

Overview and Technical Basis for the Guidelines

Appendix 1

Category 1 Qualification Basically STANAG 4671 With Revisions

Category 1R Restricted Flight Qualification Limited Testing

Category 1P Prototype Qualification Proof Testing

Appendix 2

Category 2 Qualification Based on Light Aircraft Analysis and Test Guidelines

Category 2R Restricted Flight Qualification Limited Testing

Category 2P Prototype Qualification Proof Testing

Appendix 3

Category 3 Qualification Analysis & Flight Testing Determines Payload Weight and Balance Limits

Appendix A

Linking UAV Categories to Safety and Risk for Structural Design Guidelines

Conventional Qualification

Material Selection
- Metals
- Composites

Manufacturing Process
- Process Development
- NDT Standards

Material Properties
- Repair
- Physical/ Chemical/ Processing
- Environmental Effects
- Mechanical Properties
- Statistical Knockdown
- Fatigue Scatter
- Effects of Defects/Damage

Elements/ Subcomponents
- Design Details
- Damage Tolerance
- Repair
- Validation of Analysis Methodology
- Fatigue
- Static
- Acoustic

Components
- Configuration Details
- Damage Tolerance
- Static Proof tests
- Fatigue
- Repair
- Validation of Analysis Methodology

Certification Tests
- Static Proof Tests
- Dynamic Loads

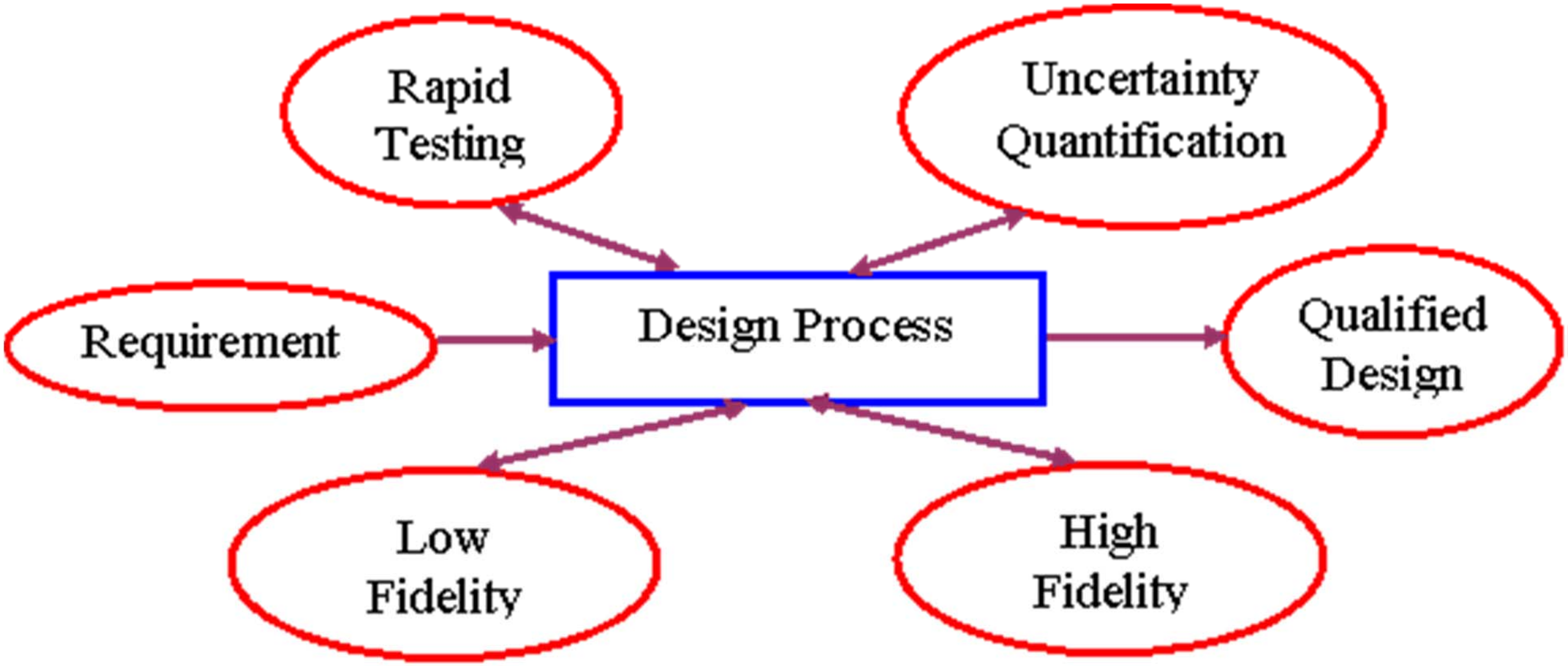
Ground Test

