DESIGN FOR DEMISE BREADBOARDING – MLI CCN

FINAL PRESENTATION

D4D-BB TEAM

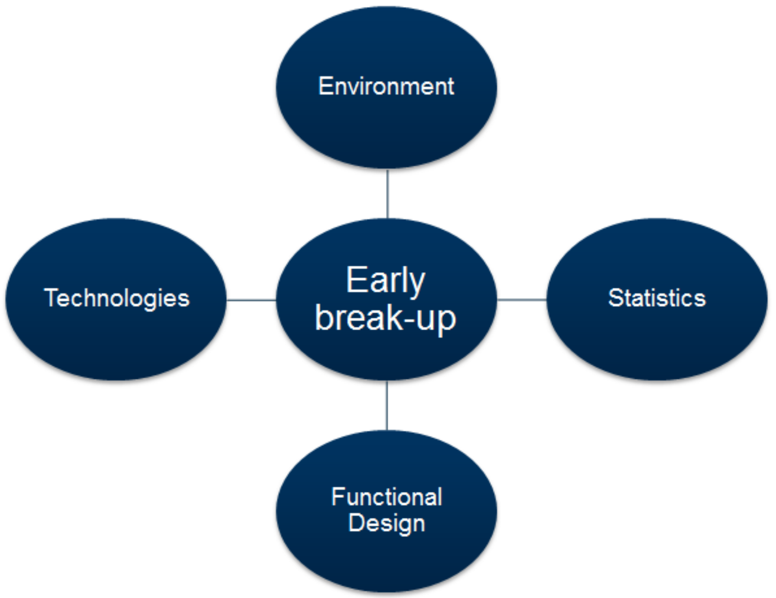
25.03.2022

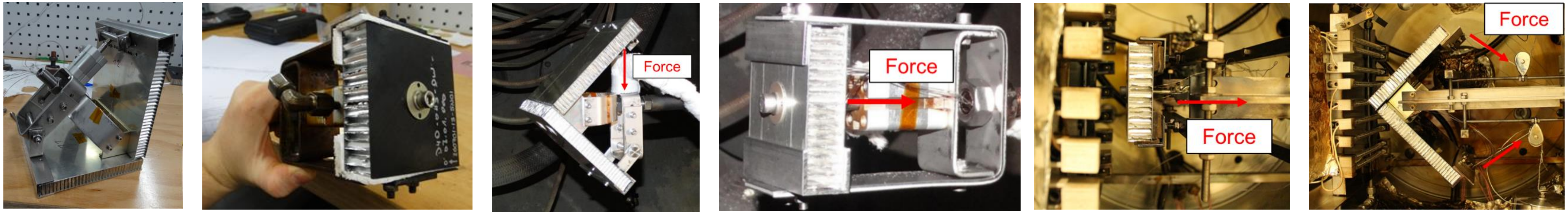
AGENDA

- Introduction
- Study Objectives & Overview
- ATOX Test Results
- Demise Test Results
- Lessons Learned & Conclusions

INTRODUCTION - D4DBB STUDY

- To define feasible design concepts to achieve a spacecraft structure to **break-up** or **structure opening** at an altitude above its natural altitude
- To demonstrate the feasibility of selected technologies by **breadboard development and testing.**
- Focus is set on technologies to open and/or release **external structural elements and spacecraft modules** (e.g. payloads and large appendages) to increase the overall spacecraft demiseability





STUDY OBJECTIVE - MLI CCN

- Through the successful activities in D4DBB, a risk has been identified which was not within the scope of the previous study.
- The multi-layer insulation (MLI) which is expected to be present on most spacecraft is generally assumed to have been removed due to the interaction with atomic oxygen in the atmosphere during the mission lifetime and orbital decay phase, or if not, to be removed by the low forces in the very initial stages of re-entry.
- Given the high altitudes identified for the potential structural break-ups, the presence of MLI can have a significant impact in delaying the heat soak to the structure and thus the fragmentation of the spacecraft. Therefore, in order to verify the performance of the early structure break-up breadboards, an assessment of the MLI behaviour is required.

STUDY OVERVIEW - MLI CCN

- The first step was to obtain an understanding of the state of the MLI material after the mission and orbital decay timescale.
  - This was done using the ESTEC ATOX facility which can provide a fluence of atomic oxygen to a set of material samples.

