16th AIAA Aviation Technology, Integration, and Operations Conference
Transformational Flight Session: SCEPTOR Distributed Electric Propulsion X-Plane

SCEPTOR Power System Design:
Experimental Electric Propulsion System Design and Qualification for Crewed Flight Testing

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NASA SCEPTOR X-Plane

(Scalable Convergent Electric Propulsion Technology Operations Research)

Distributed Electric Propulsion (DEP) is a new technology frontier,

enabling ultra-high efficiency, low carbon emissions,
low community noise, and low operating costs.

When coupled with the autonomy technology frontier,
will enable transformative high-speed On-Demand Mobility

SCEPTOR X-Plane Objectives

<u>Primary Objective</u>

Goal: 5x Lower Energy Use (Compared to Original P2006T @ 175 mph)

- IC Engine vs Electric Propulsion Efficiency changes from 28% to 92% (~3.3x)
- Synergistic Integration (~1.5x)

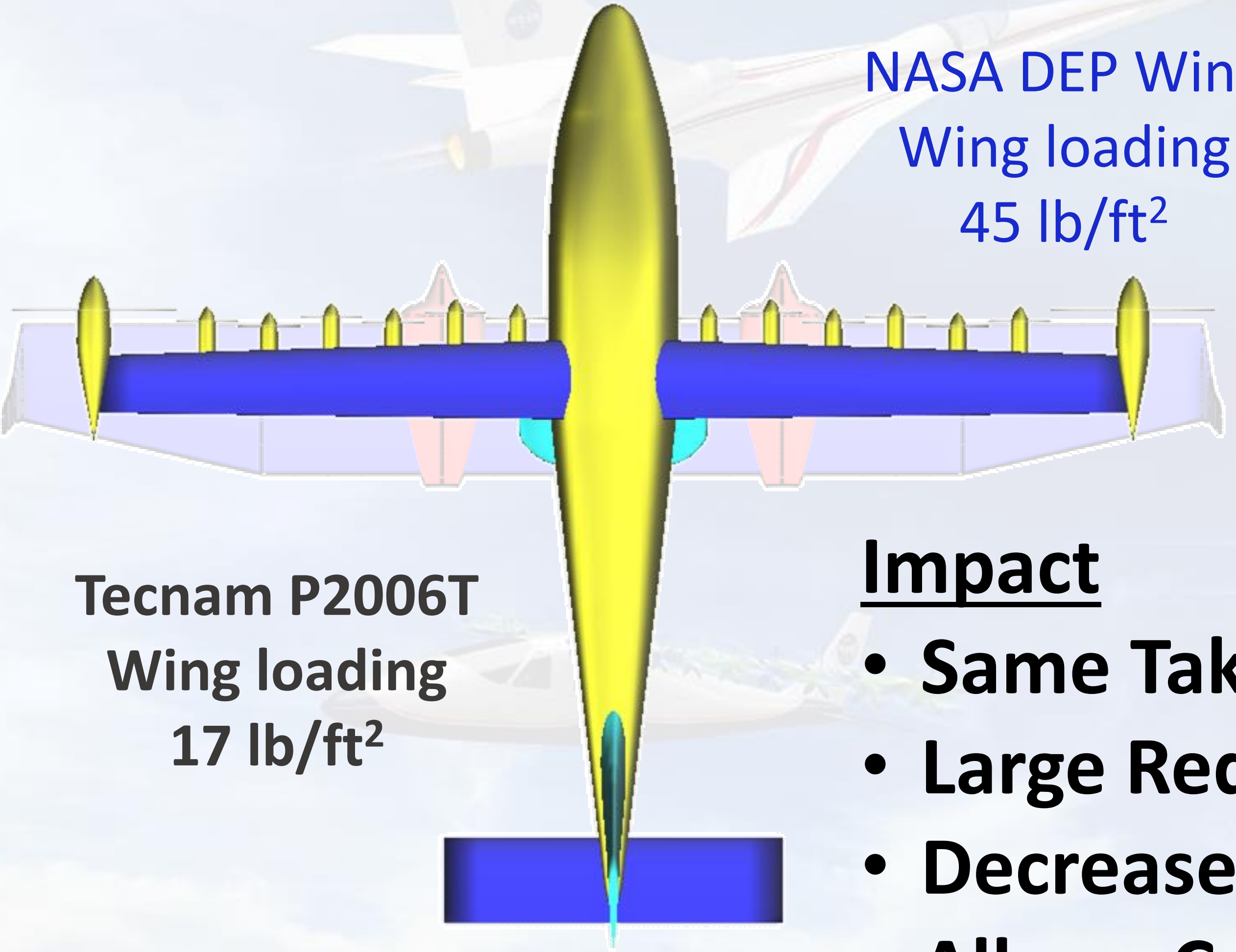
<u>Derivative Objectives</u>

- ~30% Lower Total Operating Cost
- Zero In-flight Carbon Emissions

<u>Secondary Objectives</u>

- 15 dB Lower community noise
- Flight control redundancy and robustness
- Improved ride quality
- Certification basis for DEP technologies

SCEPTOR Wing Sizing Impact



NASA DEP Wing
Wing loading
45 lb/ft^2

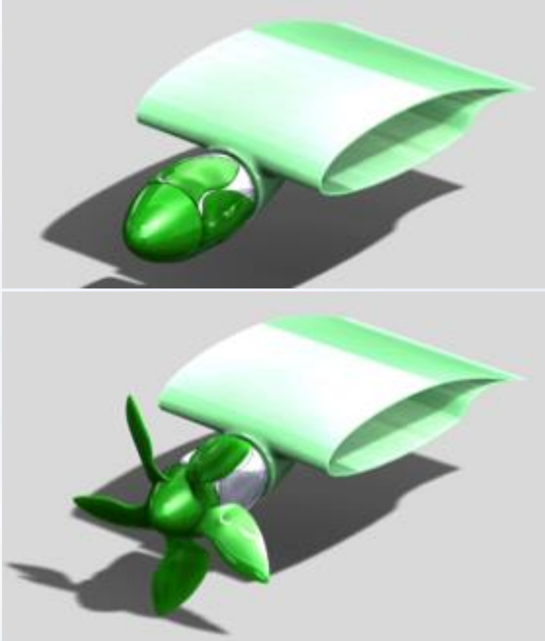
Tecnam P2006T
Wing loading
17 lb/ft^2

Impact

- **Same Takeoff/Landing Speed**
- **Large Reduction in Wing Area**
- **Decreases the Friction Drag**
- **Allows Cruise at High Lift Coefficient**
- **Less Gust/Turbulence Sensitivity**

DEP Integration Synergistic Design

Folding Inboard Propellers with Low Tip Speeds



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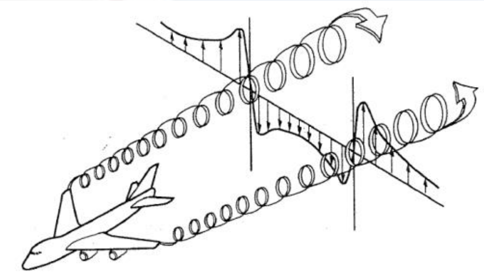
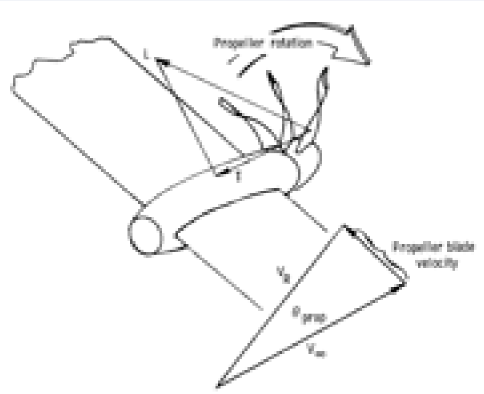
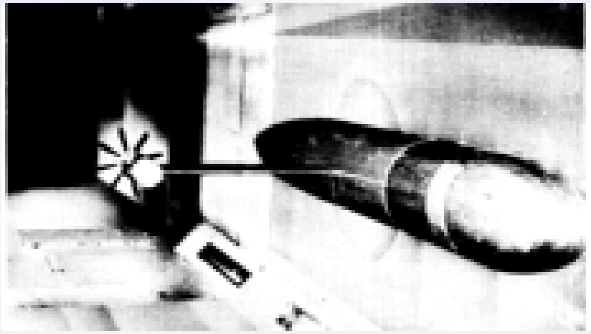
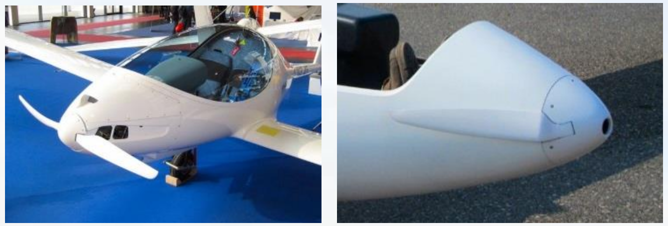
Wingtip Vortex Propeller Integration

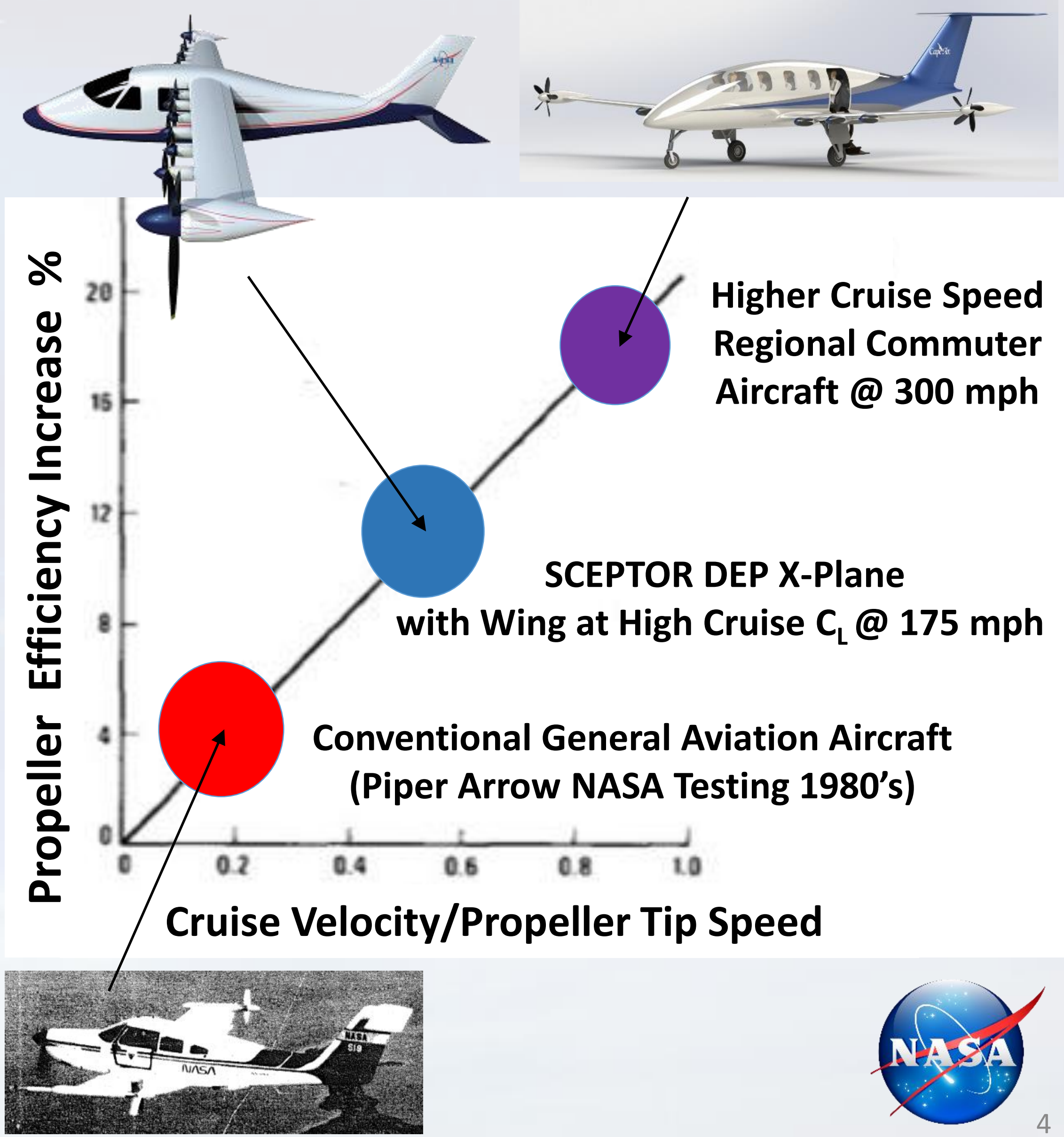






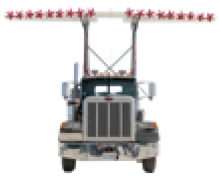


Viva and Alisport Motorgliders



SCEPTOR Project Approach

Mod 1



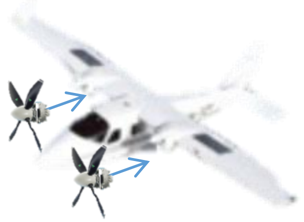
Ground validation of DEP highlift system

Flight testing of baseline Tecnam P2006T

Goals:

- Establish Baseline Tecnam Performance
- Pilot Familiarity

Mod 2

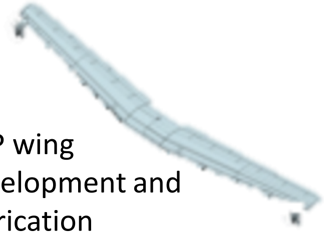


Ground and flight test validation of electric motors, battery, and instrumentation.

Goals:

- Establish Electric Power System Flight Safety
- Establish Electric Tecnam Retrofit Baseline

Mod 3



DEP wing development and fabrication

Flight test electric motors relocated to wingtips on DEP wing including nacelles (but no DEP motors, controllers, or folding props).

Achieves Primary Objective of High Speed Cruise Efficiency

Mod 4

Flight test with integrated DEP motors and folding props (cruise motors remain in wing-tips).