Production Verification

Full Scale Laboratory

Flight

Qualification by Analysis


Rapid Testing

Uncertainty Quantification

Requirement

Design Process

Qualified Design

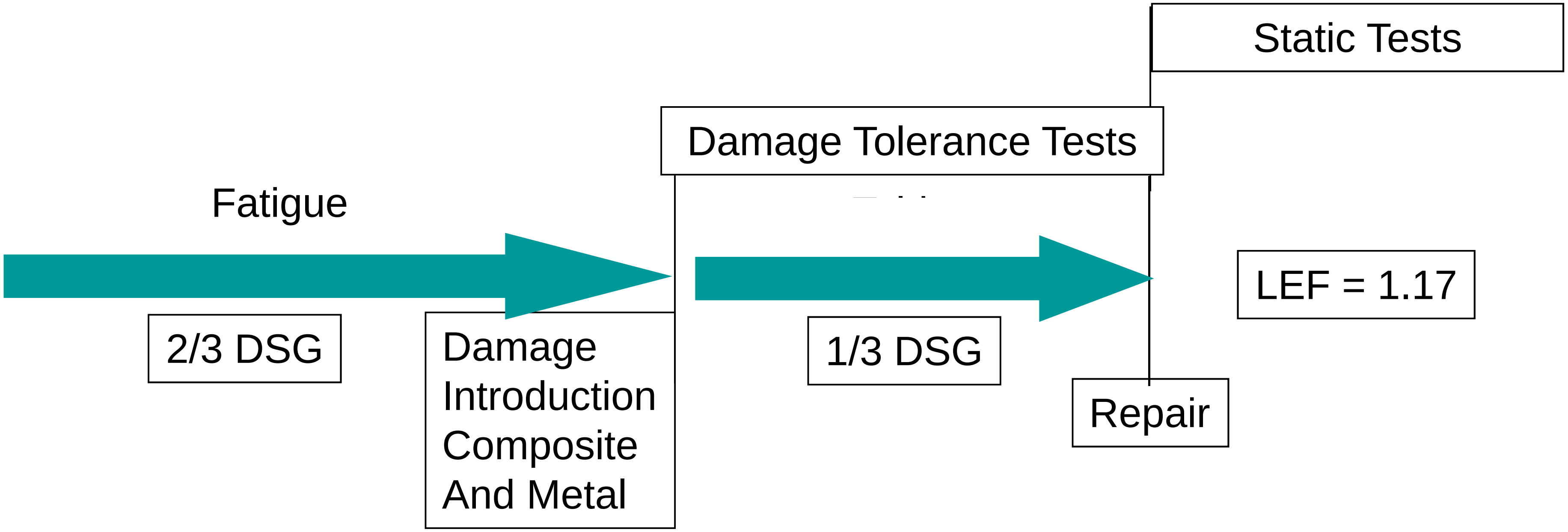
Low Fidelity

High Fidelity

Consider modifying to include aspects of
USAF AWB-013A, Risk Identification and Acceptance for Airworthiness Determinations

Qualification of Hybrid Structures

- Fatigue / damage tolerance test sequence example for combined metallic and composite structures:



Static Tests

Damage Tolerance Tests

Fatigue

LEF = 1.17

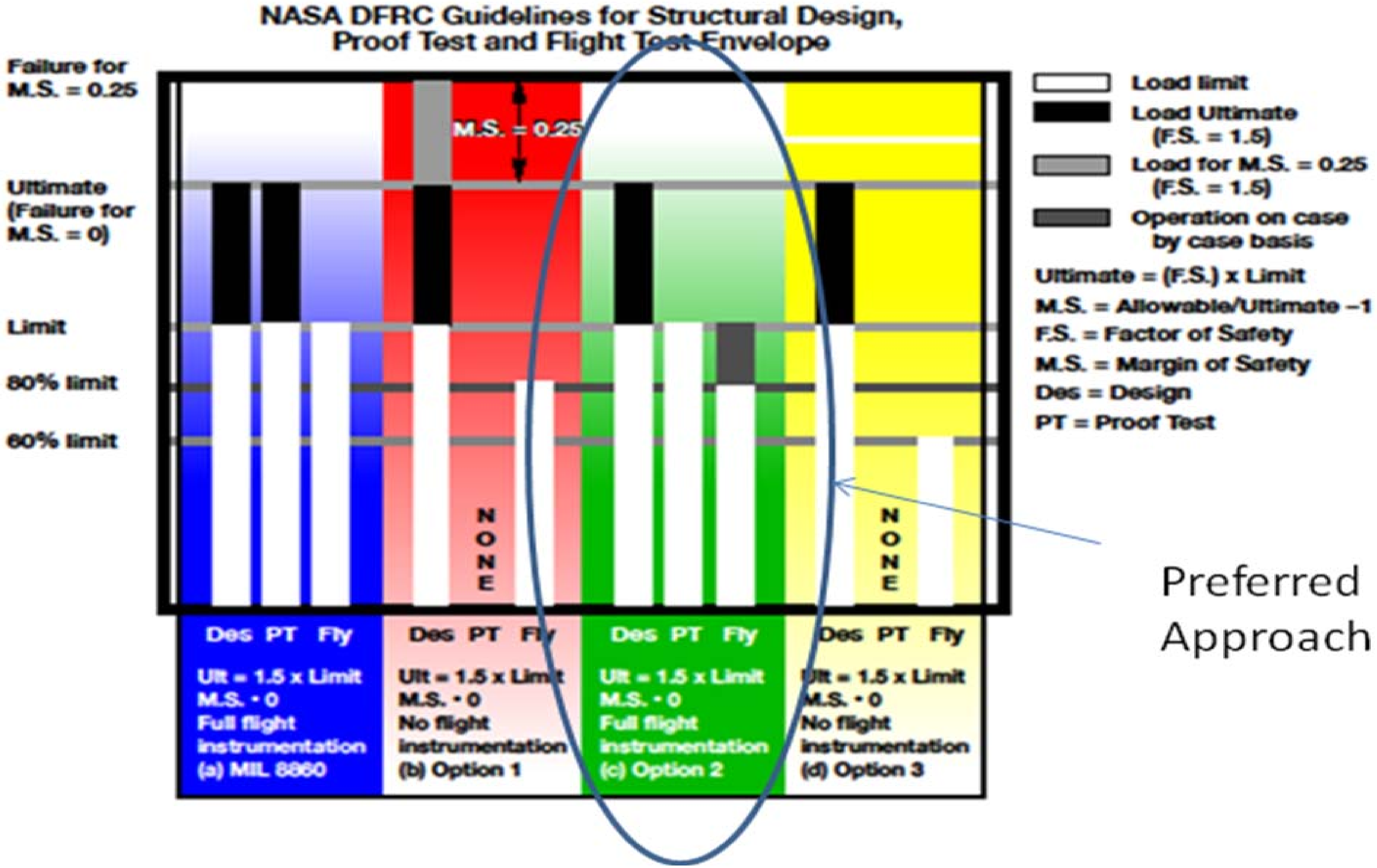
2/3 DSG

Damage
Introduction
Composite
And Metal

1/3 DSG

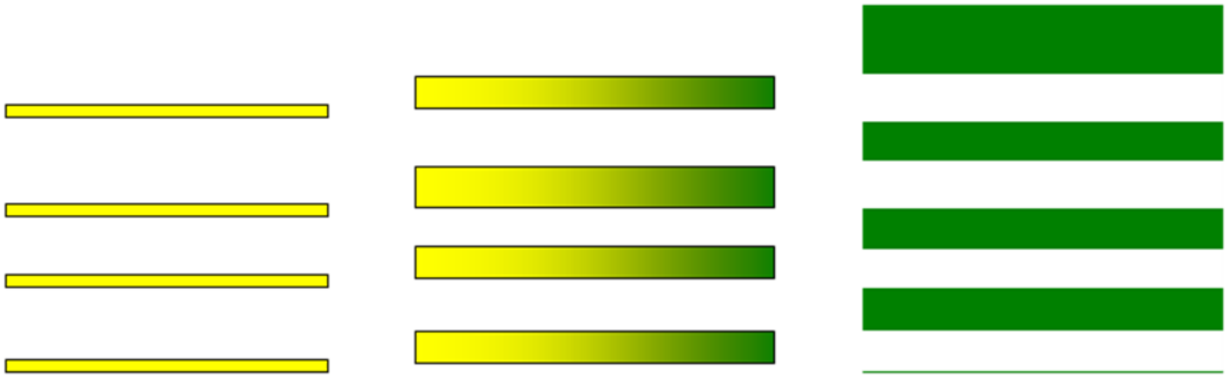
Repair

Strength Margins Required for Prototype Flight



Preferred Approach

Nested Qualification



Spiral 1 Prototype Flight Qualification	Spiral 2 Restricted Flight Operations	Spiral 3 Fully Operational & Non-Expendable UAVs
Proof Test Flight Structures 80% DLL	Test Structural Article & Critical Joints 100% DLL + 2 x Life (Clear Flt. Envelope)	Test Structural Article Critical Subcomponents and Allowables Tests DUL + 2 x Life + DTT (Clear Full Envelope)
GVT	GVT - Systems	GVT – Payload and Stores
Taxi Tests	Taxi – Landing Gear Monitoring	
Flight Loads Monitoring	Flight Loads Validation	Real Time Flight Loads Monitoring