- The second step of the activity was to assess the impact of MLI presence on the structural break-up.
  - This was done by extending the test campaign at AAC to include samples with MLI attached.
  - In order to obtain a sensitivity, samples with standard inserts were tested as well as breadboard demisable joints.
  - Further, tests were done with intact MLI material, and degraded MLI material in order to understand the differences which would be observed, based on the understanding from the atomic oxygen testing.

ATOX TEST RESULTS

TEST SAMPLES AND SETUP – ATOX

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- Material selection based upon typical LEO MLI configurations
- De-orbit initial altitude of 650km considered
- De-orbit timeframe of 25 years assessed
- ATOX fluence calculated with 7.5 km/s velocity assumed

Baseline fluence of approximately $3x10^{21}$ atoms/cm² of interest

Fluence achievable by facility was in the order of $2x10^{21}$ atoms/cm²

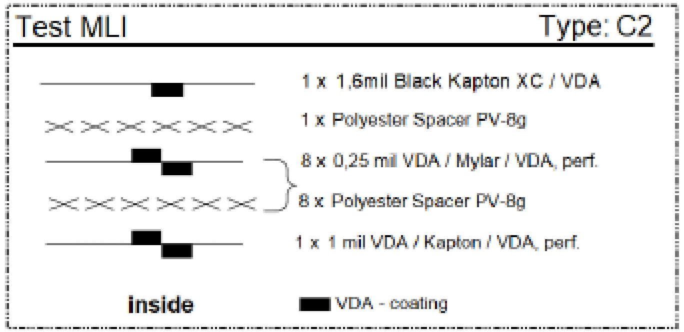
TEST SAMPLES AND SETUP – ATOX

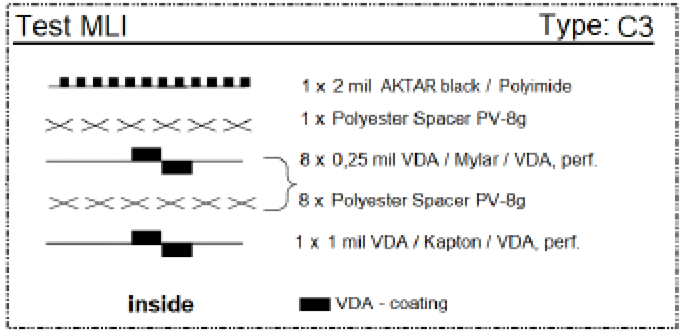
- Samples to be manufactured similarly to typical LEO satellites
  - 3 different MLI configurations
  - 2 different fixation technologies

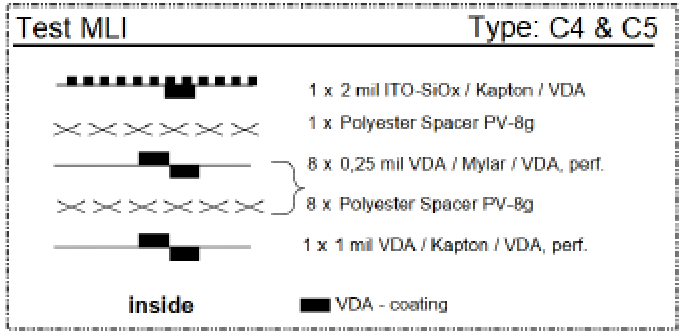
    Technology 1
    - Aluminium standoffs
    - Vespel SP1 clip-washers
    - 2x Betacloth washer loops
    - 2x Kapton washer loops

    Technology 2
    - Velcro square patches
    - Aluminium standoffs

Config. Number	Test Type	MLI Configuration	Attachment Method	Size [mm x mm]
1	Control	No MLI	-	26 x 114
2	Black Kapton XC/VDA	Black Kapton outer MLI layer	Velcro	26 x 114
3	ACKTAR Black	Black paint applied to outer MLI layer	Velcro	26 x 114
4	"Nominal" MLI	ITO-SiOx outer MLI layer coating	Velcro	26 x 114
5	"Nominal" MLI	ITO-SiOx outer MLI layer coating	Stand-offs	26 x 114