Achieves Secondary Objectives

- DEP Acoustics Testing
- Low Speed Control Robustness
- Certification Basis of DEP Technologies

Mod 1

Mod 2

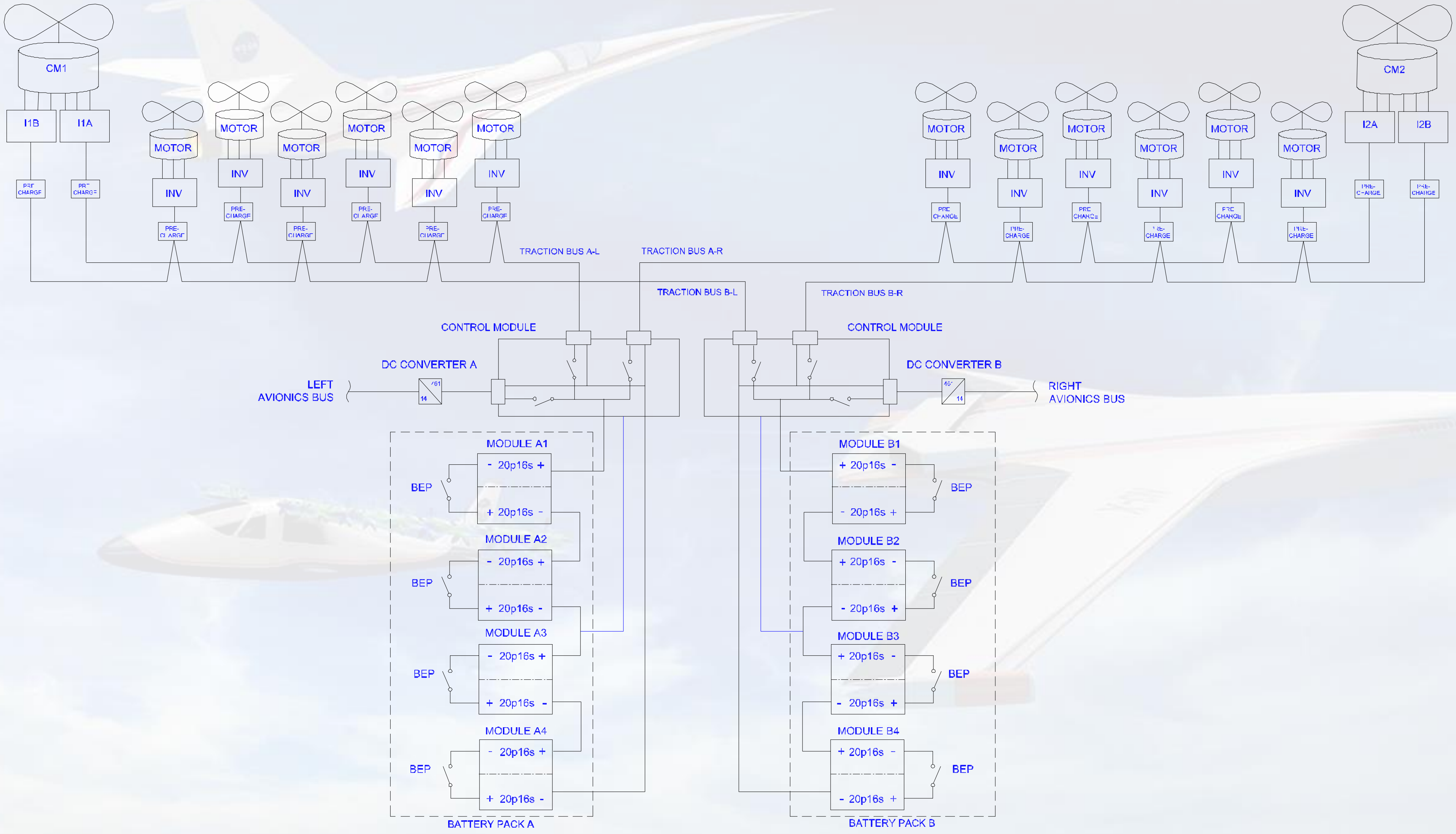
Mod 3

Mod 4

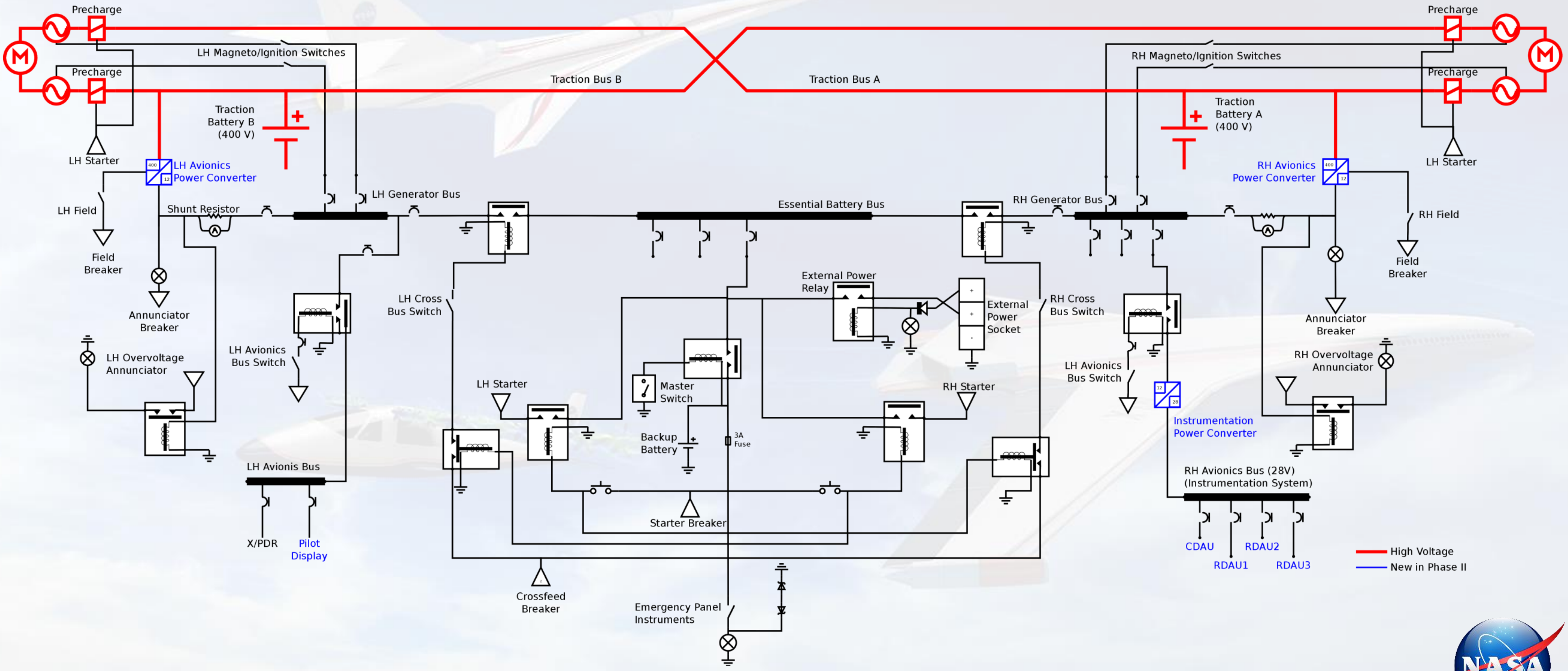
Spiral development process

- Build – Fly – Learn

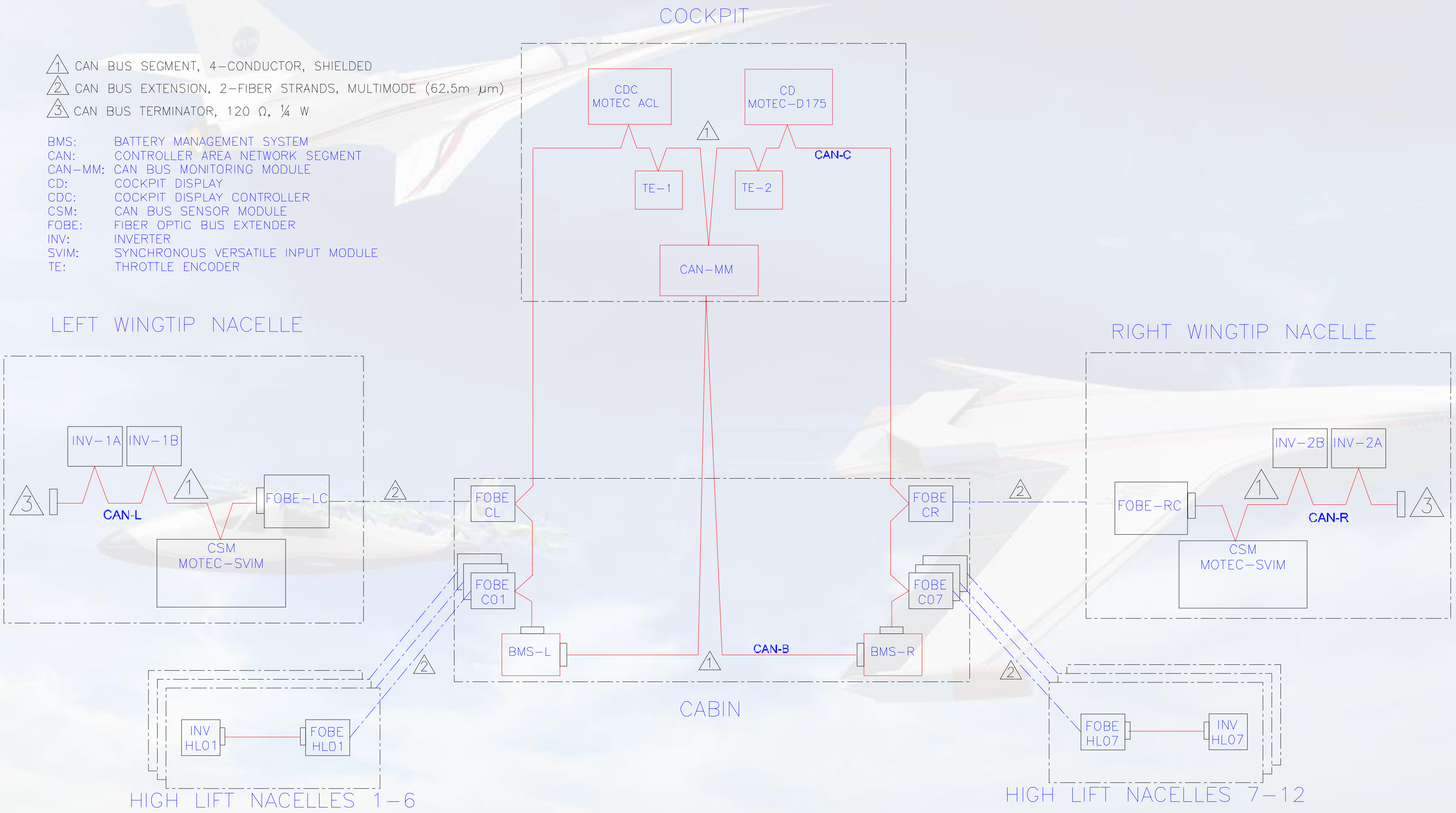
Traction Power System Architecture



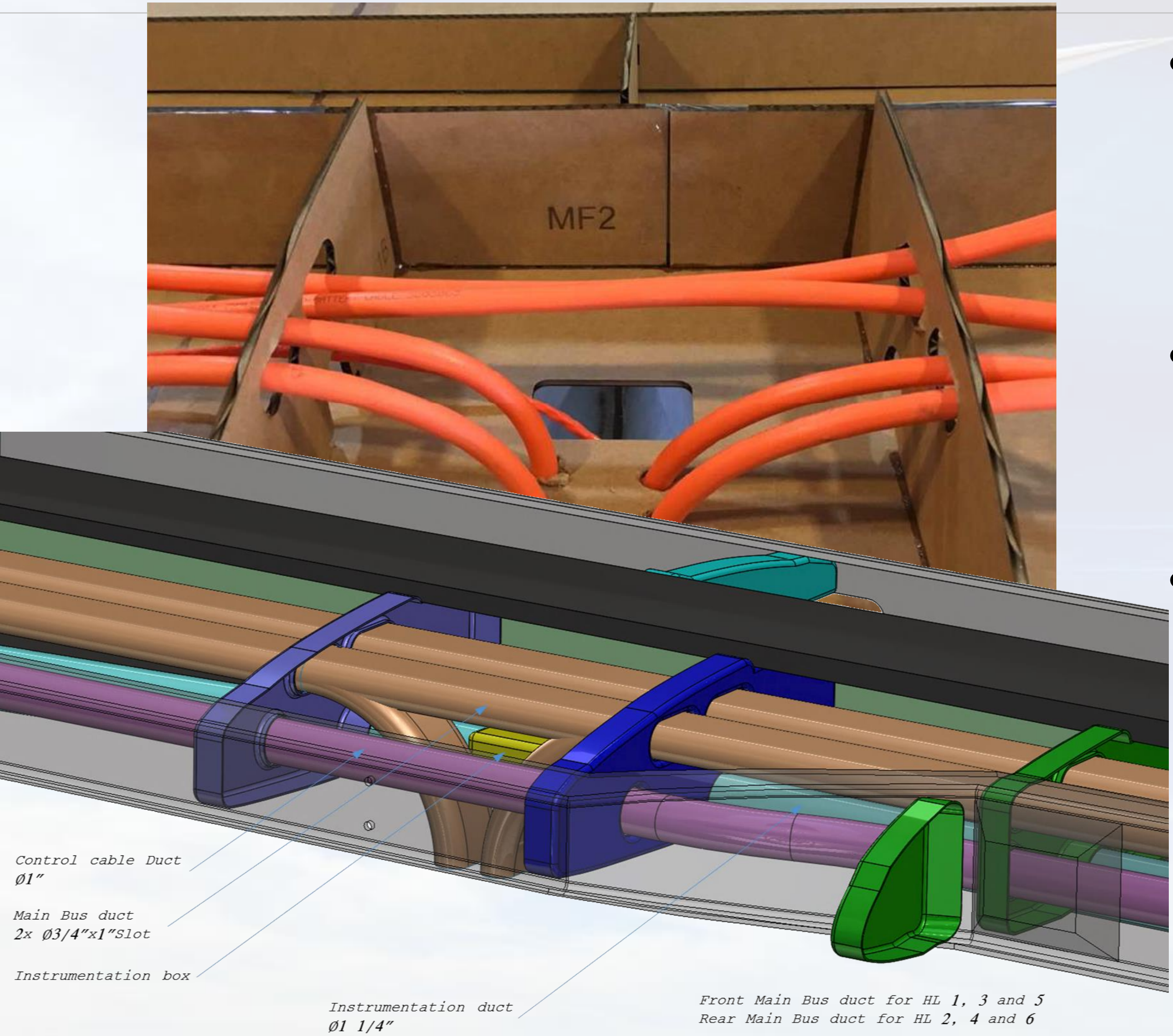
Traction Power System Integration with Avionics



Command System Architecture



Traction Bus



- Redundant traction buses. Each high-lift motor alternates buses, cruise motors pull 50% power from each bus.
- Buses protected in separate ducts for isolation, shielding and protection
- Command and Instrumentation systems routed and shielded separately to avoid interference and common failures

ESAERO Xperimental, LLC

Environmental Test Standards

- NASA AFRC DCP-O-018 *Environmental Acceptance Testing: Electronic & Electromechanical Equipment* describes standard vibration and thermal testing approaches for equipment to be flown at AFRC.
  - Doesn’t (yet!) include guidance for electric propulsion motors
- MIL-HDKB-344A, §5.4 describes Environmental Stress Screening for workmanship flaw detection.
  - Recommends lower vibration test duration than DCP-O-018 for most curves
  - Recommends more thermal test cycles depending on the ramp rate