Appendix A
Justification for Categories 1-3 UAVs

Overview and Technical Basis for the Guidelines

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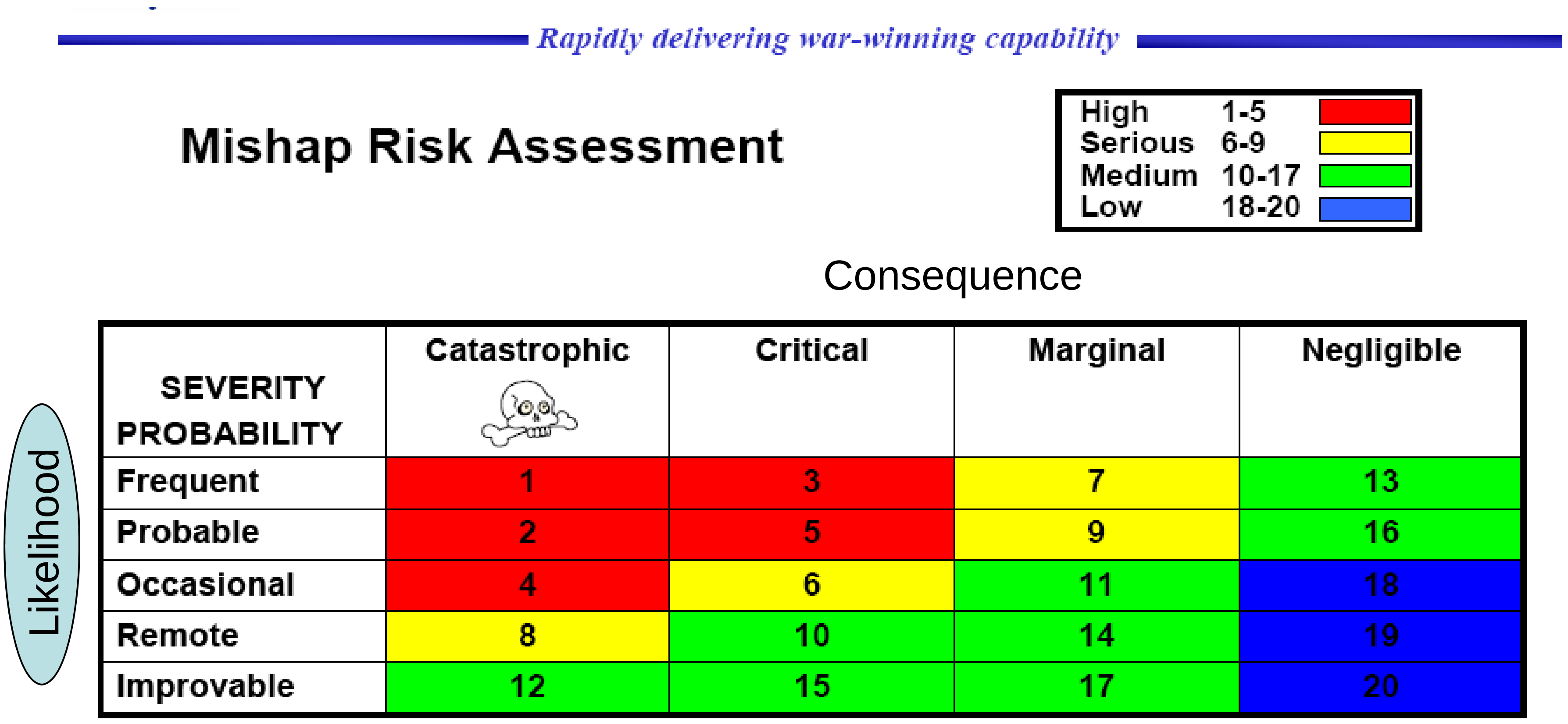
Appendix 3

Category 3 Qualification Analysis & Flight Testing Determines Payload Weight and Balance Limits