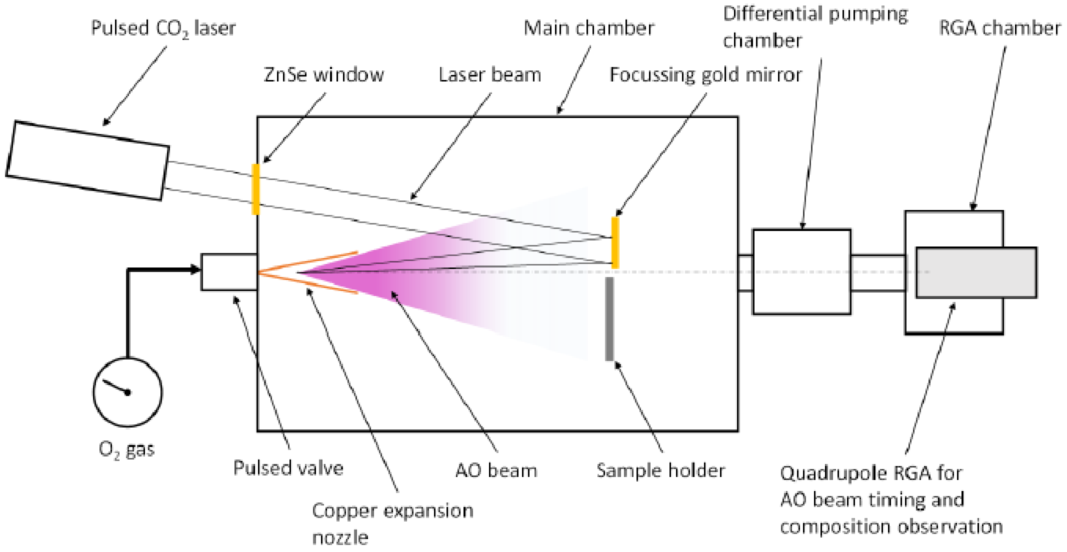






TEST SAMPLES AND SETUP – ATOX

- Testing conducted at ESTEC TEC-QEE LEOX facility
  - ACKTAR Black (C3)
  - ITO-SiOx with Standoffs (C5)
  - Bare CFRP (C1)
  - ITO-SiOx with Velcro (C4)
  - Black Kapton XC/VDA (C2)



TEST CONDITIONS – ATOX

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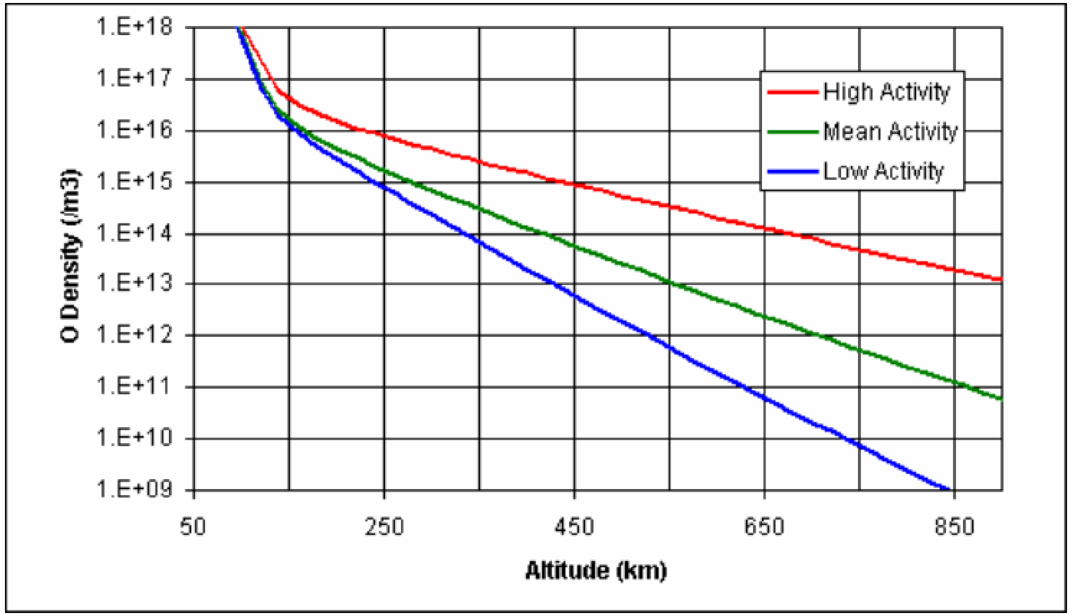
- Initial Fluence Estimates
  - Based on 25 year decaying circular orbit from ~600km
  - Increase in density with reducing altitude
    - Atomic oxygen prevalent species down to ~150km
    - Variation with solar flux
- Lower Altitudes
  - High flux v. short time