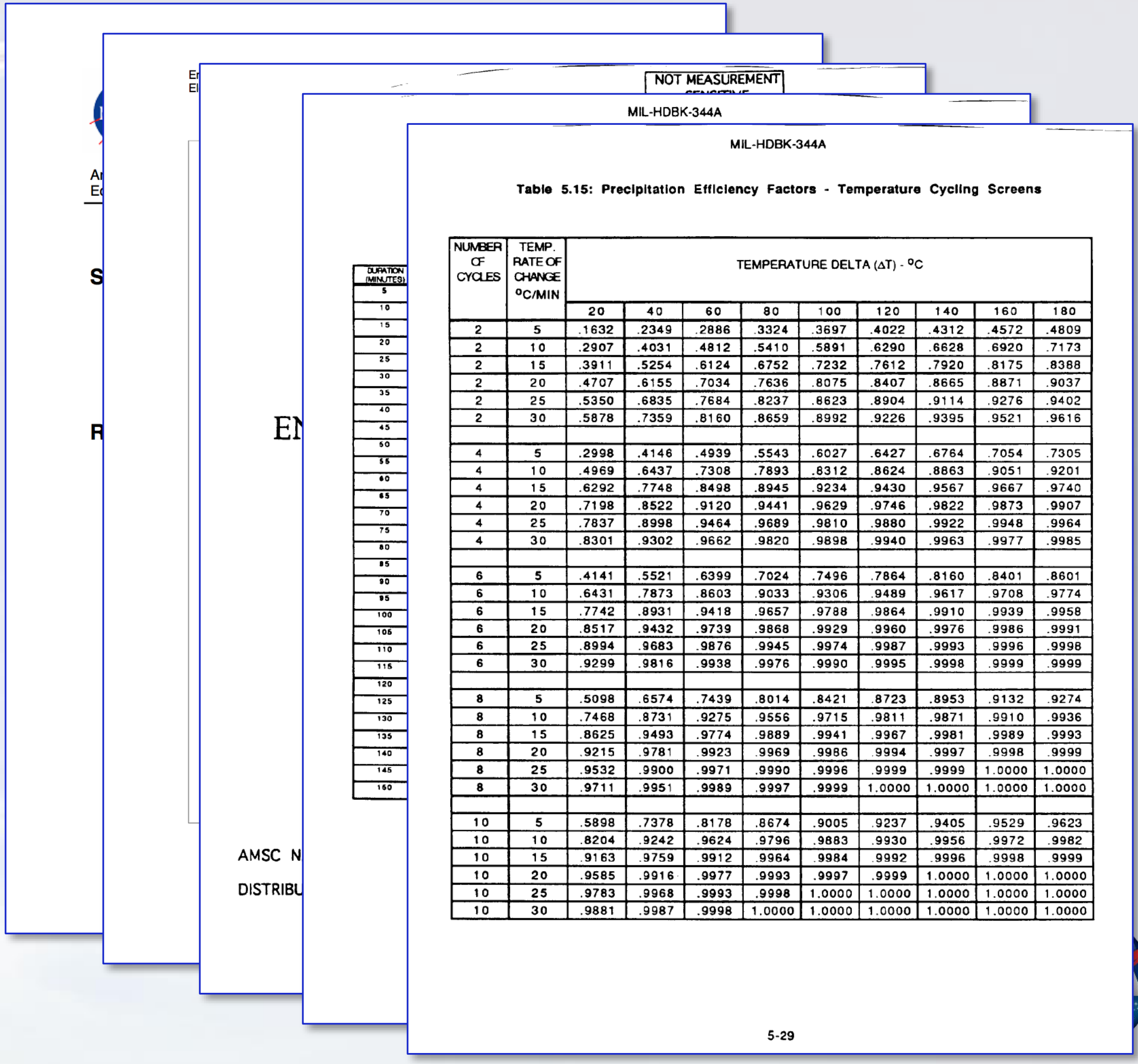

MIL-HDBK-344A

Table 5.15: Precipitation Efficiency Factors - Temperature Cycling Screens

NUMBER OF CYCLES	TEMP. RATE OF CHANGE °C/MIN	TEMPERATURE DELTA (ΔT) - °C								
		20	40	60	80	100	120	140	160	180
2	5	.1632	.2349	.2886	.3324	.3697	.4022	.4312	.4572	.4809
2	10	.2907	.4031	.4812	.5410	.5891	.6290	.6628	.6920	.7173
2	15	.3911	.5254	.6124	.6752	.7232	.7612	.7920	.8175	.8388
2	20	.4707	.6155	.7034	.7636	.8075	.8407	.8665	.8871	.9037
2	25	.5350	.6835	.7684	.8237	.8623	.8904	.9114	.9276	.9402
2	30	.5878	.7359	.8160	.8659	.8992	.9226	.9395	.9521	.9616
4	5	.2998	.4146	.4939	.5543	.6027	.6427	.6764	.7054	.7305
4	10	.4969	.6437	.7308	.7893	.8312	.8624	.8863	.9051	.9201
4	15	.6292	.7748	.8498	.8945	.9234	.9430	.9567	.9667	.9740
4	20	.7198	.8522	.9120	.9441	.9629	.9746	.9822	.9873	.9907
4	25	.7837	.8998	.9464	.9689	.9810	.9880	.9922	.9948	.9964
4	30	.8301	.9302	.9662	.9820	.9898	.9940	.9963	.9977	.9985
6	5	.4141	.5521	.6399	.7024	.7496	.7864	.8160	.8401	.8601
6	10	.6431	.7873	.8603	.9033	.9306	.9489	.9617	.9708	.9774
6	15	.7742	.8931	.9418	.9657	.9788	.9864	.9910	.9939	.9958
6	20	.8517	.9432	.9739	.9868	.9929	.9960	.9976	.9986	.9991
6	25	.8994	.9683	.9876	.9945	.9974	.9987	.9993	.9996	.9998
6	30	.9299	.9816	.9938	.9976	.9990	.9995	.9998	.9999	.9999
8	5	.5098	.6574	.7439	.8014	.8421	.8723	.8953	.9132	.9274
8	10	.7468	.8731	.9275	.9556	.9715	.9811	.9871	.9910	.9936
8	15	.8625	.9493	.9774	.9889	.9941	.9967	.9981	.9989	.9993
8	20	.9215	.9781	.9923	.9969	.9986	.9994	.9997	.9998	.9999
8	25	.9532	.9900	.9971	.9990	.9996	.9999	.9999	1.0000	1.0000
8	30	.9711	.9951	.9989	.9997	.9999	1.0000	1.0000	1.0000	1.0000
10	5	.5898	.7378	.8178	.8674	.9005	.9237	.9405	.9529	.9623
10	10	.8204	.9242	.9624	.9796	.9883	.9930	.9956	.9972	.9982
10	15	.9163	.9759	.9912	.9964	.9984	.9992	.9996	.9998	.9999
10	20	.9585	.9916	.9977	.9993	.9997	.9999	1.0000	1.0000	1.0000
10	25	.9783	.9968	.9993	.9998	1.0000	1.0000	1.0000	1.0000	1.0000
10	30	.9881	.9987	.9998	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

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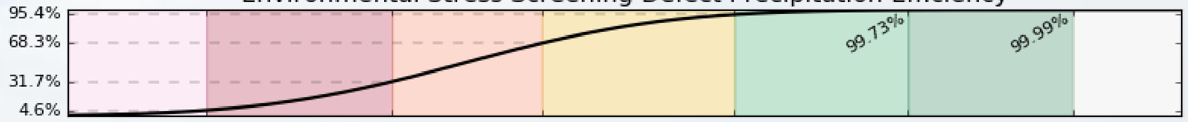
SCEPTOR Environmental Test and Analysis Program

- CEPT-007 Env. Test Plan is using extrapolated random vibration and thermal test duration cycle time based on guidance from DCP-O-018 and MIL-HDKB-344A
  - Motor testing while loaded on a vibration table infeasible; instead will take credit for “FAR Part 33-Like” endurance testing on static test stand due to self-induced vibration environment
  - Thermal testing for custom components will use 10+ ESS cycles based on 344A.
- Test severity is based on ground/flight test environment and operational limits
- Shock and impulse testing/analysis based on FAR Part 23, DO-160
  - New added or modified components must meet Landing loads (with margin) and crash loads (18g ultimate)

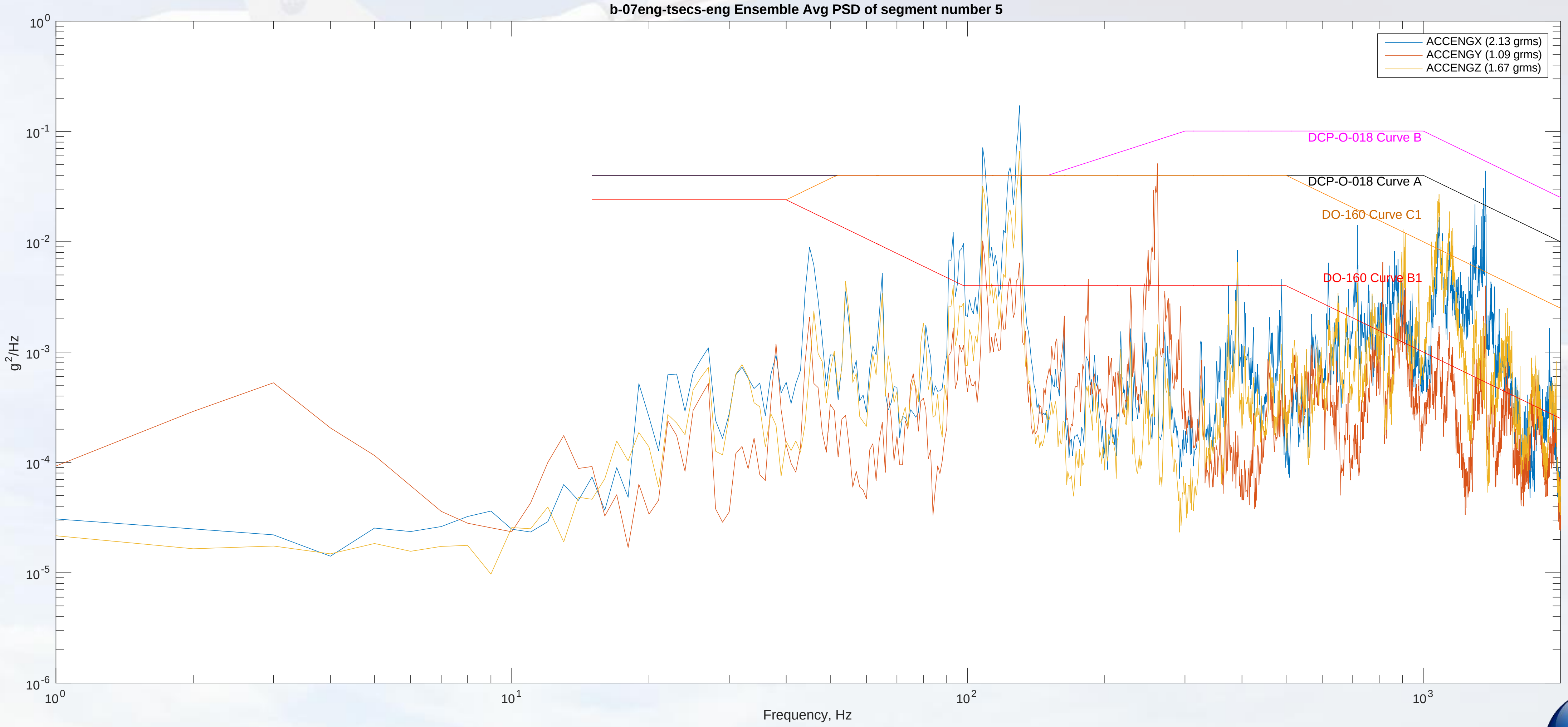
Duration	Acceleration Level (G-RMS)															
(Minutes)	0.5	0.75	1	1.55	2	2.5	3	4.12	5	6	8	10	12.2	15	17.1	19.1
4.0	0.006	0.011	0.018	0.038	0.058	0.084	0.113	0.187	0.251	0.326	0.475	0.611	0.734	0.849	0.906	0.942
4.3	0.006	0.012	0.020	0.041	0.063	0.090	0.121	0.200	0.267	0.345	0.500	0.637	0.760	0.869	0.921	0.953
4.6	0.006	0.013	0.021	0.044	0.067	0.096	0.129	0.212	0.282	0.364	0.523	0.662	0.782	0.886	0.934	0.962
4.9	0.007	0.014	0.022	0.047	0.071	0.102	0.137	0.224	0.298	0.383	0.546	0.685	0.803	0.901	0.945	0.970
5.3	0.007	0.015	0.024	0.050	0.077	0.110	0.147	0.240	0.318	0.407	0.574	0.714	0.827	0.918	0.956	0.977
5.8	0.008	0.016	0.026	0.055	0.084	0.120	0.160	0.259	0.342	0.435	0.607	0.745	0.854	0.935	0.967	0.984
6.3	0.009	0.018	0.029	0.059	0.090	0.130	0.173	0.278	0.365	0.462	0.638	0.774	0.876	0.949	0.976	0.989
6.9	0.010	0.019	0.031	0.065	0.099	0.141	0.188	0.300	0.392	0.493	0.671	0.804	0.898	0.961	0.983	0.993
7.5	0.010	0.021	0.034	0.070	0.107	0.152	0.202	0.322	0.418	0.522	0.701	0.830	0.917	0.971	0.988	0.995
8.0	0.011	0.022	0.036	0.075	0.113	0.162	0.214	0.339	0.438	0.545	0.724	0.849	0.929	0.977	0.991	0.997
9.0	0.013	0.025	0.041	0.084	0.127	0.180	0.237	0.373	0.477	0.588	0.765	0.880	0.949	0.986	0.995	0.998
10	0.014	0.028	0.045	0.093	0.140	0.198	0.260	0.404	0.514	0.627	0.800	0.906	0.964	0.991	0.997	0.999
11	0.015	0.030	0.049	0.102	0.153	0.215	0.282	0.434	0.548	0.662	0.830	0.925	0.974	0.994	0.998	1.000
13	0.018	0.036	0.058	0.119	0.178	0.249	0.324	0.490	0.608	0.722	0.877	0.953	0.987	0.998	1.000	1.000
15	0.021	0.041	0.067	0.136	0.202	0.282	0.363	0.540	0.661	0.772	0.911	0.971	0.993	0.999	1.000	1.000
17	0.024	0.047	0.075	0.152	0.226	0.313	0.401	0.585	0.706	0.813	0.935	0.982	0.996	1.000	1.000	1.000
19	0.026	0.052	0.084	0.169	0.249	0.342	0.436	0.626	0.746	0.846	0.953	0.989	0.998	1.000	1.000	1.000
22	0.030	0.060	0.096	0.193	0.282	0.384	0.484	0.680	0.795	0.885	0.971	0.994	0.999	1.000	1.000	1.000
25	0.035	0.068	0.109	0.216	0.314	0.424	0.529	0.726	0.835	0.915	0.982	0.997	1.000	1.000	1.000	1.000
30	0.041	0.081	0.129	0.253	0.363	0.484	0.595	0.789	0.885	0.948	0.992	0.999	1.000	1.000	1.000	1.000
35	0.048	0.094	0.149	0.289	0.409	0.538	0.651	0.837	0.920	0.968	0.996	1.000	1.000	1.000	1.000	1.000
42	0.057	0.111	0.176	0.336	0.469	0.604	0.718	0.886	0.952	0.984	0.999	1.000	1.000	1.000	1.000	1.000
50	0.068	0.131	0.205	0.385	0.529	0.668	0.778	0.925	0.973	0.993	1.000	1.000	1.000	1.000	1.000	1.000
60	0.081	0.155	0.241	0.442	0.595	0.734	0.836	0.955	0.987	0.997	1.000	1.000	1.000	1.000	1.000	1.000
70	0.094	0.179	0.275	0.494	0.651	0.786	0.878	0.973	0.994	0.999	1.000	1.000	1.000	1.000	1.000	1.000
90	0.119	0.224	0.339	0.584	0.742	0.862	0.933	0.991	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000
110	0.143	0.266	0.397	0.657	0.809	0.911	0.964	0.997	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
140	0.179	0.325	0.475	0.744	0.878	0.954	0.985	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
180	0.224	0.397	0.563	0.827	0.933	0.981	0.996	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
230	0.276	0.476	0.653	0.893	0.969	0.994	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
300	0.344	0.570	0.748	0.946	0.989	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
390	0.422	0.666	0.834	0.978	0.997	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
500	0.505	0.755	0.900	0.992	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
700	0.626	0.860	0.960	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1000	0.755	0.940	0.990	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1300	0.839	0.974	0.997	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1900	0.931	0.995	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2700	0.978	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
4000	0.996	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
6000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Environmental Stress Screening Defect Precipitation Efficiency