Appendix A

Linking UAV Categories to Safety and Risk for Structural Design Guidelines

Risk is a Matter of Likelihood and Consequence



Rapidly delivering war-winning capability

Mishap Risk Assessment

High	1-5	🟥
Serious	6-9	🟨
Medium	10-17	🟩
Low	18-20	🟦

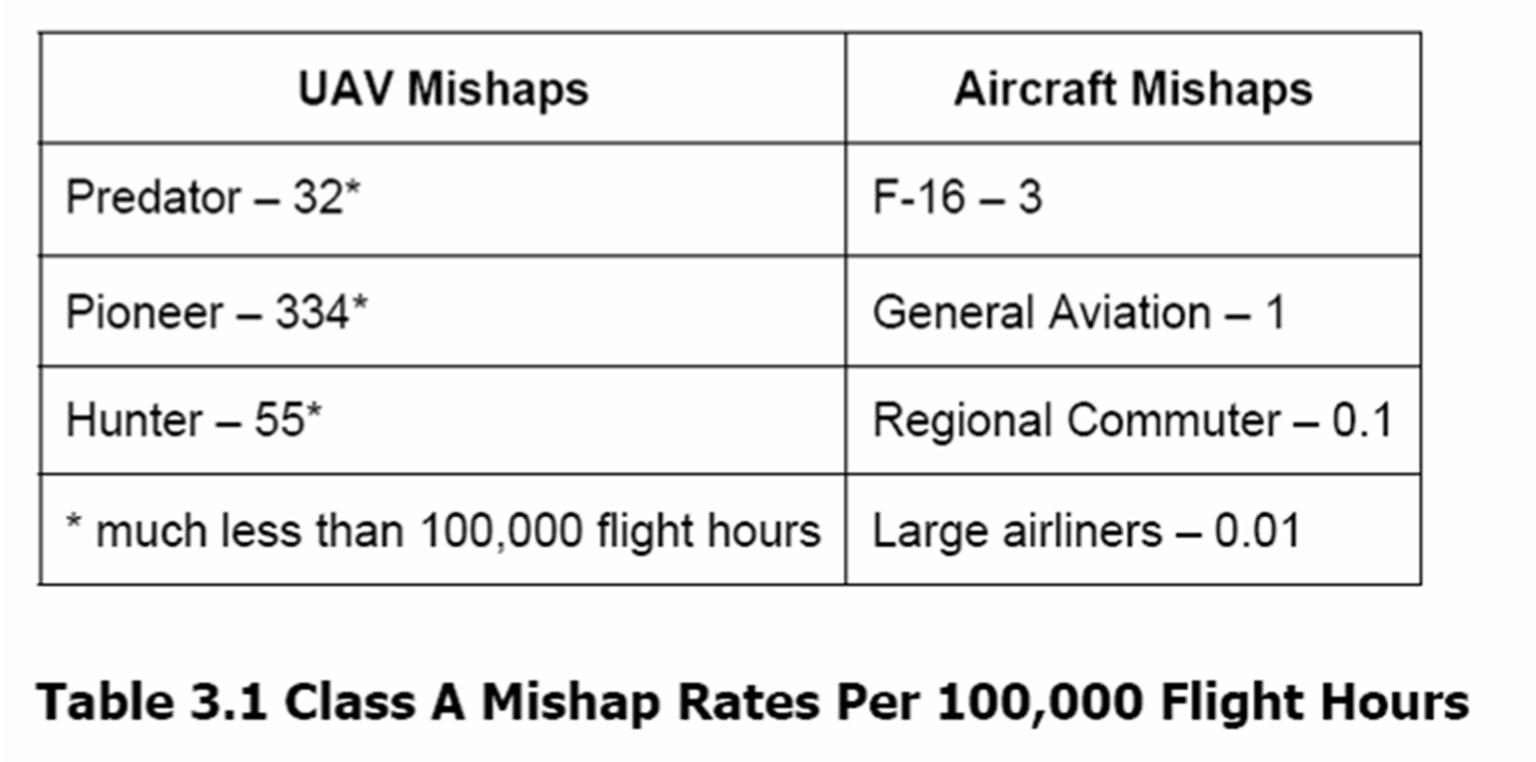
Consequence

Likelihood

SEVERITY PROBABILITY	Catastrophic	Critical	Marginal	Negligible
Frequent	1	3	7	13
Probable	2	5	9	16
Occasional	4	6	11	18
Remote	8	10	14	19
Improvable	12	15	17	20

What is the Likelihood of an In-Flight Failure of a UAV?