TEST CONDITIONS – ATOX

- Refined Fluence Estimates
  - Tumbling spacecraft
    - Average of surface area to projected area is 0.25 (theorem)
    - Reduces expected fluence from initial estimate (0.7 used)
  - Mapping of oxygen atom number density to altitude
    - Use data from COSPAR reference atmosphere
    - Use data from Jacchia-Roberts atmosphere
  - Assess re-entry data from 25 year re-entry
    - Circular decaying orbit
    - Both atmosphere models used

TEST CONDITIONS – ATOX

- Refined Fluence Estimates
  - Best estimates; good agreement
  - Refines estimate to ~3e21 /cm^2
  - Close to capability of ATOX facility (2e21/ cm^2)

	COSPAR	Jacchia Roberts
25 years	3.32e21	2.95e21
20 years	3.21e21	2.89e21
15 years	3.07e21	2.86e21
10 years	2.88e21	2.58e21
5 years	2.55e21	2.38e21
Last Day	1.5e20	1.5e20

TEST RESULTS – ATOX

- Use Full Fluence
  - Variation across samples (1.36e21 to 2.78e21 / cm^2)
- Observations
  - Darkening of Kapton Black, CFRP
  - Erosion of Kapton loops
  - Some MLI damage around staples
  - Very minor impact

TEST RESULTS – ATOX

- Changes in Optical Properties
  - Darkening of Kapton Black, CFRP
    - Roughening of surface
  - Change in emittance of MLI
    - No absorptance change, no visible change
    - Uncertainty in measurement?
    - No impact on modelling

Sample	Thermal Emittance		Solar Absorptance	
	Start	End	Start	End
Kapton Black	0.84	0.93	0.91	0.99
CFRP	0.81	0.85	0.89	0.98
Standard MLI	0.74	0.79	0.36	0.37
Acktar Black	0.84	0.85	0.97	0.97

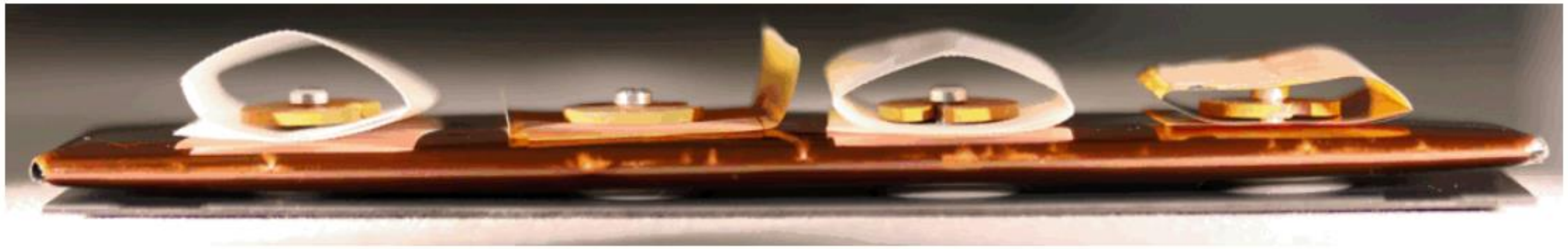
TEST RESULTS – ATOX

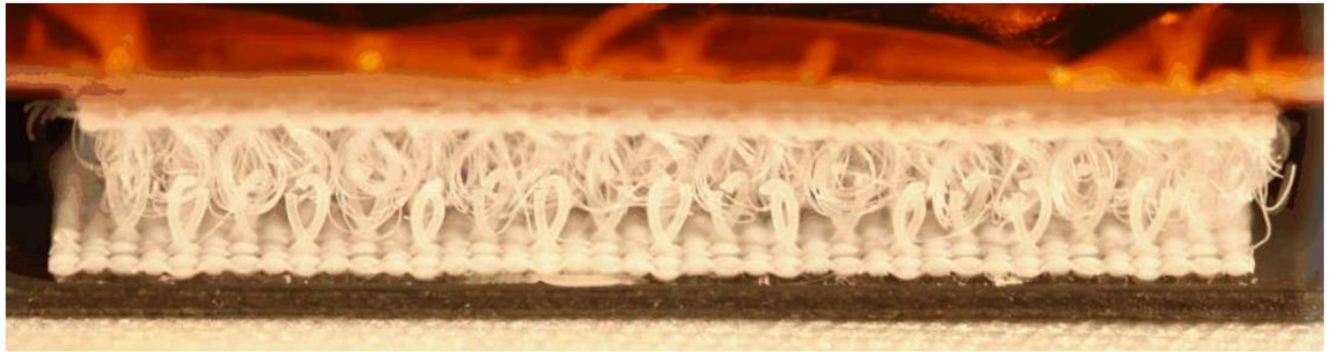
- Mass Loss
  - Base on Kapton reference (3e-24 cm^3/atom)
  - Kapton loop data is consistent
    - Based on area scaling
  - Kapton Black about half Kapton erosion
  - MLI shows very low erosion; essentially intact