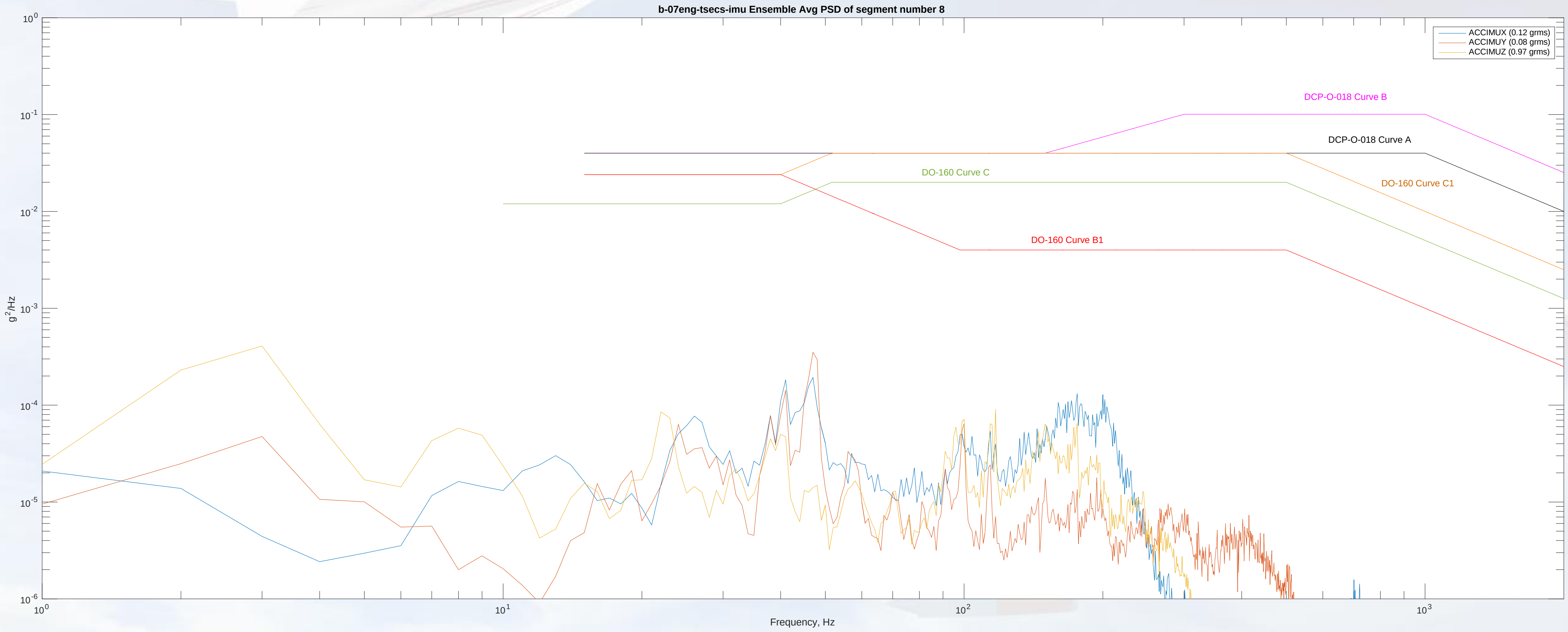


Liklihood that latent defects (with some residual strength) will be converted to patent defects.

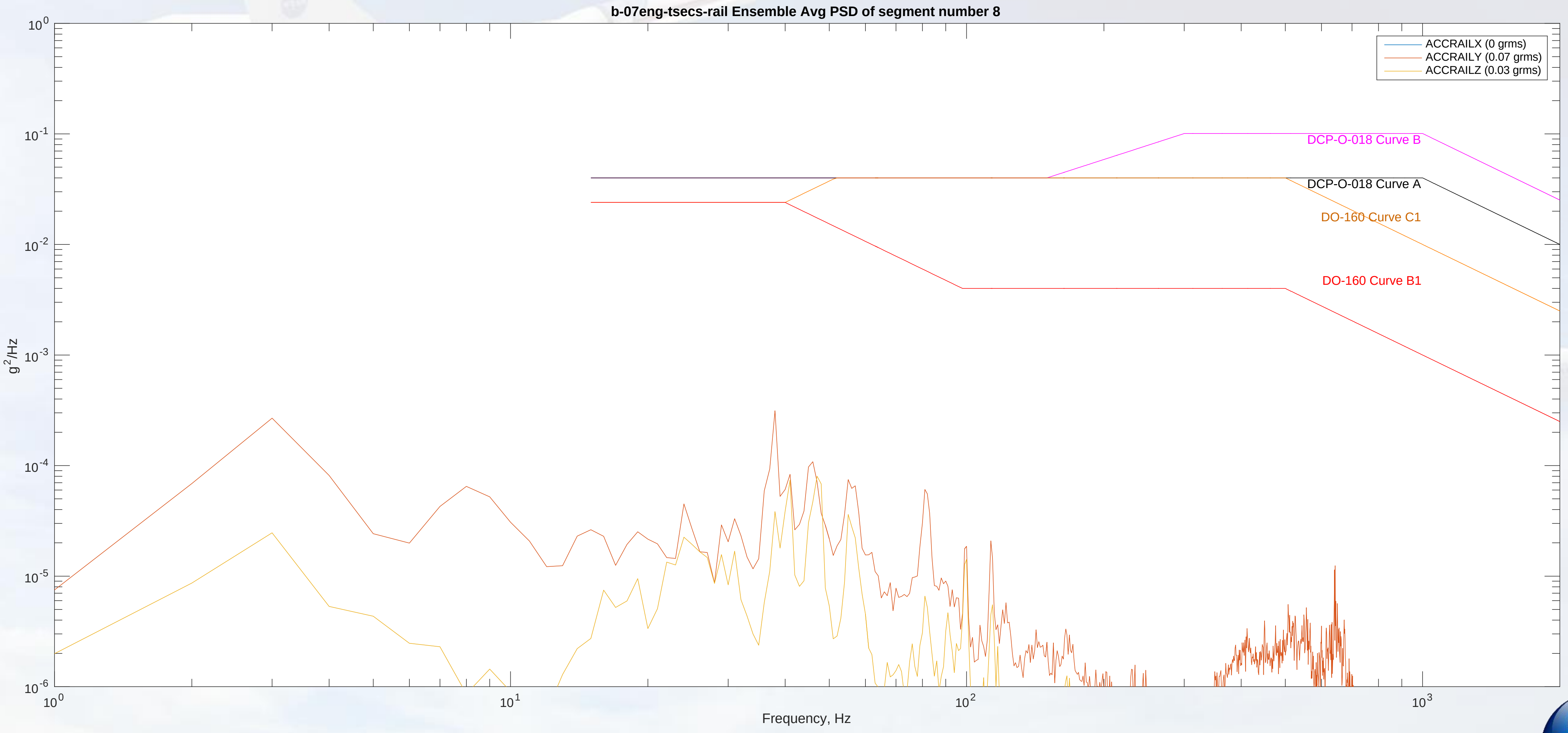
Mod I Engine Nacelle Vibration
Rental Tecnam – Rotax Engine



Mod I Motion Pack
Rental Tecnam – Seat Rails

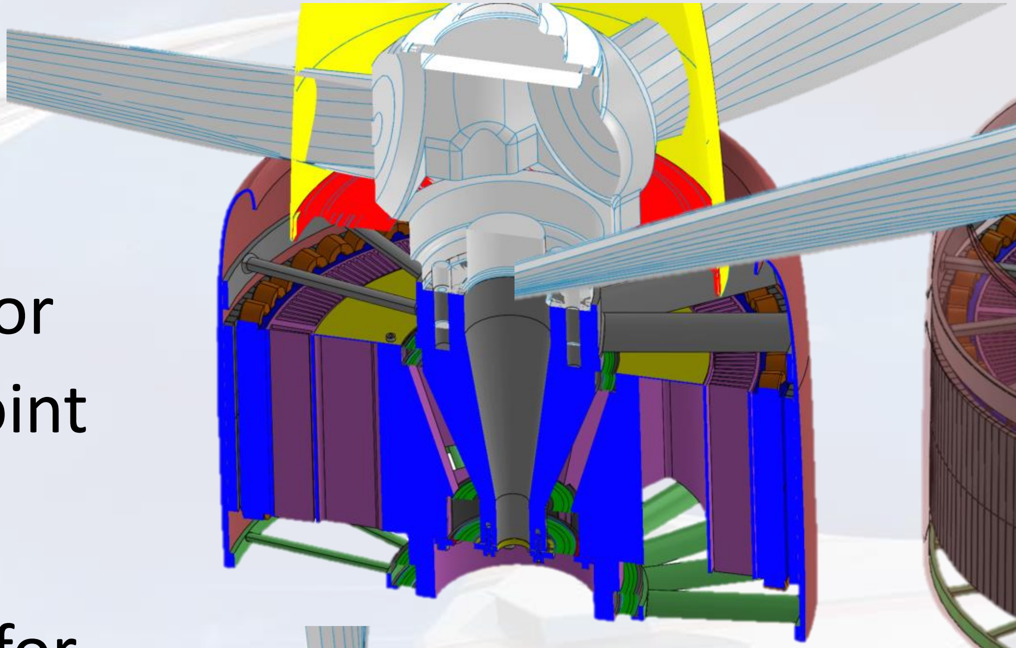


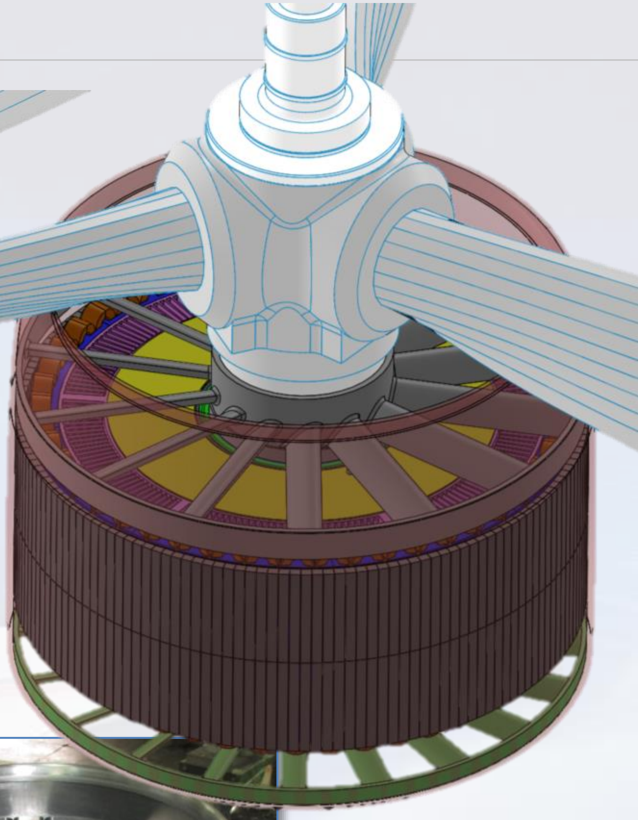
Mod I Seat Rail Vibration
3 single axis accels

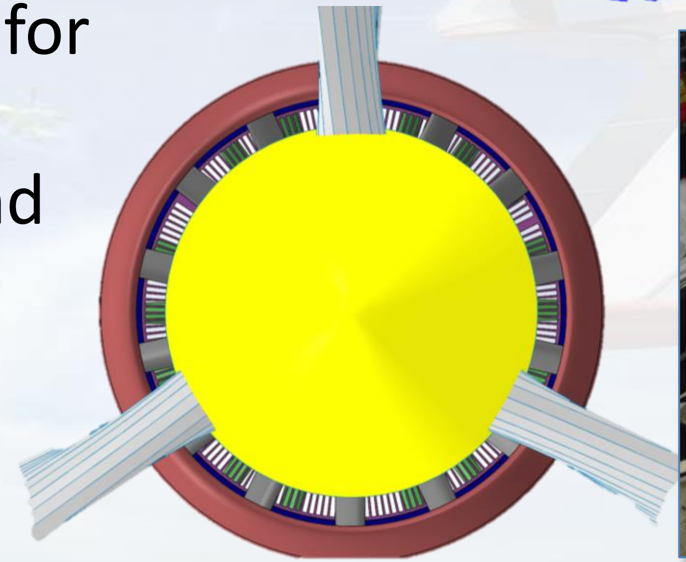


SCEPTOR Cruise Motors

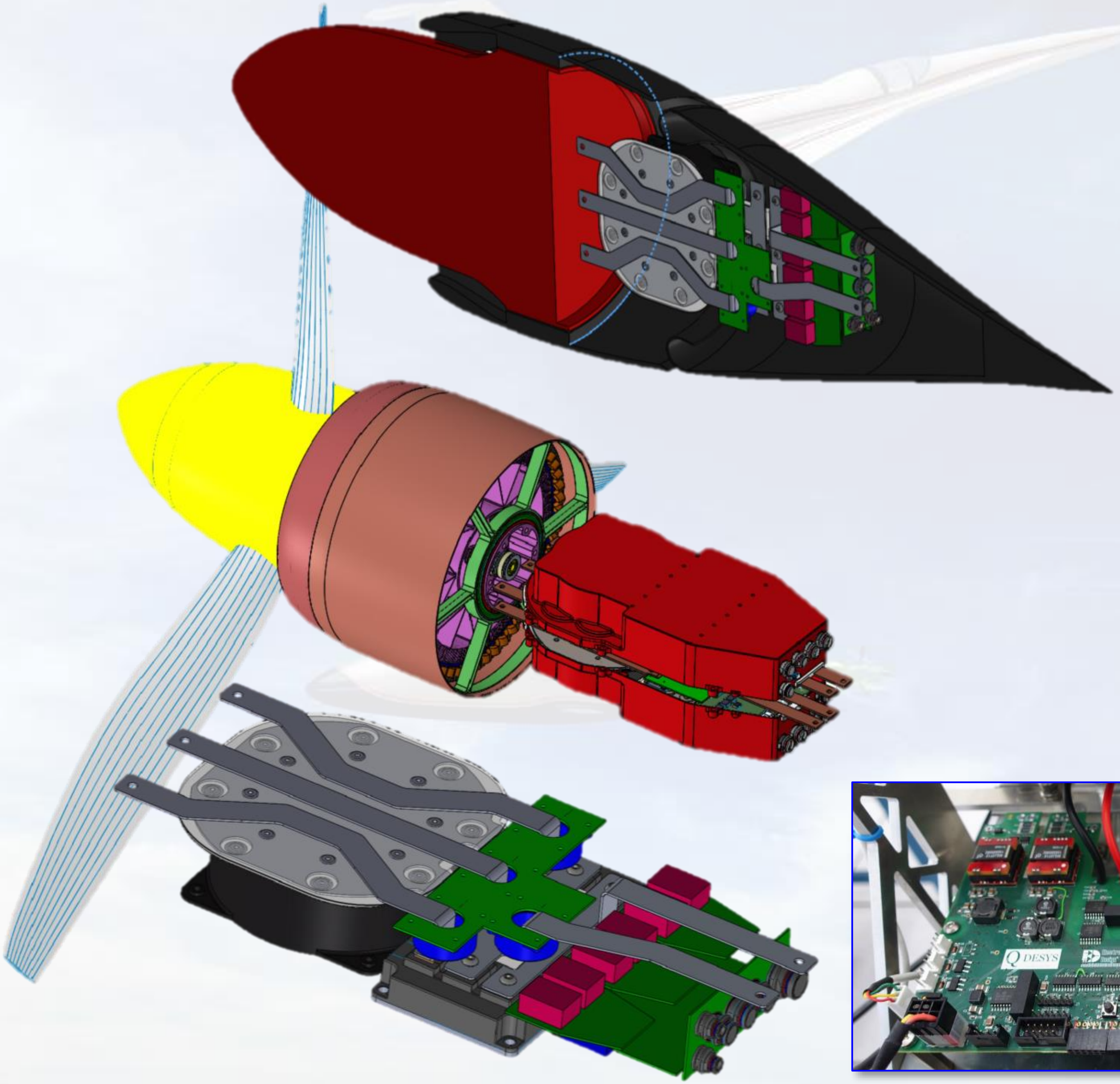
- Air cooled, direct drive outrunner
- Replaces 100 HP Rotax 912S engine with 60 kW Joby motor
- Expected cruise operating point between 42 and 45 kW
- Tailoring FAA engine design acceptance testing (Part 33) for NASA flight qualification
- Electrodynamics, thermal and control modeling and prototyping underway