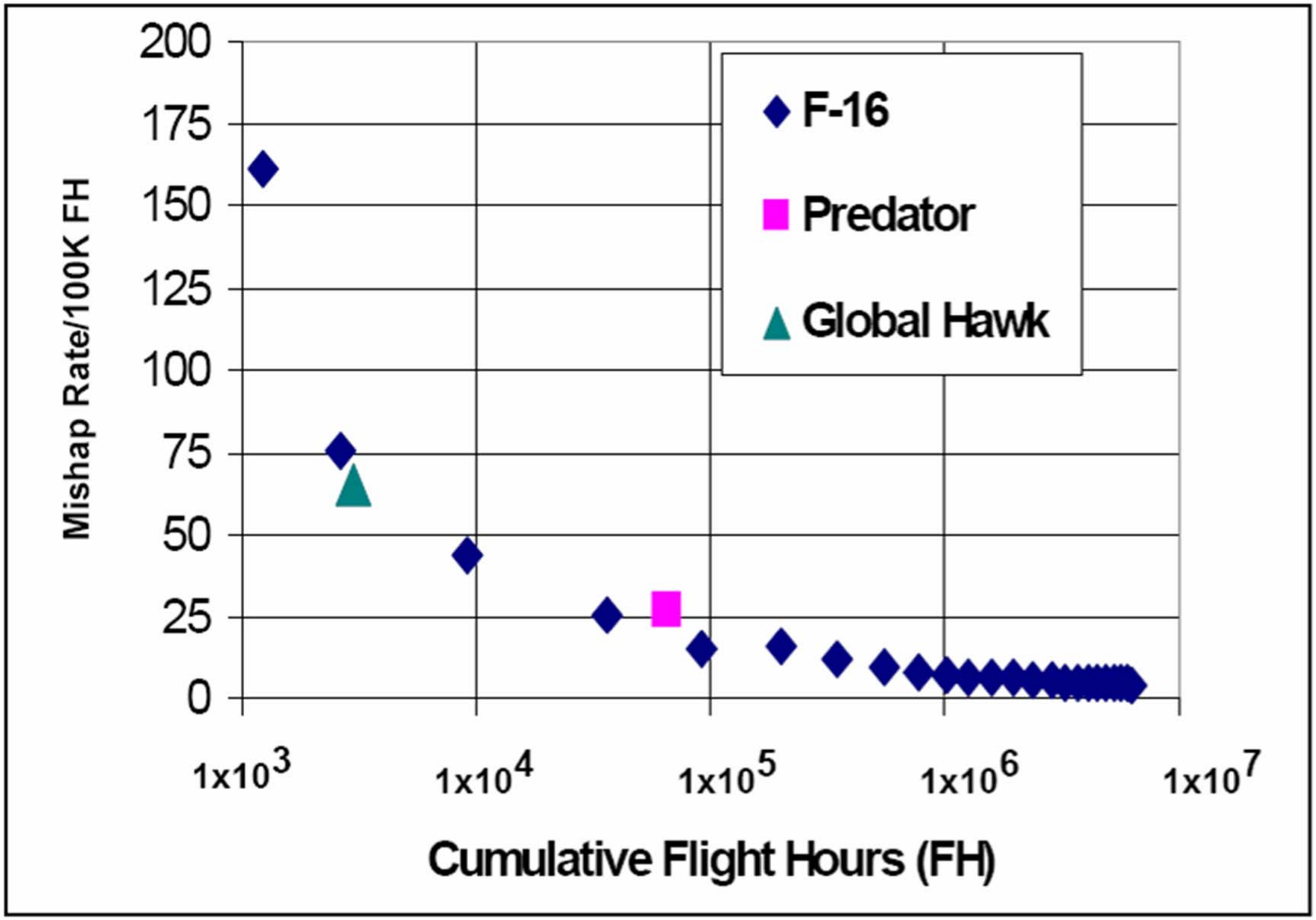
UAVs Tend to Have More Accidents



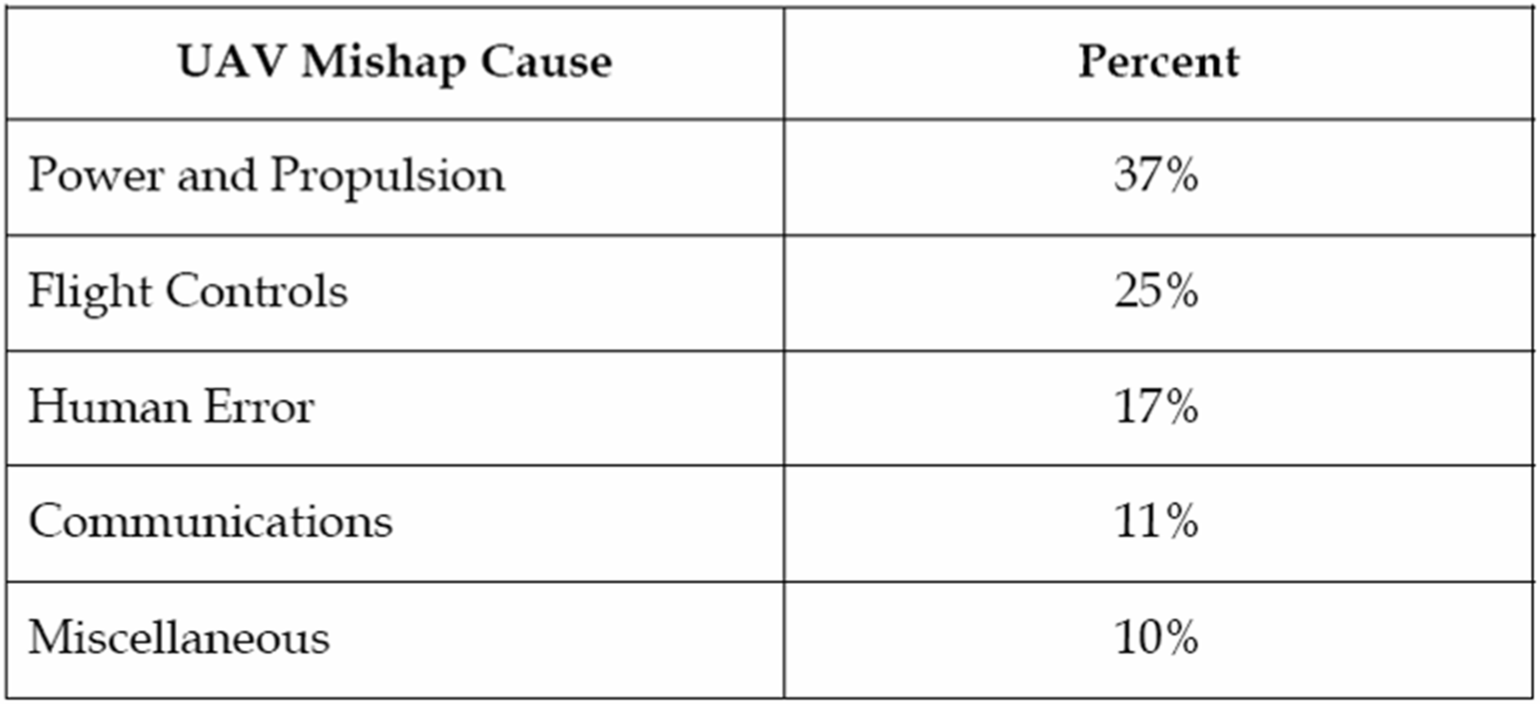
UAV Mishaps	Aircraft Mishaps
Predator – 32*	F-16 – 3
Pioneer – 334*	General Aviation – 1
Hunter – 55*	Regional Commuter – 0.1
* much less than 100,000 flight hours	Large airliners – 0.01