#	Material	Erosion Yield	Relative Erosion Yield
	Kapton (reference)	2.8e-24	1.0
1	Kapton Black	1.5e-24	0.5
2	Kapton protective loops	2.7e-24	1.0
3	CFRP	4.7e-25	0.2
4	Standard MLI	1.7e-25	0.06
5	Acktar Black	7.6e-26	0.03

TEST RESULTS – ATOX

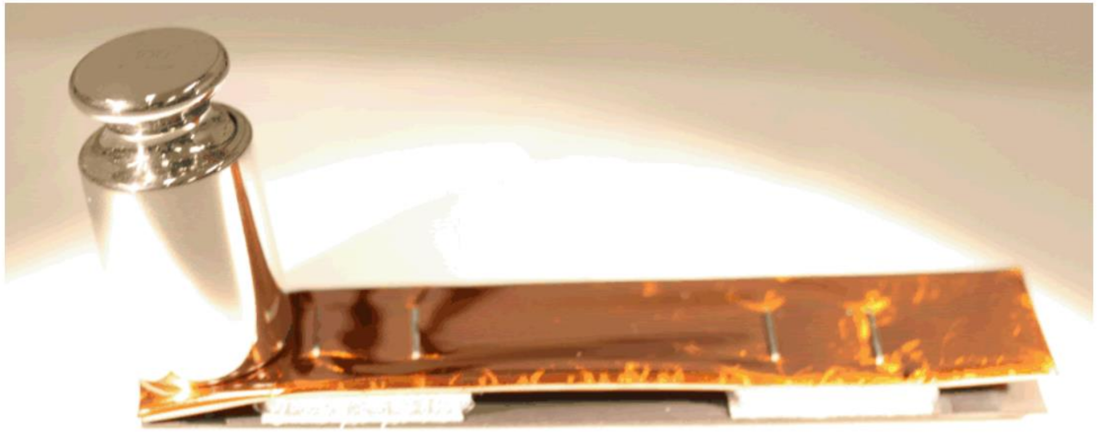
- Connections
  - Standoffs / Velcro intact
    - No impact observed on connections





TEST RESULTS – ATOX

- Brittleness Test
  - To confirm visual story
    - Surface may be brittle, easier to crack
    - Apply force to assess
  - MLI remains malleable after 100g applied
    - No cracking observed
    - More discoloration in this image