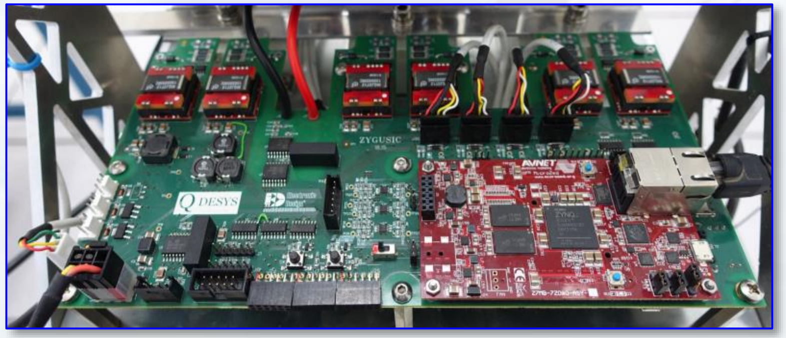




SCEPTOR Cruise Inverters

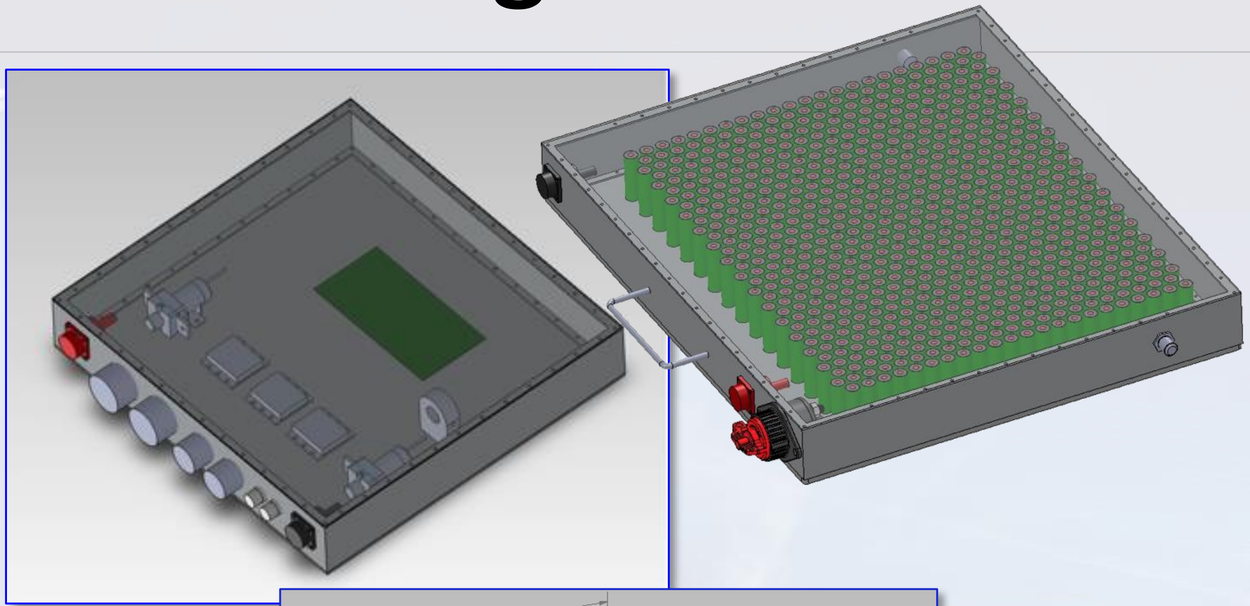


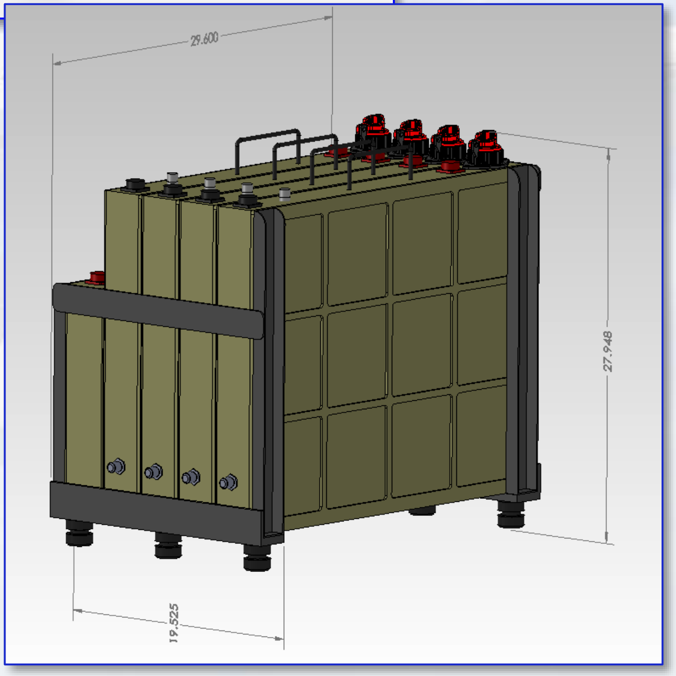
- Qdesys Motor Control implemented on Xilinx Zynq FPGA+ARM
- FPGA based variable frequency switching (real time peak seeking controller)
- Redundant architecture: each power train contributes half of the torque
- Three SiC half bridges for power switches: Cree CAS300M12BM2
- One 500uF CAP for DC link: SBE 700D406 (Eliminates snubber CAPs)
- Isolated carrier board for I/O
- Aluminum enclosure (EMI shielding) Aerospace connectors for I/O



SCEPTOR Battery Module Configuration

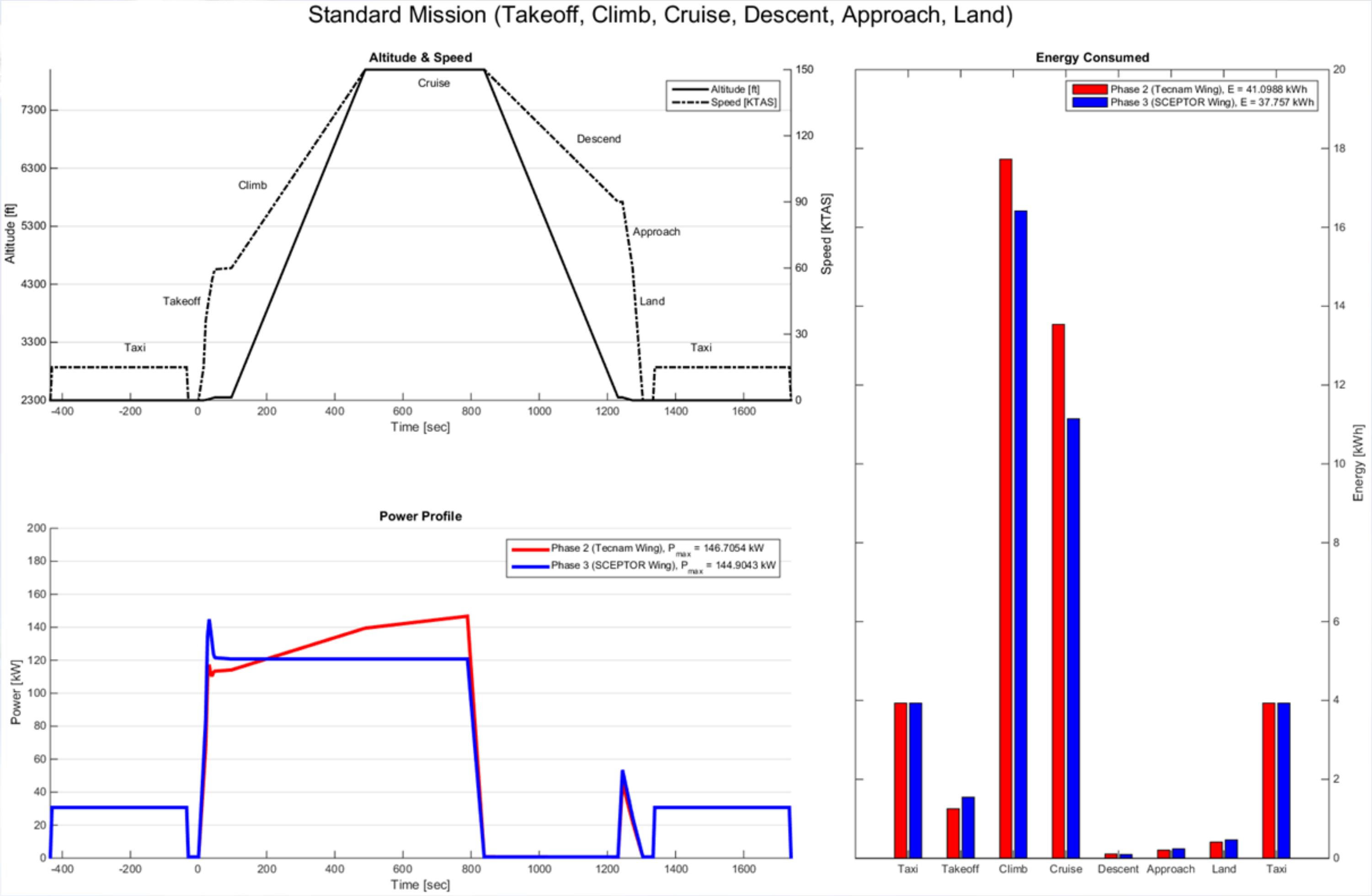
- Electric Power Systems design
- Organized into 8 battery modules per aircraft, split into two packs, each with 4 battery modules and a control module
- Cooling analysis will drive module spacing, cells spaced at 4mm
- Nickel Cobalt Aluminum 18650 cells selected; provides sufficient energy density and discharge rate for SCEPTOR mission. Cells arranged in 20p32s modules with BEP between series halves.
- Each pack is 20p128s; 47 kWh useful capacity, 461 VDC nominal (416 to 525 across SOC range), peak discharge of 132 kW.
- Will comply with flight environment, including 18 g crash loads, -5 to +45 °C operating environment





Mission Planning Power Estimate

- Modeling power and energy required for various reference missions
- Based on the VSP reference design 3.3
- For the primary objective mission in Mod III, currently predicts 38 kWh required with a peak demand of 145 kW

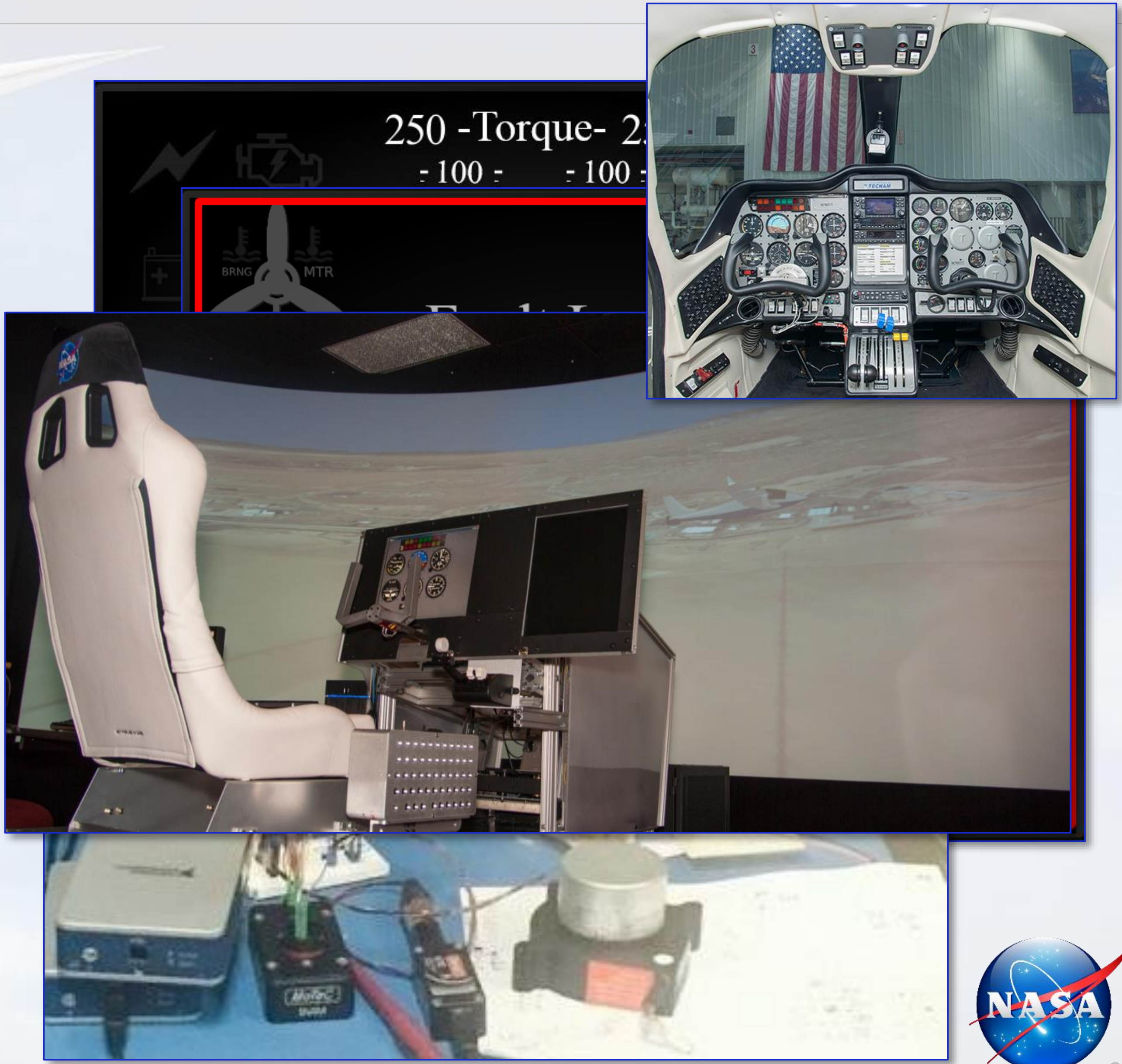


Command System Hardware

- CAN Bus used as the common command and data handling backbone
- Command system will use COTS throttle position encoders and programmable digital display units in the cockpit
- Fiber Optic Bus Extenders will tunnel C&DH bus through fiber down the length of the wing (avoid EMI)
- Additional data collection via analog-to-CAN measurement system

Command System Hardware

- Custom Propulsion System displays developed with test pilot feedback
- Includes fault identification logic
- Identifies command bus failures
- Proof of concept HIL complete; building full scale system now
- Pilot interface, mission profile and emergency procedures will be developed in 180° flight sim



In every branch of knowledge the progress is proportional to the amount of facts on which to build, and therefore to the facility of obtaining data.