Table 3.1 Class A Mishap Rates Per 100,000 Flight Hours

But Experience May Be a Big Driver



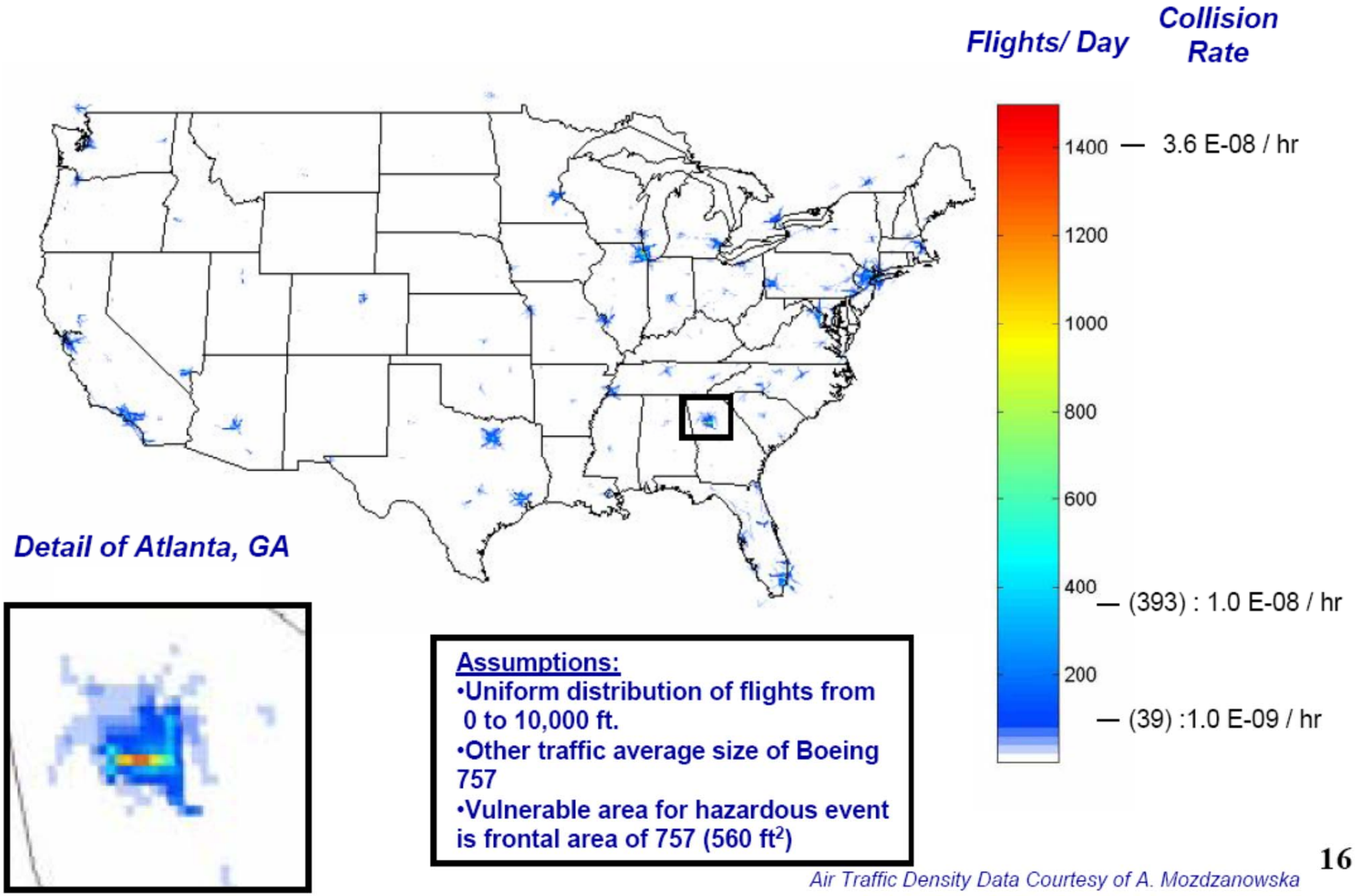
The Cause is Rarely Structures



UAV Mishap Cause	Percent
Power and Propulsion	37%
Flight Controls	25%
Human Error	17%
Communications	11%
Miscellaneous	10%

Structures <2%

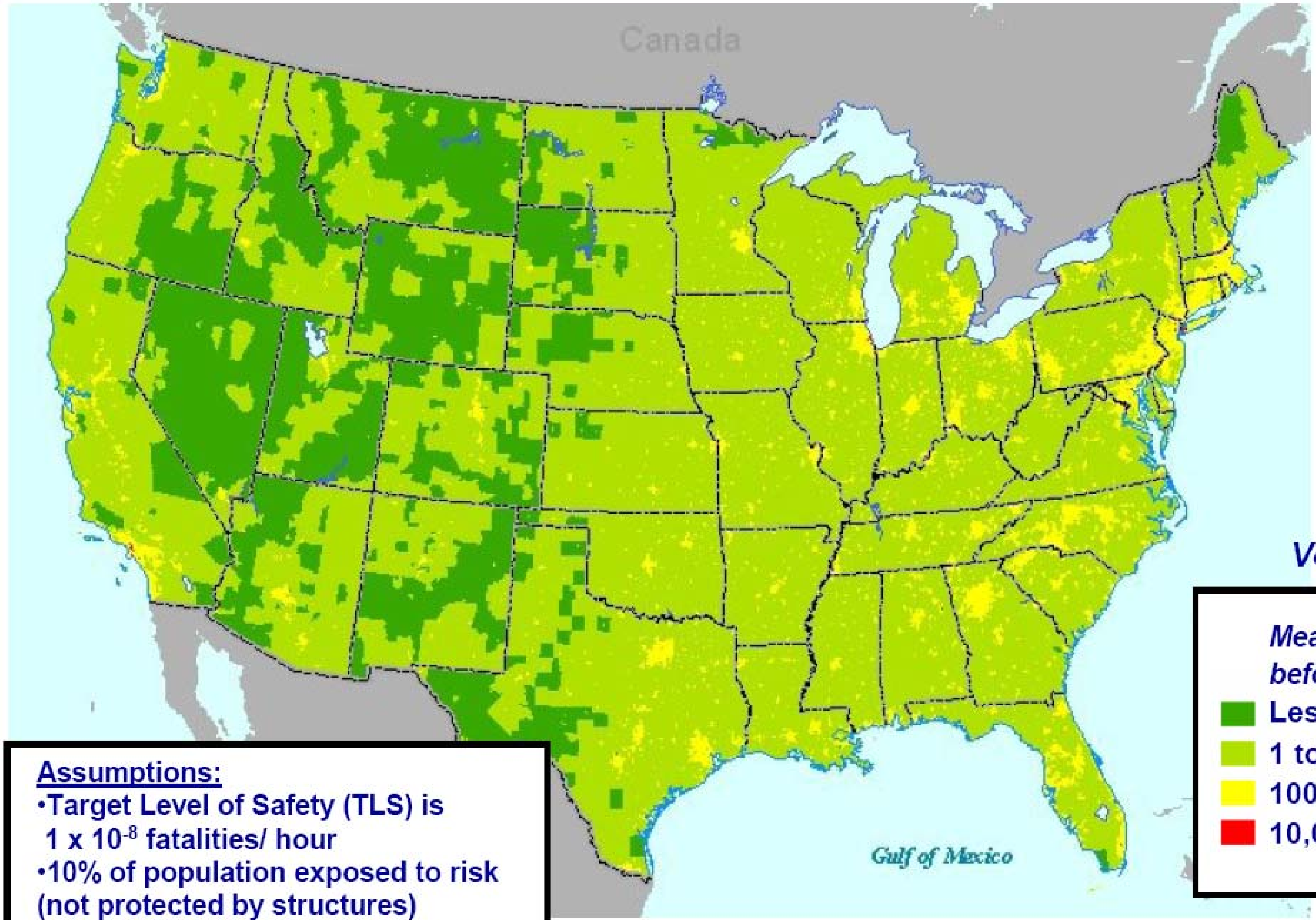
Midair Collision Risk Results



Assumptions:
- Uniform distribution of flights from 0 to 10,000 ft.
- Other traffic average size of Boeing 757
- Vulnerable area for hazardous event is frontal area of 757 (560 ft^2)

Air Traffic Density Data Courtesy of A. Mozdzanowska

Pointer Reliability Requirements to meet TLS of 10^{-8} /hr



Aerovironment
Pointer – 9.6 lb

Vehicle Reliability

	Mean op. hours before failure	*% of US by Area*
🟩	Less than 1 hr	34.0%
🟩	1 to 100 hr	60.8%
🟨	100 to 10,000 hr	5.2%
🟥	10,000 hr and up	0.02%