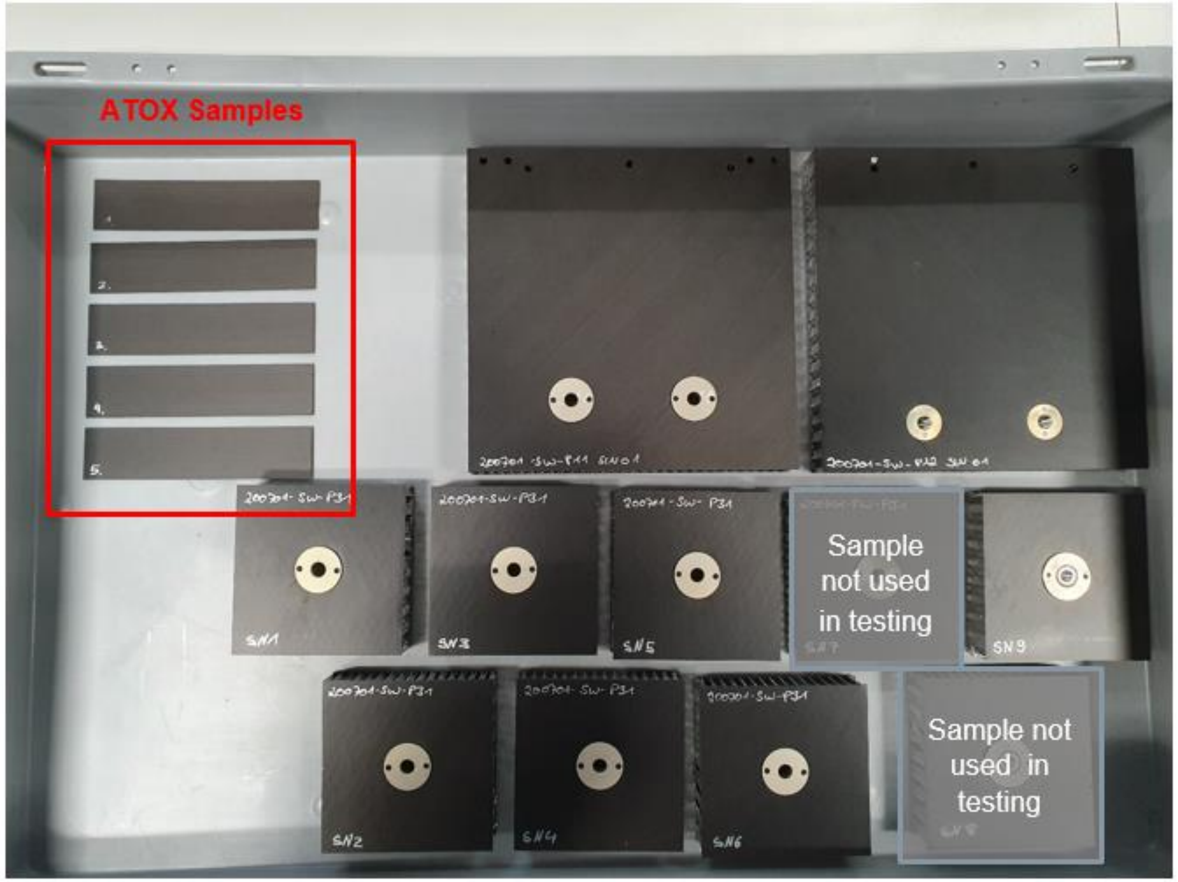
TEST CONCLUSIONS – ATOX

- ATOX Tests Performed
  - Close to correct fluence
  - No major impact on any surface
    - Not expected result
    - Fragile final samples were expected
- Recommendations
  - A samples do not appear fragile, can be directly tested at AAC
  - Baseline is that MLI is undamaged
    - Test virgin MLI samples in AAC
    - Impact of connections (standoff/Velcro) to be assessed
  - Compared to no MLI for impact

DEMISE TEST RESULTS

TEST SAMPLES – DEMISE

- Simulated re-entry conditions at AAC test facility
- Single,
  80mm x 80mm samples tested
- Dual “corner”,
  160mm x 160mm sample tested
- ATOX-aged and virgin,
  114mm x 26mm samples tested