– James Clerk Maxwell (1851)

Backup

NASA Aircraft Electric Propulsion Ground Testbeds

Capability	PEGS	1MW CRC	AirVolt	NEAT	HEIST
Max Power Level (kW)	3	1,000	100	24,000	250
Components Tested	Scaled Electric Grid	Cryo Motor, Drives	Powertrain performance	Flight-Weight Powertrain	Wing Integration, Flight Controls
TRL Demo	3	4	5	6	7
Aircraft Size	NA	NA	2-20 PAX	150 PAX	2-4 PAX
Cryogenic	No	500 gal LH2	No	3000 gal LH2, LN, LNG	No
Chiller	No	No	No	Yes	No
HVAC	No	No	No	Yes	No
Aerodynamic Loading	No	No	Yes	No	Yes
Thermal	No	No	Yes	Yes	Yes
Control	No	No	No	Yes	Yes
Atmospheric Pressure	Yes	NA	Yes	Yes	Yes

"Hands-on" testing

- Compliments analytical systems studies
- Implementation challenges compared across configurations
- Informs next-gen ground and flight test beds

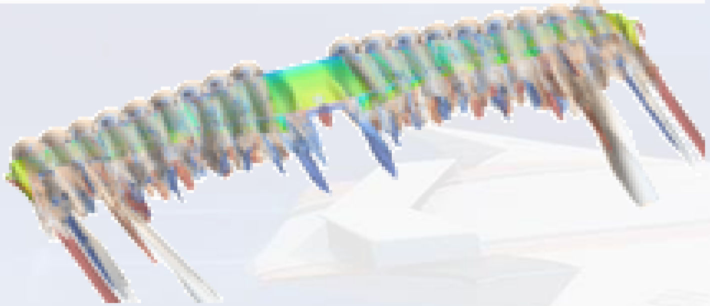
HEIST/LEAPTech: Propulsion-Airframe Integration Validation



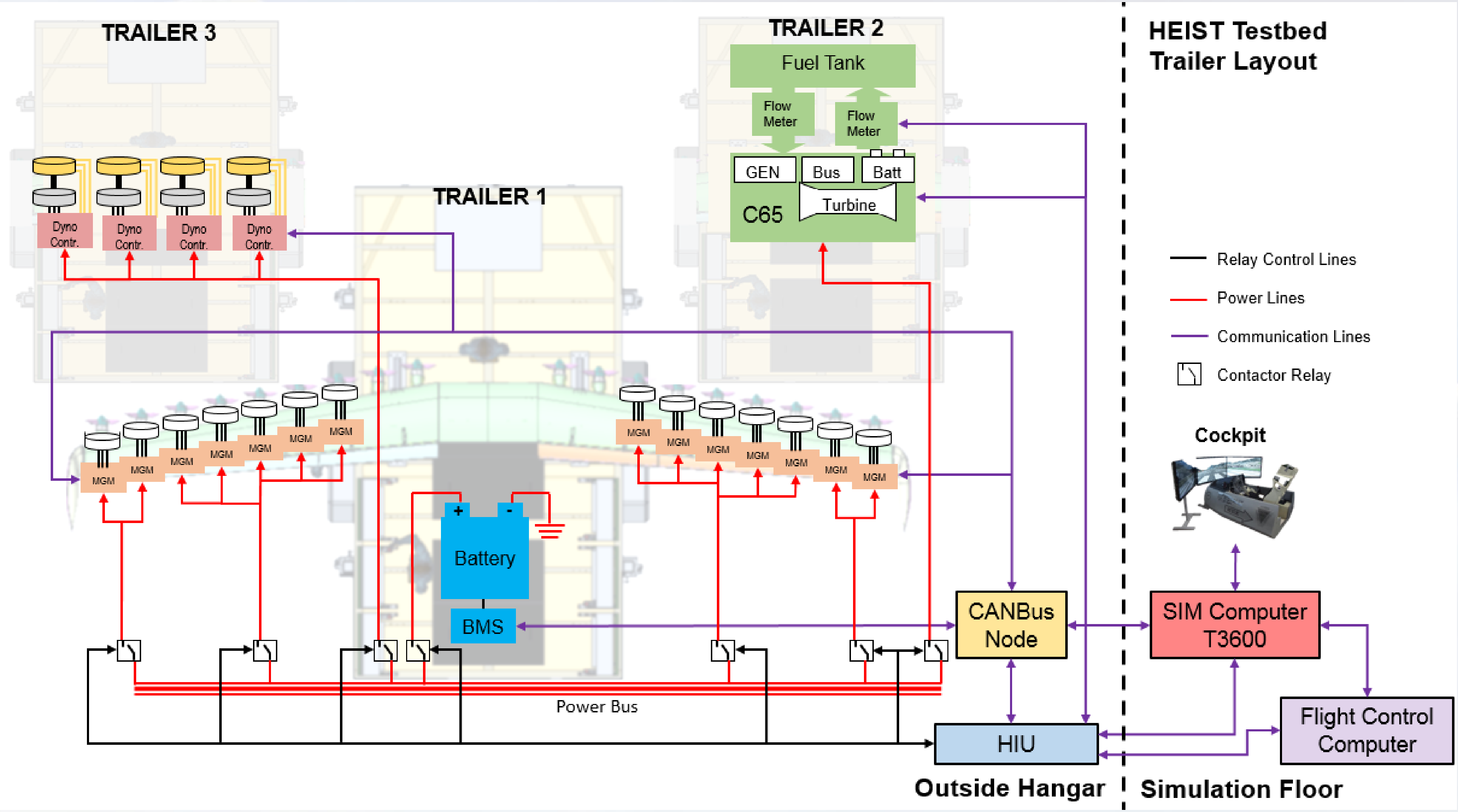









HEIST/Ironbird: Hybrid Sources, Real Time Flight Sim



NASA New Aviation Horizons Initiative

10 Year, $4 Billion Initiative to Return NASA to X-Planes

New Aviation Horizons – Hybrid Electric Build/Fly/Learn

AATT – BLI/DTF

AATT –BLI Wind Tunnel Test

REQ. Input

AATT - Propulsion System Conceptual Design
AATT - High Efficiency Power Density Electric Machines 1 MW
AATT – Turbine/Generator Integration & Controls

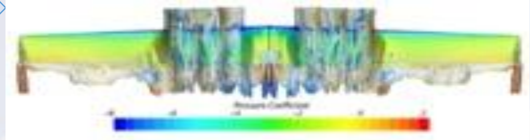
AATT –2 MW Pwr

Possible Tailcone Thruster

REQ. Input

FY20 NEAT – MW Flight Wt Power Mngt & Electronics
FY19 HEIST – 200kW Hybrid Closed Loop PMAD/Flt Ctr
FY16 CAS – CDR Flt Req. for Power Sys and A/C Design
FY19 FDC – Simple Closed Loop Ctr PMAD/Flt

REQ. Input



TTT
SA&I

REQ. Input

LEAPTech -
OpenLoop Ctr
260kW All Elec
High Lift Sys CL = 5

REQ. Input

Low Noise

CFD Validation/Calibration

Thin Haul Studies

TTT
SA&I

CAS
HVHEP
LEAPTech

CAS
SOFC
Adv. Mat

?

TTT
SA&I

FY15 FY16 FY17 FY18 FY19 FY20 FY21 FY22 FY23 FY24 FY25 FY26

Hybrid Electric Propulsion

Prove Out Transformational Potential

Roadmap

Near-term test facilities at NASA Armstrong Flight Research Center

FY13	FY14	FY15	FY16	FY17	FY18	FY19	FY20

Adv Air Transport Technology AFRC/GRC

Capturing Complexities of Hybrid Architectures

1-2 MW Flight Project

Performance and Control of Integrated Systems Testing in Preparation for 1-2MW flight demonstrator

Convergent Aeronautics Solutions AFRC/LARC/GRC ESAero/Joby Aviation

3000 lb

Spiral Development for MW scale

Team Seedling AFRC/LARC ESAero/Joby

Risk Reduction Testing for Airplane

Risk Reduction for kW airplane

Conclusion

We're at the beginning of a 30-50 year propulsion revolution

Green Flight Challenge
2011

UAVs
Now

General Aviation
2020

9 Passenger Commuters
2025

Regional Airliners
2030

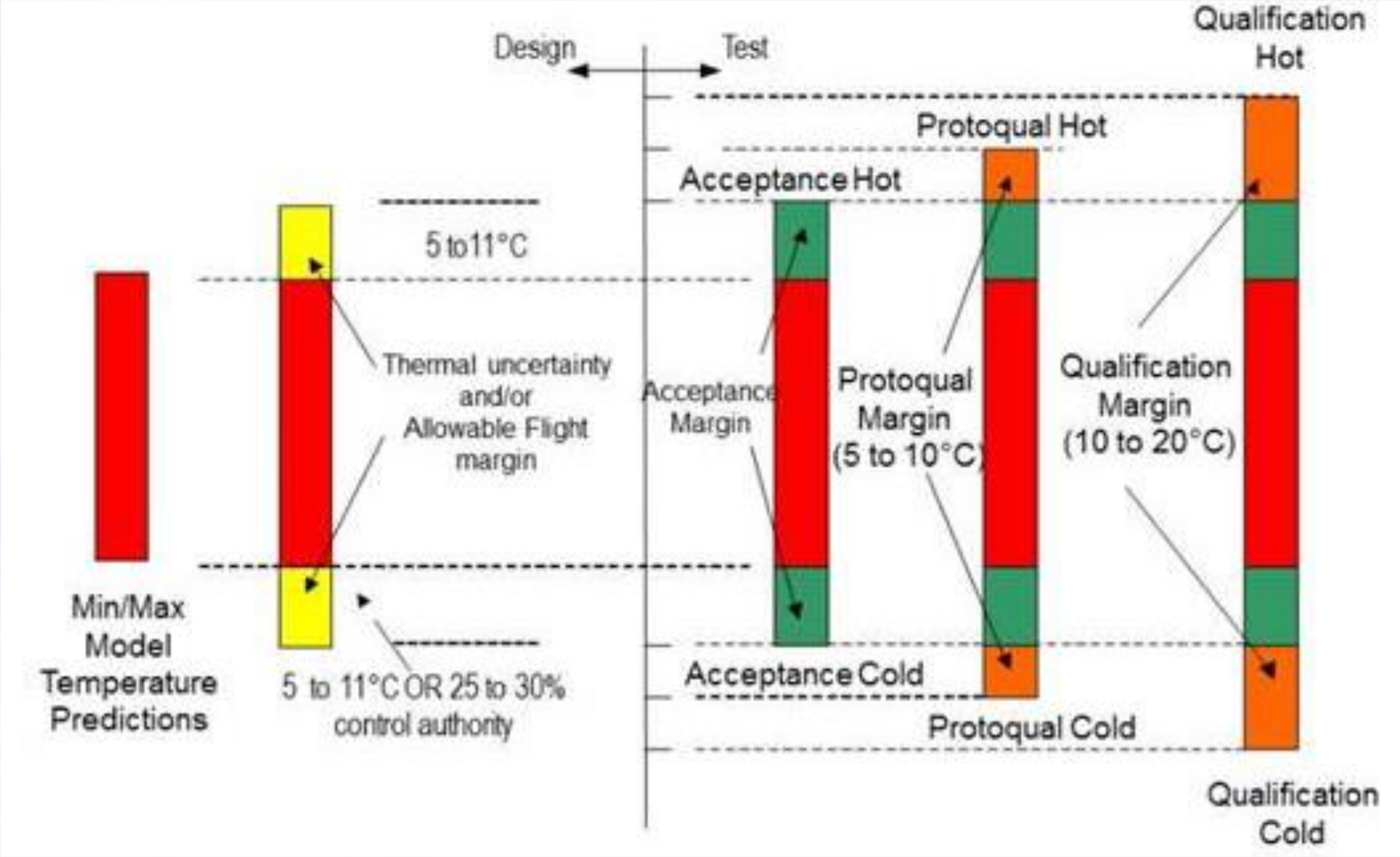
Large Aviation
2035

Electric propulsion is not merely about propulsion, it's about being able to apply a scale-free technology to fundamentally change how we design vehicles

Synergistic integration of Distributed Electric Propulsion will transform aircraft, and the missions they perform, and potentially society

The age of on-demand services is about to lead to On-Demand Mobility

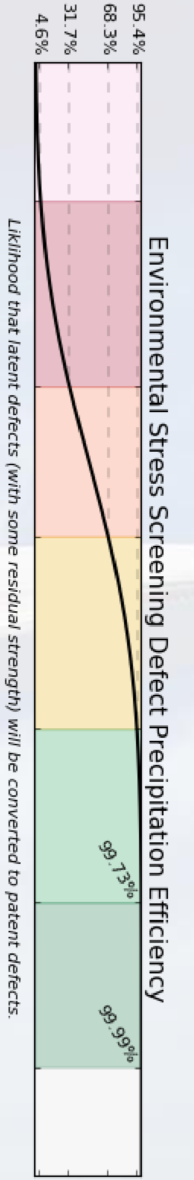
Establishing Unit Level Test Temperatures



Environmental Stress Screening: Thermal Cycle Test

Temp Rate of Change °C/min	Number of Cycles	Temperature Delta (ΔT) - °C											
		40	50	60	70	80	90	100	110	120	130	140	150
2	1	0.057	0.065	0.072	0.078	0.085	0.090	0.096	0.101	0.106	0.111	0.116	0.121
	2	0.111	0.125	0.138	0.151	0.162	0.173	0.183	0.192	0.202	0.210	0.219	0.227
	4	0.209	0.235	0.258	0.279	0.298	0.316	0.332	0.348	0.363	0.376	0.390	0.402
	6	0.296	0.330	0.360	0.387	0.412	0.434	0.454	0.473	0.491	0.508	0.523	0.538
	8	0.374	0.414	0.449	0.480	0.507	0.532	0.554	0.575	0.594	0.611	0.627	0.643
	10	0.443	0.488	0.525	0.558	0.587	0.613	0.636	0.657	0.676	0.693	0.709	0.724
	13	0.533	0.581	0.620	0.654	0.683	0.708	0.731	0.751	0.769	0.785	0.799	0.812
	16	0.608	0.657	0.696	0.729	0.757	0.781	0.801	0.819	0.835	0.849	0.861	0.872
	20	0.690	0.737	0.775	0.805	0.829	0.850	0.867	0.882	0.895	0.906	0.915	0.924
3	1	0.080	0.091	0.100	0.109	0.118	0.126	0.134	0.141	0.148	0.154	0.161	0.167
	2	0.153	0.173	0.191	0.207	0.222	0.236	0.249	0.262	0.274	0.285	0.296	0.306
	4	0.283	0.316	0.345	0.371	0.395	0.416	0.436	0.455	0.472	0.489	0.504	0.518
	6	0.393	0.434	0.470	0.501	0.529	0.554	0.577	0.598	0.617	0.634	0.651	0.666
	8	0.486	0.532	0.571	0.604	0.634	0.659	0.682	0.703	0.722	0.738	0.754	0.768
	10	0.565	0.613	0.653	0.686	0.715	0.740	0.761	0.781	0.798	0.813	0.827	0.839
	13	0.661	0.709	0.747	0.778	0.804	0.826	0.845	0.861	0.875	0.887	0.898	0.907
	16	0.736	0.781	0.816	0.843	0.866	0.884	0.899	0.912	0.922	0.932	0.939	0.946
	20	0.810	0.850	0.879	0.902	0.919	0.932	0.943	0.952	0.959	0.965	0.970	0.974
4	1	0.103	0.116	0.129	0.140	0.151	0.161	0.170	0.179	0.188	0.196	0.204	0.212
	2	0.195	0.219	0.241	0.261	0.279	0.296	0.312	0.327	0.341	0.354	0.367	0.379
	4	0.352	0.390	0.424	0.454	0.480	0.504	0.526	0.547	0.565	0.583	0.599	0.614
	6	0.478	0.524	0.563	0.596	0.625	0.651	0.674	0.695	0.714	0.731	0.746	0.760
	8	0.580	0.628	0.668	0.701	0.730	0.754	0.776	0.795	0.811	0.826	0.839	0.851
	10	0.662	0.710	0.748	0.779	0.805	0.827	0.846	0.862	0.876	0.888	0.898	0.908
	13	0.756	0.800	0.833	0.860	0.881	0.898	0.912	0.924	0.933	0.942	0.949	0.955
	16	0.824	0.862	0.890	0.911	0.927	0.940	0.950	0.958	0.964	0.970	0.974	0.978
	20	0.886	0.916	0.937	0.951	0.962	0.970	0.976	0.981	0.985	0.987	0.990	0.991
5	1	0.125	0.142	0.157	0.170	0.183	0.195	0.206	0.217	0.227	0.237	0.246	0.255
	2	0.235	0.263	0.289	0.311	0.332	0.352	0.370	0.386	0.402	0.417	0.431	0.445
	4	0.415	0.457	0.494	0.526	0.554	0.580	0.603	0.624	0.643	0.660	0.676	0.691
	6	0.552	0.600	0.640	0.674	0.702	0.728	0.750	0.769	0.786	0.802	0.816	0.829
	8	0.657	0.705	0.744	0.775	0.801	0.823	0.842	0.858	0.872	0.885	0.895	0.905
	10	0.738	0.783	0.818	0.845	0.867	0.885	0.901	0.913	0.924	0.933	0.940	0.947
	13	0.825	0.863	0.891	0.912	0.928	0.940	0.950	0.958	0.965	0.970	0.974	0.978
	16	0.883	0.913	0.934	0.949	0.961	0.969	0.975	0.980	0.984	0.987	0.989	0.991
	20	0.931	0.953	0.967	0.976	0.982	0.987	0.990	0.992	0.994	0.995	0.996	0.997
6	1	0.147	0.166	0.183	0.199	0.214	0.227	0.240	0.252	0.264	0.275	0.285	0.295
	2	0.273	0.305	0.333	0.359	0.382	0.403	0.423	0.441	0.458	0.474	0.489	0.503
	4	0.471	0.517	0.555	0.589	0.618	0.643	0.667	0.687	0.706	0.723	0.739	0.753
	6	0.615	0.664	0.703	0.736	0.764	0.787	0.807	0.825	0.841	0.854	0.867	0.877
	8	0.720	0.766	0.802	0.831	0.854	0.873	0.889	0.902	0.914	0.923	0.932	0.939
	10	0.797	0.838	0.868	0.891	0.910	0.924	0.936	0.945	0.953	0.960	0.965	0.970
	13	0.874	0.906	0.928	0.944	0.956	0.965	0.972	0.977	0.981	0.985	0.987	0.989
	16	0.922	0.945	0.961	0.971	0.979	0.984	0.988	0.990	0.993	0.994	0.995	0.996
	20	0.959	0.974	0.983	0.988	0.992	0.994	0.996	0.997	0.998	0.998	0.999	0.999