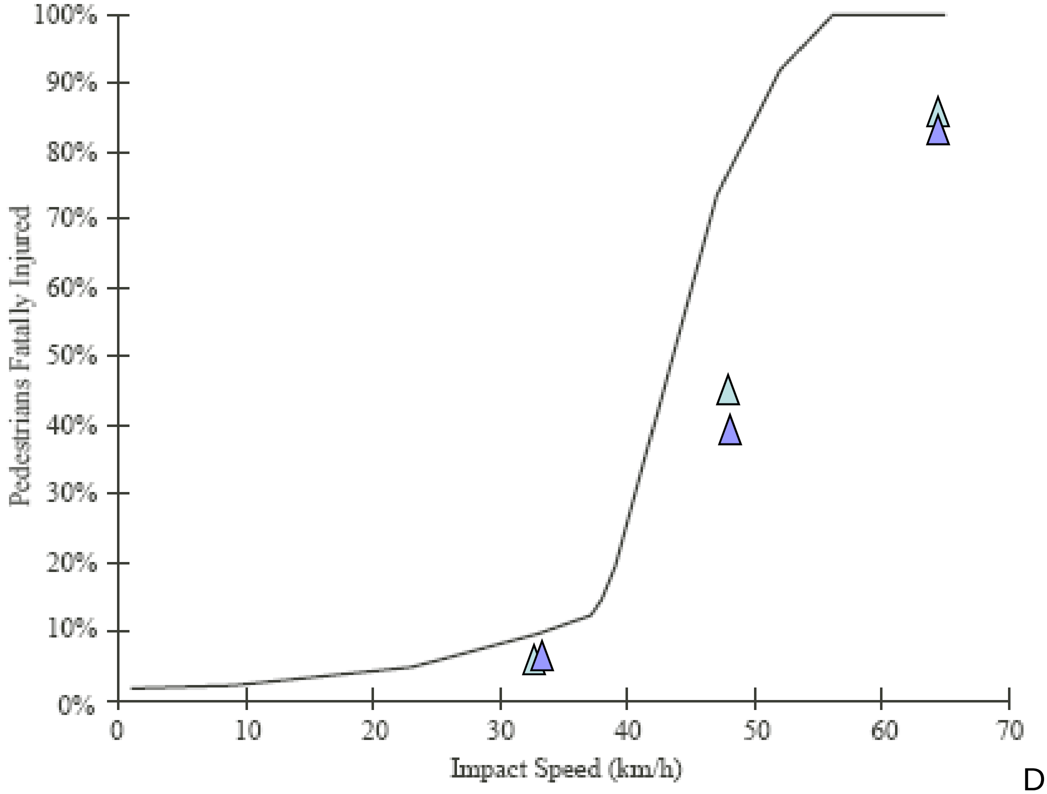
<u>Assumptions:</u>

- Target Level of Safety (TLS) is 1×10^{-8} fatalities/ hour
- 10% of population exposed to risk (not protected by structures)
- Avg area of fatality for UAV crash is $1.7\ ft^2$

Consequences of UAS Failure

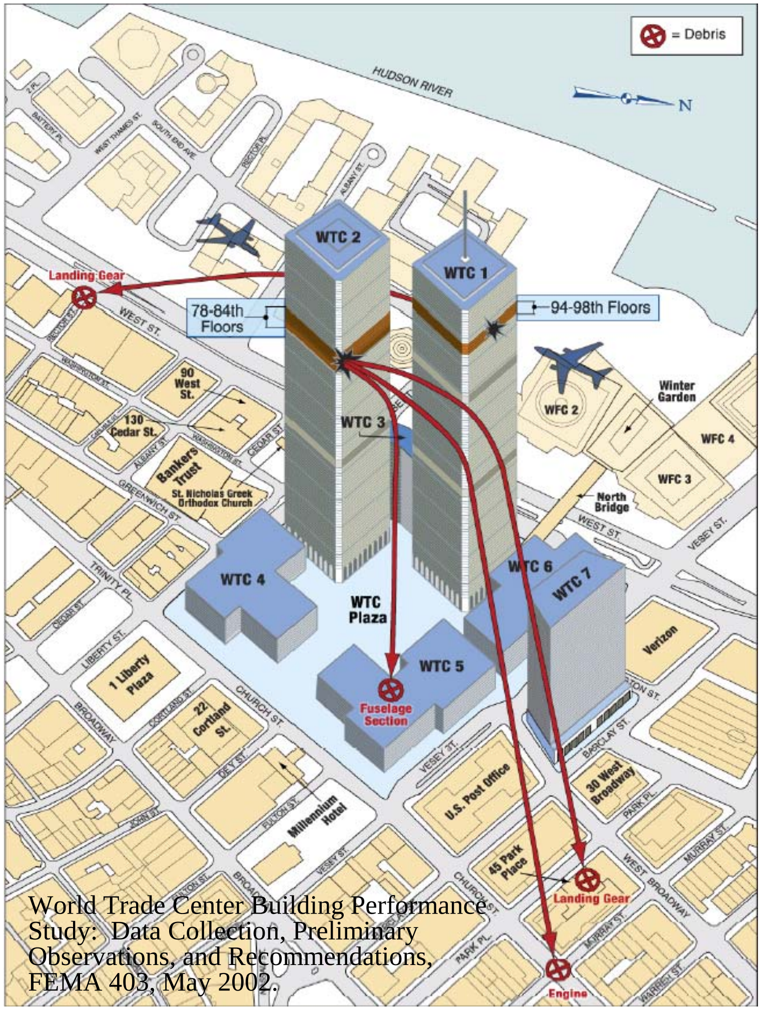
- **Probability of Fatality on the Ground is Greater than in the Air**
- **Probability of Fatality is Greater with at Higher Population Densities**
- **Probability of Fatality is Greater the Higher the Mass and Speed of the Aircraft**
- **Probability of Fatality Can Be High if Carrying Lethal Weapons**
- **Higher Usage Requires Higher Reliability to Meet Safety Standards**

Auto Fatalities are Linked to Kinetic Energy



Data from
University of Adelaide, Australia,
Dept of Transportation, London, UK, and
Dept of Transportation Australia

Extreme Ground Fatality Data



World Trade Center Building Performance Study: Data Collection, Preliminary Observations, and Recommendations, FEMA 403, May 2002.