TEST MATRIX - DEMISE

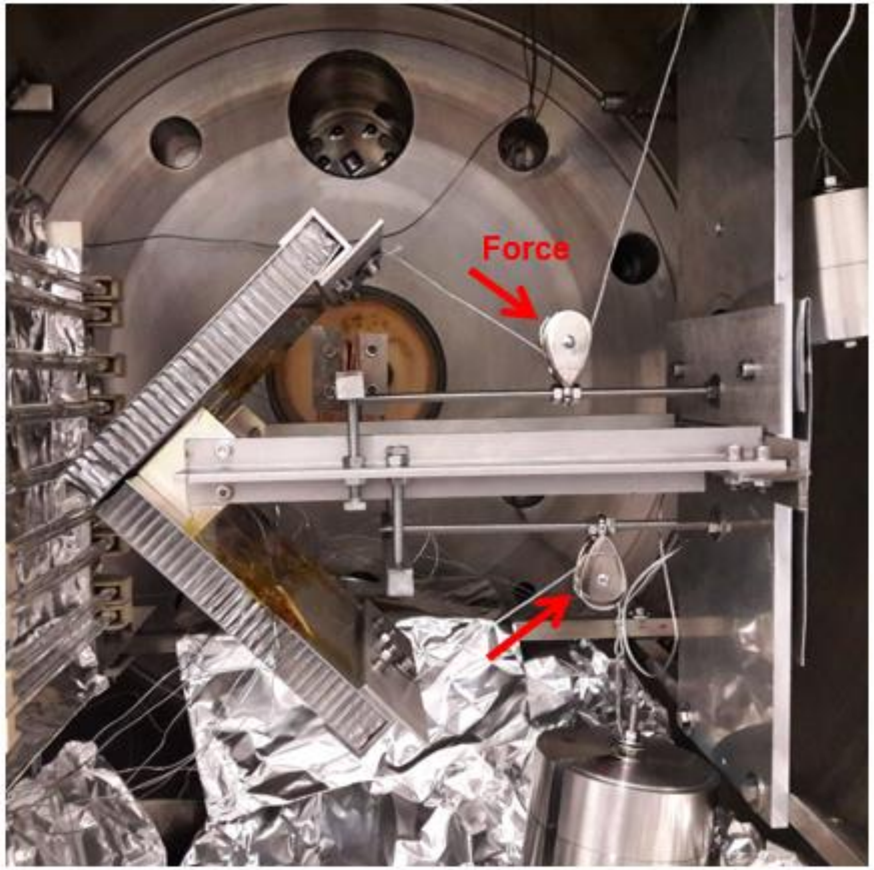
Test ID	1	2	3	4	5	6	7	8	9	10
Panel S/N	SN6	SN1	SN2	N/A (ATOX)	SN5	SN4	N/A (ATOX)	SN3	SN9	S/N01 (2 panels)
Test Condition	TC2	TC2	TC2	TC2	TC2	TC2	TC2	TC2	TC2	TC2
Applied Load	20	20	20	None	20	20	None	20	20	20
MLI Config. Type	N/A	C5	C4	C5 w/ stand-offs	C2	C2	C2 w/ velcro	C3	C5	Aged or unaged, C5
Tech Config.	No MLI	Unaged MLI	Unaged MLI	Exposed Sample 2 with MLI Coupon for same material	Unaged MLI	Unaged MLI	Exposed Sample 4 with MLI Coupon for same material	Unaged MLI	Unaged MLI with Demisable Insert	overlapping unaged MLI
MLI Fixation	N/A	Stand-offs	Velcro	N/A	Stand-offs	Velcro	N/A	Stand-offs	Stand-offs	Stand-offs
Insert Type	Spool	Spool	Spool	N/A	Spool	Spool	N/A	Spool	Demisable Spool	2 x Spool and 2 x Standard
Panel Setup	Control / 80x80	80x80	80x80	114 x 26 (ATOX)	80x80	80x80	114 x 26 (ATOX)	80x80	80x80	2x 160x160

TEST SETUP – DEMISE

- Heat flux profile with max. flux of 50kW/m²

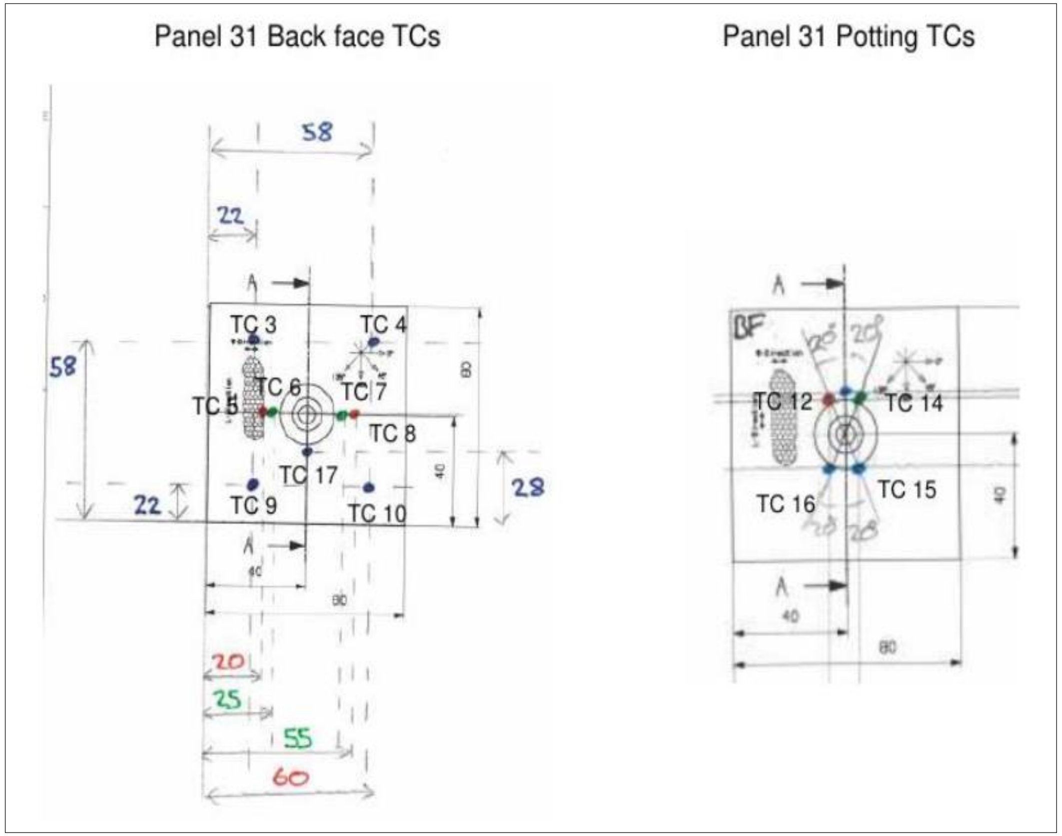
Time (s)	Heat Flux (kW/m²)
0	3.2
285	3.2
465	5
765	20
965	50