Temp Rate of Change °C/min	Number of Cycles	Temperature Delta (ΔT) - °C											
		40	50	60	70	80	90	100	110	120	130	140	150
8	1	0.189	0.213	0.234	0.253	0.271	0.287	0.303	0.317	0.331	0.344	0.357	0.369
	2	0.342	0.380	0.413	0.442	0.468	0.492	0.514	0.534	0.553	0.570	0.586	0.601
	4	0.567	0.615	0.655	0.689	0.717	0.742	0.764	0.783	0.800	0.815	0.829	0.841
	6	0.715	0.762	0.798	0.826	0.850	0.869	0.885	0.899	0.911	0.921	0.929	0.937
	8	0.813	0.852	0.881	0.903	0.920	0.934	0.944	0.953	0.960	0.966	0.971	0.975
	10	0.877	0.908	0.930	0.946	0.958	0.966	0.973	0.978	0.982	0.985	0.988	0.990
	13	0.934	0.955	0.969	0.977	0.984	0.988	0.991	0.993	0.995	0.996	0.997	0.997
	16	0.965	0.978	0.986	0.991	0.994	0.996	0.997	0.998	0.998	0.999	0.999	0.999
	20	0.985	0.992	0.995	0.997	0.998	0.999	0.999	1.000	1.000	1.000	1.000	1.000
10	1	0.227	0.255	0.280	0.302	0.322	0.341	0.359	0.375	0.391	0.406	0.419	0.432
	2	0.403	0.445	0.481	0.513	0.541	0.566	0.589	0.610	0.629	0.647	0.663	0.678
	4	0.644	0.692	0.731	0.763	0.789	0.812	0.831	0.848	0.862	0.875	0.886	0.896
	6	0.787	0.829	0.860	0.884	0.903	0.918	0.931	0.941	0.949	0.956	0.962	0.967
	8	0.873	0.905	0.928	0.944	0.956	0.965	0.971	0.977	0.981	0.984	0.987	0.989
	10	0.924	0.947	0.962	0.973	0.980	0.985	0.988	0.991	0.993	0.994	0.996	0.997
	13	0.965	0.978	0.986	0.991	0.994	0.996	0.997	0.998	0.998	0.999	0.999	0.999
	16	0.984	0.991	0.995	0.997	0.998	0.999	0.999	0.999	1.000	1.000	1.000	1.000
	20	0.994	0.997	0.999	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
12	1	0.263	0.294	0.322	0.346	0.369	0.390	0.409	0.427	0.444	0.459	0.474	0.488
	2	0.457	0.502	0.540	0.573	0.602	0.628	0.651	0.671	0.690	0.708	0.723	0.738
	4	0.705	0.752	0.788	0.817	0.841	0.861	0.878	0.892	0.904	0.915	0.924	0.931
	6	0.840	0.876	0.902	0.922	0.937	0.948	0.957	0.965	0.970	0.975	0.979	0.982
	8	0.913	0.938	0.955	0.967	0.975	0.981	0.985	0.988	0.991	0.993	0.994	0.995
	10	0.953	0.969	0.979	0.986	0.990	0.993	0.995	0.996	0.997	0.998	0.998	0.999
	13	0.981	0.989	0.994	0.996	0.997	0.998	0.999	0.999	1.000	1.000	1.000	1.000
	16	0.992	0.996	0.998	0.999	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	20	0.998	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
14	1	0.296	0.330	0.360	0.386	0.411	0.433	0.453	0.472	0.490	0.507	0.522	0.537
	2	0.504	0.551	0.590	0.624	0.653	0.678	0.701	0.722	0.740	0.757	0.772	0.785
	4	0.754	0.798	0.832	0.858	0.879	0.897	0.911	0.923	0.932	0.941	0.948	0.954
	6	0.878	0.909	0.931	0.947	0.958	0.967	0.973	0.978	0.982	0.986	0.988	0.990
	8	0.939	0.959	0.972	0.980	0.985	0.989	0.992	0.994	0.995	0.996	0.997	0.998
	10	0.970	0.982	0.988	0.992	0.995	0.997	0.998	0.998	0.999	0.999	0.999	1.000
	13	0.990	0.994	0.997	0.998	0.999	0.999	1.000	1.000	1.000	1.000	1.000	1.000
	16	0.996	0.998	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	20	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
16	1	0.326	0.362	0.394	0.423	0.449	0.472	0.493	0.513	0.531	0.548	0.564	0.579
	2	0.546	0.594	0.633	0.667	0.696	0.721	0.743	0.763	0.780	0.796	0.810	0.823
	4	0.794	0.835	0.865	0.889	0.908	0.922	0.934	0.944	0.952	0.958	0.964	0.969
	6	0.906	0.933	0.951	0.963	0.972	0.978	0.983	0.987	0.989	0.992	0.993	0.994
	8	0.957	0.973	0.982	0.988	0.991	0.994	0.996	0.997	0.998	0.998	0.999	0.999
	10	0.981	0.989	0.993	0.996	0.997	0.998	0.999	0.999	0.999	1.000	1.000	1.000
	13	0.994	0.997	0.999	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	16	0.998	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	20	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000



Source: MIL-HDKB-344A, §5.4

Objectives

- Qualify electrical and electromechanical systems for the flight environment with demonstrated margin
- Environmentally screen equipment for manufacturing defects
  - Goal of precipitation factor > 95%

Test Types

- Acceptance Test
  - Required for flight units
  - Primarily a workmanship screening
- Proto-Qualification Test
  - Units can be used for flight
  - Primarily used to demonstrate design margin while maintaining serviceability for flight
    - 5 – 10° C margin for thermal
    - +3db margin for vibration
- Qualification Test
  - Units not used for flight
  - Primarily used to demonstrate higher design margin
    - 10 – 20° C margin for thermal
    - +6db margin for vibration
  - No qualification testing currently planned

Test Conditions

- Thermal Definitions
  - *UUT Thermally stabilized, operating*: no more than 2 deg C per hour deviation
  - *UUT Thermally stabilized, non-operating*: within 3 deg C of specified test temperature
- Control temps are measurements of the chamber air near the UUT (not the chamber wall)
- Chamber ramp is 10° C minimum per minute *on the UUT*
- All units must be operated during all tests and pass a pre- and post-environmental functional test, unless test logistics require a deviation from this approach

Motors

- Acceptance Test
  - Thermal Temperature Variation Per DO-160 Section 5
    - -35° to +45° C, 12 cycles, ramp at 10° C per minute
  - Random Vibration – Not planned
    - Shaft vibration measured during static testing
    - Multiple hours (50+) of static testing => high precipitation factor
    - Random vibe test for motor while operating => high test complexity for little return
  - High Potential Test, motor windings
    - 1000 volts plus twice the rated voltage of the motor
- Proto-Qualification Test
  - Acceptance test as above
  - Thermal Temperature Variation Per DO-160 Section 5
    - -40° to +50° C, 12 cycles, ramp at 10° C per minute
  - Altitude to 15,000 ft per DO-160 Section 4.6.1 for 2 hours

SCEPTOR Motor Operating and Test Temperatures

(at ground level pressure)

Motors (cont'd)

- Proto-Qualification Test (cont'd)
  - EMI/EMC
    - Emissions Tests per DO-160 Section 21
      - Currently not planned
      - Design using best practice
      - Conduct system level tests
        - Combined Systems Test (CST)
        - Hanger Radiation Test (HRT)
  - Shock per DO-160 Section 7 Operational Shocks and Crash Safety, Category A
    - 6 g's, 11 ms pulse duration, terminal sawtooth

Controllers

- Acceptance Test
  - Thermal Temperature Variation Per DO-160 Section 5
    - -45° to +70° C, 12 cycles, ramp at 10° C per minute
    - From DO-160 Table 4-1, Category B2
  - Random Vibration per DCP-O-018 Curve A, 8 gRMS
    - Duration: 20 minutes, each axis
- Proto-Qualification Test
  - Acceptance test as above
  - Thermal Temperature Variation Per DO-160 Section 5
    - -55° to +80° C, 12 cycles, ramp at 10° C per minute
    - From Acceptance + 10° C
  - Random Vibration per DCP-O-018 Curve A +3db, 11.3 gRMS
    - Duration: 20 minutes, each axis
  - Altitude to 15,000 ft per DO-160 Section 4.6.1 for 2 hours

Controllers (cont'd)

- Proto-Qualification Test (cont'd)
  - EMI/EMC
    - Emissions Tests per DO-160 Section 21
      - Currently not planned
      - Design using best practice
      - Conduct system level tests
        - Combined Systems Test (CST)
        - Hanger Radiation Test (HRT)
  - Shock per DO-160 Section 7 Operational Shocks and Crash Safety, Category A
    - 6 g's, 11 ms pulse duration, terminal sawtooth

Traction Battery

- Acceptance Test
  - Thermal Temperature Variation Per DO-160 Section 5
    - -15° to +60° C, 12 cycles, ramp at 10° C per minute
    - Discharge during final cycle
  - Random Vibration per DO-160 Curve C, 4.12 gRMS
    - Duration: 60 minutes per axis
    - Meets DO-311 requirement per Section 3.2.1.1
- Proto-Qualification Test
  - Acceptance test as above
  - Thermal Temperature Variation Per DO-160 Section 5
    - -20° to +65° C, 12 cycles, ramp at 10° C per minute
    - Discharge during final cycle
  - Random Vibration per DO-160 Curve C + 3db, 5.83 gRMS
    - Duration: 60 minutes per axis
  - Altitude to 15,000 ft per DO-160 Section 4.6.1 for 2 hours

SCEPTOR Battery Operating and Test Temperatures

Non DO-160 Compatible (at ground level pressure)

Traction Battery (cont'd)

- Proto-Qualification Test (cont'd)
  - Shock per DO-160 Section 7 Operational Shocks and Crash Safety, Category A
    - 6 g's, 11 ms pulse duration, terminal sawtooth
    - Per DO-311, do not shock in the suspended upside down position
    - While mounted in the flight configuration with flight mounts, perform 20g, 11ms crash test (TBD1)
  - EMI/EMC
    - Per DO-311 paragraph 2.3.20 (TBD2)

Note: There are several additional non-environmental Qualification Tests. See traction battery specification CEPT-SPEC-002 and DO-311.

- Charge / Discharge cycles
- Short-circuit test
- Overcharge test
- Endurance test
- Explosive containment test

Throttle Encoder

- Acceptance Test
  - Thermal Temperature Variation Per DO-160 Section 5
    - -45° to +70° C, 12 cycles, ramp at 10° C per minute
    - From DO-160 Table 4-1, Category B2
  - Random Vibration per DCP-O-018 Curve A, 8 gRMS
    - Duration: 20 minutes, each axis
- Proto-Qualification Test
  - Acceptance test as above
  - Thermal Temperature Variation Per DO-160 Section 5
    - -55° to +80° C, 12 cycles, ramp at 10° C per minute
    - From Acceptance + 10° C
  - Random Vibration per DCP-O-018 Curve A +3db, 11.3 gRMS
    - Duration: 20 minutes, each axis
  - Altitude to 15,000 ft per DO-160 Section 4.6.1 for 2 hours

Throttle Encoder (cont'd)

- Proto-Qualification Test (cont'd)
  - EMI/EMC
    - Emissions Tests per DO-160 Section 21
      - Currently not planned
      - Design using best practice
      - Conduct system level tests
        - Combined Systems Test (CST)
        - Hanger Radiation Test (HRT)
  - Shock per DO-160 Section 7 Operational Shocks and Crash Safety, Category A
    - 6 g's, 11 ms pulse duration, terminal sawtooth

Instrumentation Pallet, Power Systems, & Electromechanical Sensors – Cabin Location

- Acceptance Test
  - Thermal Temperature Variation Per DO-160 Section 5
    - -20° to +70° C, 12 cycles, ramp at 10° C per minute
    - From DO-160 Table 4-1, Category B1/B2 and DCP-O-018
  - Random Vibration per DCP-O-018 Curve A, 8 gRMS
    - Duration: 20 minutes, each axis
    - Conservative, cabin environment as measured < 1 gRMS
  - Altitude to 15,000 ft per DO-160 Section 4.6.1 for 2 hours
    - Conducted at ambient temp with equipment operating
- Proto-Qualification Test
  - Not required
  - Acceptance Random Vibe Test exceeds MPE level by > 3 db
  - Temp cycle range exceeds operational envelope by > 15° C

Instrumentation, Power Systems, & Electromechanical Sensors – Wing/Nacelle

- Acceptance Test
  - Thermal Temperature Variation Per DO-160 Section 5
    - -45° to +70° C, 12 cycles, ramp at 10° C per minute
    - From DO-160 Table 4-1, Category B2
  - Random Vibration per DCP-O-018 Curve A, 8 gRMS
    - Duration: 20 minutes, each axis
- Proto-Qualification Test
  - Acceptance test as above
  - Thermal Temperature Variation Per DO-160 Section 5
    - -55° to +80° C, 12 cycles, ramp at 10° C per minute
    - From Acceptance + 10° C
  - Random Vibration per DCP-O-018 Curve A +3db, 11.3 gRMS
    - Duration: 20 minutes, each axis
  - Altitude to 15,000 ft per DO-160 Section 4.6.1 for 2 hours

Cockpit Display

- Acceptance Test
  - Thermal Temperature Variation Per DO-160 Section 5
    - -20° to +70° C, 12 cycles, ramp at 10° C per minute
    - From DO-160 Table 4-1, Category B1/B2 and DCP-O-018
  - Random Vibration per DCP-O-018 Curve A, 8 gRMS
    - Duration: 20 minutes, each axis
    - Conservative, cabin environment as measured < 1 gRMS
  - Altitude to 15,000 ft per DO-160 Section 4.6.1 for 2 hours
- Proto-Qualification Test
  - Not required
  - Acceptance Random Vibe Test exceeds MPE level by > 3 db
  - Temp cycle range exceeds operational envelope by > 15° C

To Be Determined (TBD)

- TBD1: Crash shock specification for battery mount
- TBD2: EMI/EMC test requirements for battery, per DO-311