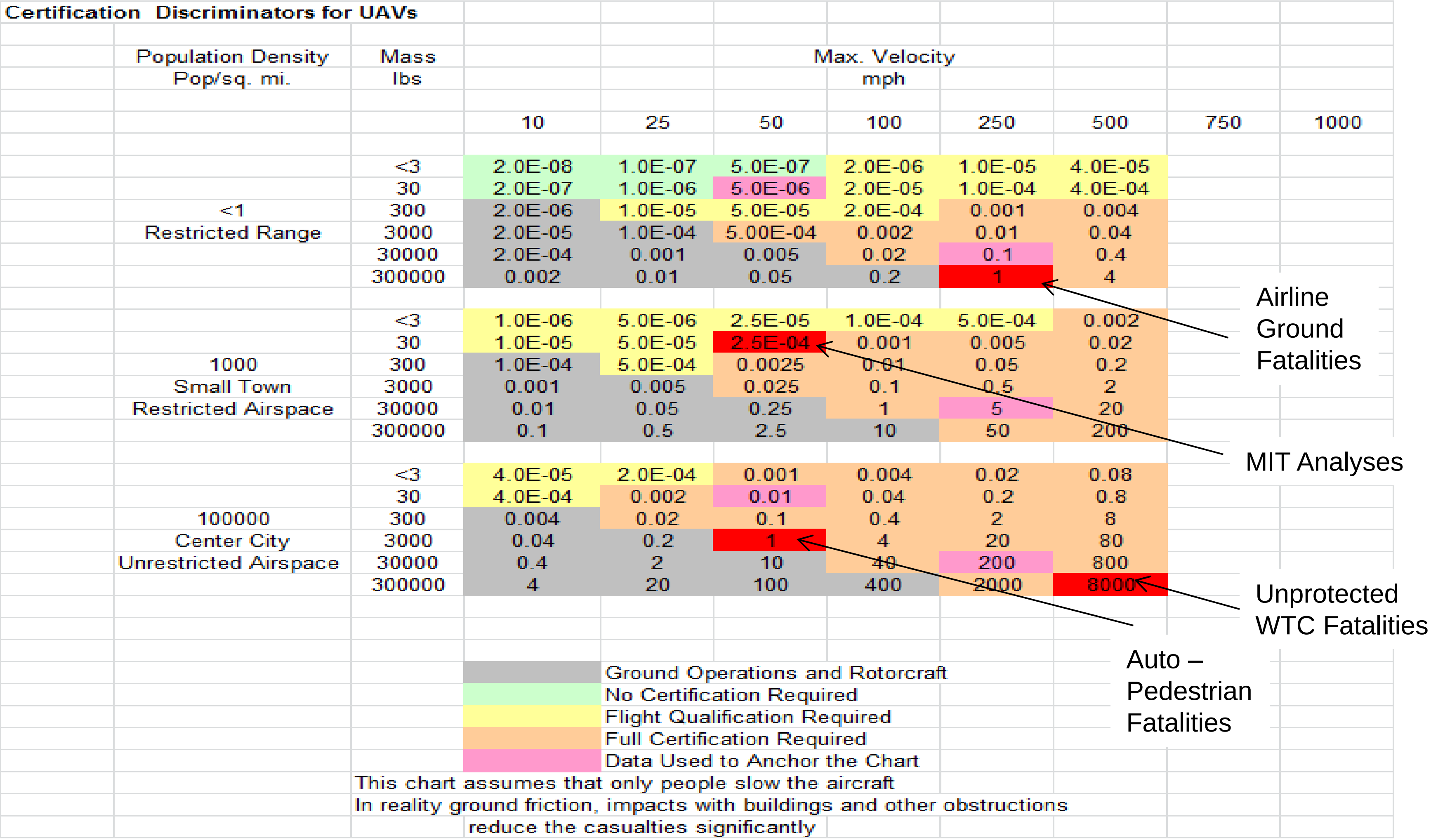
Population Density of Towers
100,000 per Sq. Mi.

4,000 people potentially killed in each building had the buildings not protected them

High mass density portion of the aircraft exited the buildings

Mass, density, speed, population density and armament all matter in determining lethality of UAV collisions with the ground.

Kinetic Energy Determines Lethality



Certification Discriminators for UAVs

Population Density Pop/sq. mi.	Mass lbs	Max. Velocity mph							
		10	25	50	100	250	500	750	1000
<1 Restricted Range	<3	2.0E-08	1.0E-07	5.0E-07	2.0E-06	1.0E-05	4.0E-05		
	30	2.0E-07	1.0E-06	5.0E-06	2.0E-05	1.0E-04	4.0E-04		
	300	2.0E-06	1.0E-05	5.0E-05	2.0E-04	0.001	0.004		
	3000	2.0E-05	1.0E-04	5.00E-04	0.002	0.01	0.04		
	30000	2.0E-04	0.001	0.005	0.02	0.1	0.4		
	300000	0.002	0.01	0.05	0.2	1	4		
1000 Small Town Restricted Airspace	<3	1.0E-06	5.0E-06	2.5E-05	1.0E-04	5.0E-04	0.002		
	30	1.0E-05	5.0E-05	2.5E-04	0.001	0.005	0.02		
	300	1.0E-04	5.0E-04	0.0025	0.01	0.05	0.2		
	3000	0.001	0.005	0.025	0.1	0.5	2		
	30000	0.01	0.05	0.25	1	5	20		
	300000	0.1	0.5	2.5	10	50	200		
100000 Center City Unrestricted Airspace	<3	4.0E-05	2.0E-04	0.001	0.004	0.02	0.08		
	30	4.0E-04	0.002	0.01	0.04	0.2	0.8		
	300	0.004	0.02	0.1	0.4	2	8		
	3000	0.04	0.2	1	4	20	80		
	30000	0.4	2	10	40	200	800		
	300000	4	20	100	400	2000	8000		

⬜	Ground Operations and Rotorcraft
🟩	No Certification Required
🟨	Flight Qualification Required
🟧	Full Certification Required
🟪	Data Used to Anchor the Chart

This chart assumes that only people slow the aircraft
In reality ground friction, impacts with buildings and other obstructions reduce the casualties significantly

Airline Ground Fatalities

MIT Analyses

Unprotected WTC Fatalities

Auto – Pedestrian Fatalities

Proposed Categories

Vehicle Type	Existing Regulatory Guidance (Reference Only)	General Guidance	International Airspace	National Airspace	DoD Airspace		
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Med/Large Fixed Wing	STANAG 4671 JSSG 2006	$mv^2>(1320 \text{ lbs})(200 \text{ kts})^2$ $mv^2>(600 \text{ kg})(370 \text{ km/h})^2$	1	1	1	1R	1P
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Light, F/W & R/W	AC 23-19A	$mv^2<(1320 \text{ lbs})(200 \text{ kts})^2$ $mv^2<(600 \text{ kg})(370 \text{ km/h})^2$	2	2	2	2R	2P
Small / Mini / Micro F/W & R/W	Association of Model Aeronautics (AMA)	$mv^2<(20 \text{ lbs})(120 \text{ kts})^2$ $mv^2<(9 \text{ kg})(190 \text{ km/h})^2$	3	3	3	3	3

Outlook

- **We recommend that in two years, NATO STO begin a new effort to revise these Guidelines to include rotorcraft UAS guidelines.**
- **Look at republishing the Guidelines in about 5 years**
- **We believe that there will be many lessons learned from UAS vehicles in the next few years as they are integrated into the national and international airspace.**
- **We address rotorcraft in these guidelines in a general sense, but not with the specifics that these vehicles require.**