Table 4.3: Assembly Defect Types Precipitated by Thermal & Vibration Screens

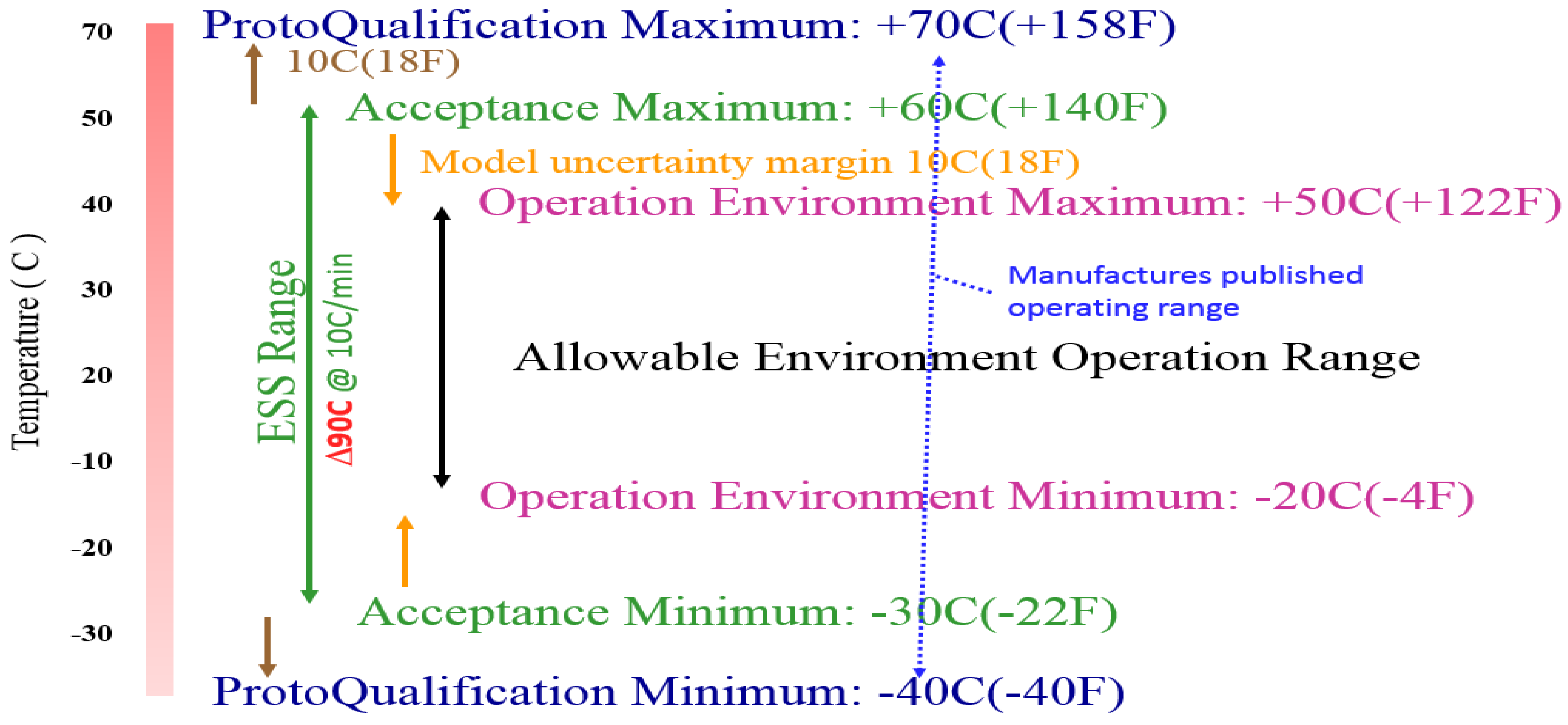
Defect Type	Thermal Screen	Vibration Screen
Defective Part	X	X
Broken Part	X	X
Improperly Installed Part	X	X
Solder Connection	X	X
PCB Etch, Shorts and Opens	X	X
Loose Contact		X
Wire Insulation	X	
Loose Wire Termination	X	X
Improper Crimp Or Mating	X	
Contamination	X	
Debris		X
Loose Hardware		X
Chafed, Pinched Wires		X
Parameter Drift	X	
Hermetic Seal Failure	X	
Adjacent Boards/Parts Shorting		X

Reference RADC-TR-82-87

Table 4.3 indicates that vibration screens are generally more effective for loose contacts, debris and loose hardware while temperature cycling screens are not effective. Thermal screens are generally more effective for part parameter drift, contamination and improper crimp or mating type defects while vibration screens are not. For other defect classes listed in the table, both thermal and vibration screens are effective, but the relative degree of effectiveness of one screen type over the other is not precisely known. These are some of the uncertainties which must be dealt with in planning a screening program. Historically, on average, 20% of the defects are found to be responsive to vibration screens and 80% to temperature cycling screens. (Reference publication IES Environmental Stress Screening Guidelines for Assemblies).

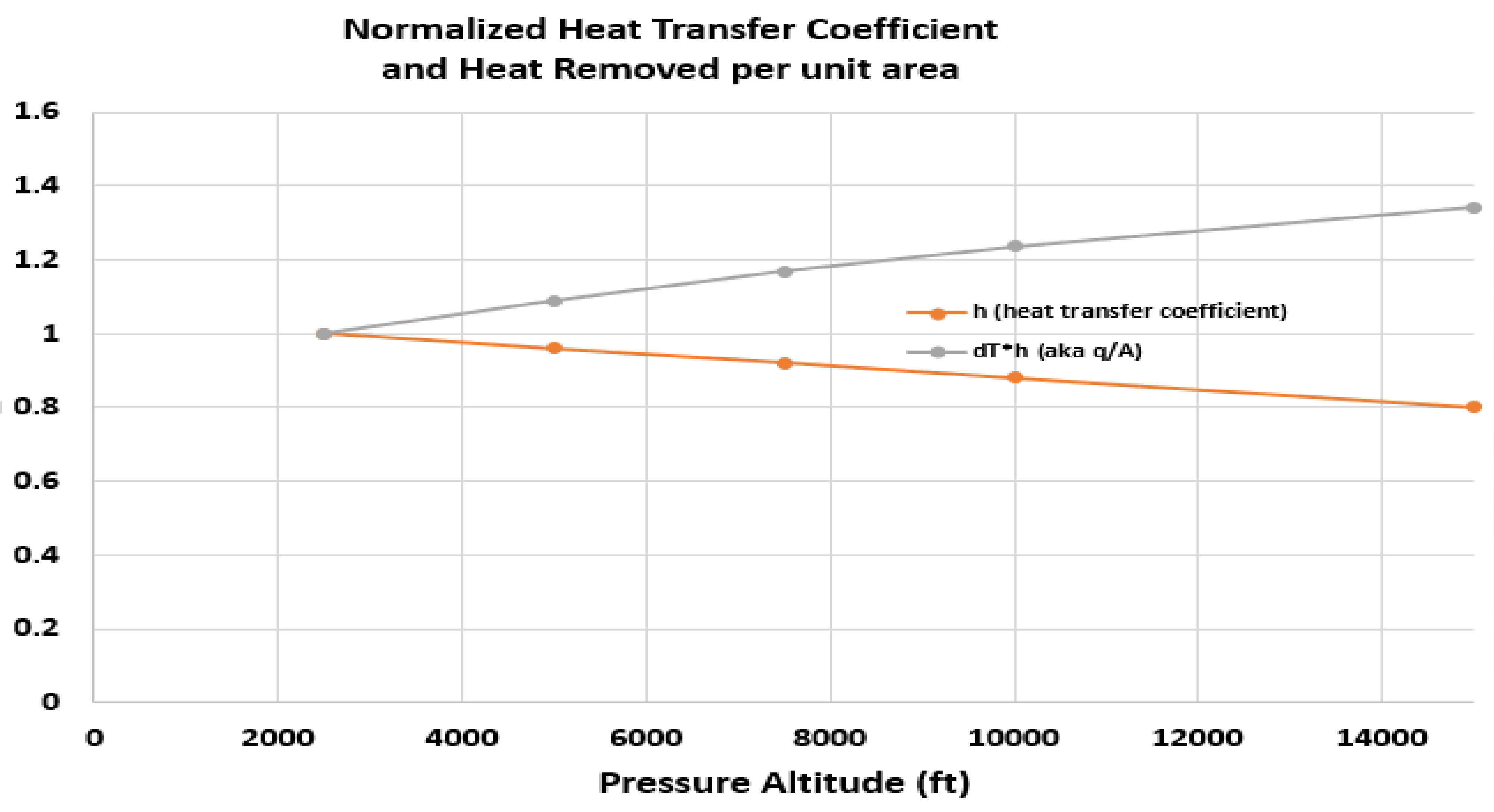
SCEPTOR Battery Operating and Test Temperatures

DO-160 Compatible (at ground level pressure)



	Altitude (ft)		Temperature (degrees F)		
	Pressurized Compartment*	Unpressurized Compartment or mounted externally	Low Temperature (external or non-temp controlled compartment)	Low Temperature (temp-controlled compartment)	High Temperature
Category I	75000	220000 or zoom altitude of aircraft	-60	0	+160
Category II	75000	100000 or zoom altitude of aircraft	-60	0	+160
Category III	40000	40000 or zoom altitude of aircraft	-60	0	+160
Category IV	45000	45000 or zoom altitude of aircraft	-20	0	+160
Category V	50000	50000 or zoom altitude of aircraft	-60	0	+160

Table 8-3: Temperature & Altitude Test Requirements


Normalized Heat Transfer Coefficient
and Heat Removed per unit area
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
2000
4000
6000
8000
10000
12000
14000
Pressure Altitude (ft)
h (heat transfer coefficient)
dT*h (aka q/A)

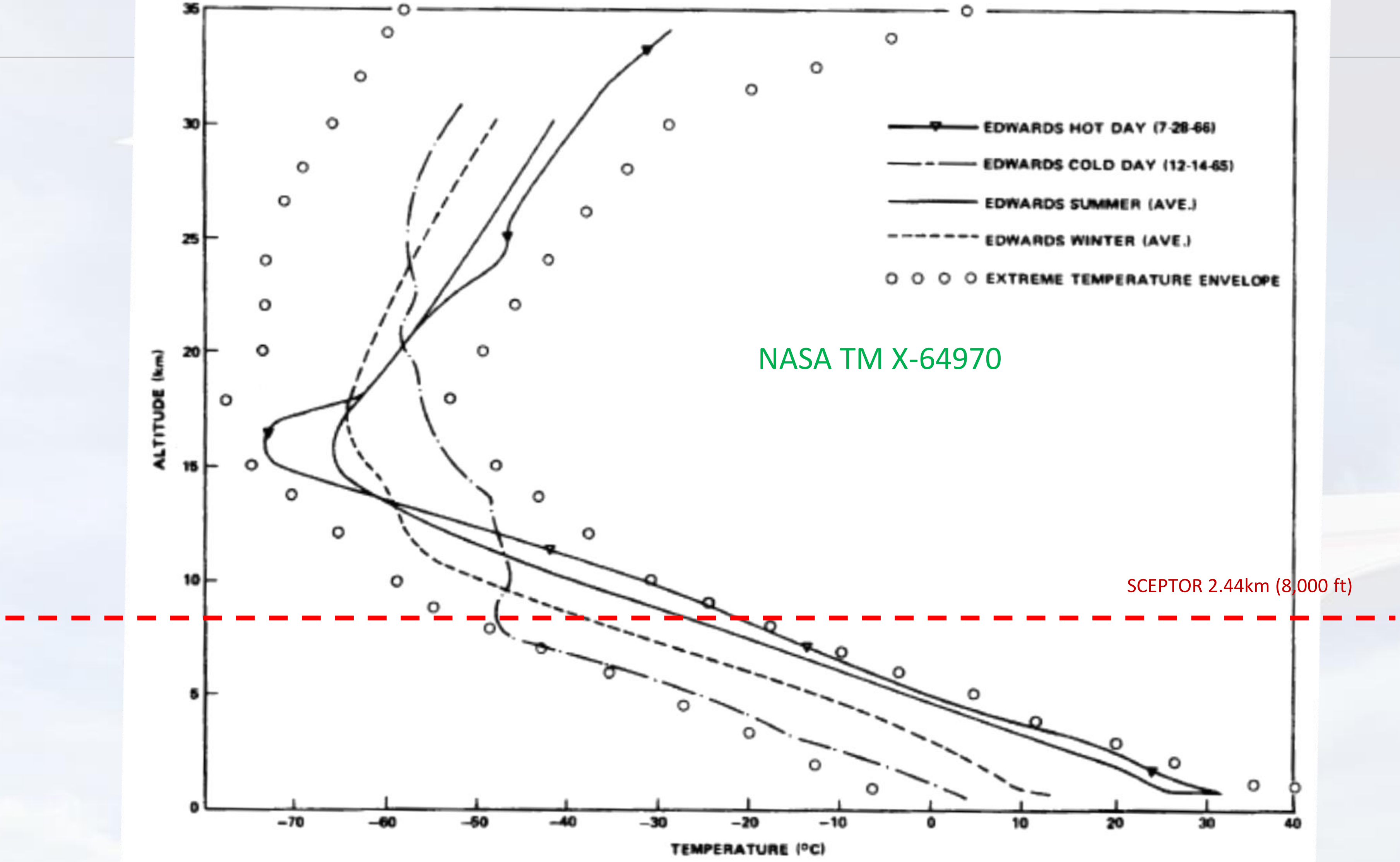
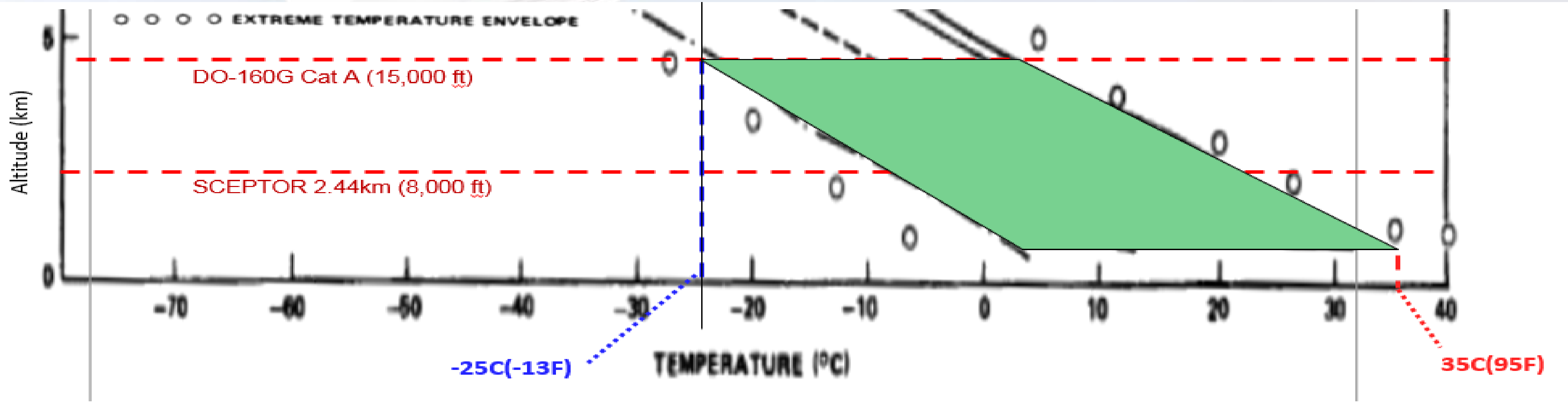


Figure 5. Seasonal mean and typical extreme temperature profiles representing summer (hot) and winter (cold) conditions over Edwards AFB.



O O O O EXTREME TEMPERATURE ENVELOPE
DO-160G Cat A (15,000 ft)
SCEPTOR 2.44km (8,000 ft)
Altitude (km)
5
0
-70
-60
-50
-40
-30
-20
-10
0
10
20
30
40
TEMPERATURE (°C)
-25C(-13F)
35C(95F)