- Loading of 20N exerted upon each sample (corner sample shown)
- Sensor locations at same locations as Breadboarding study

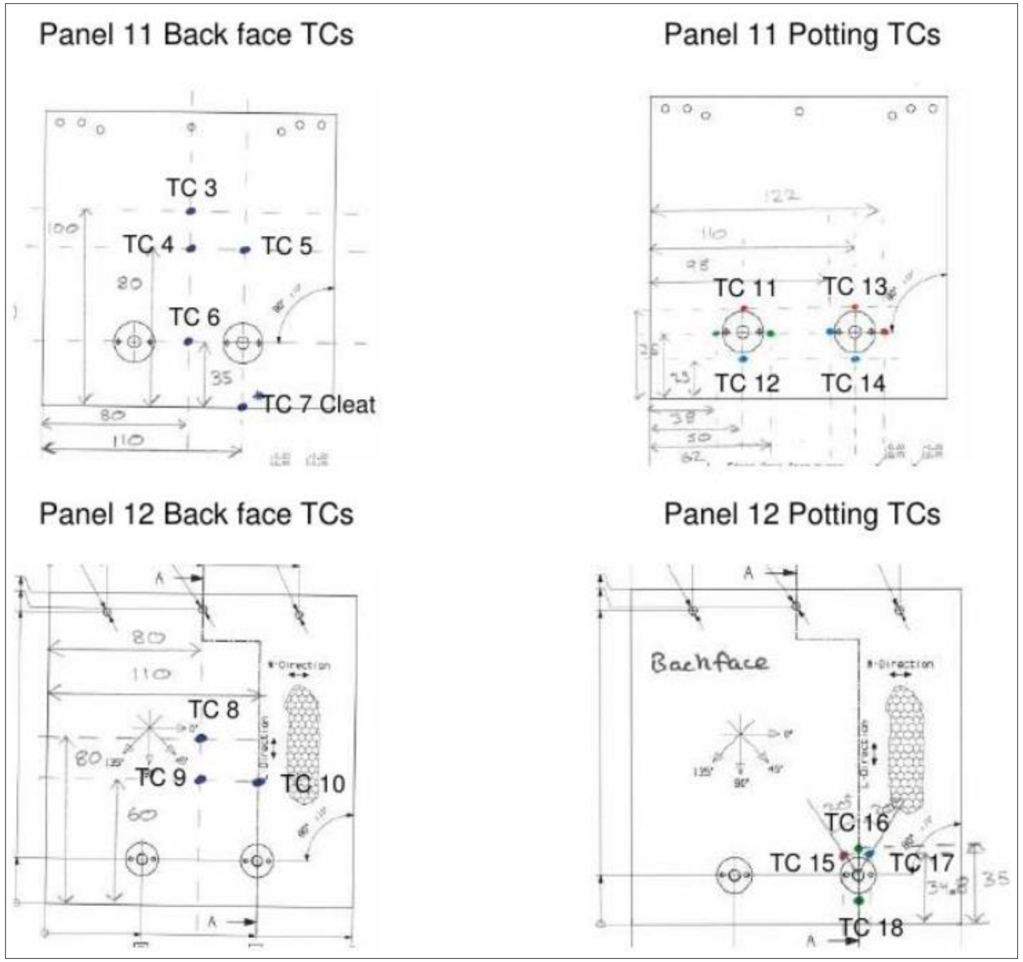


TEST SETUP – DEMISE

- Sensor locations



Single panels

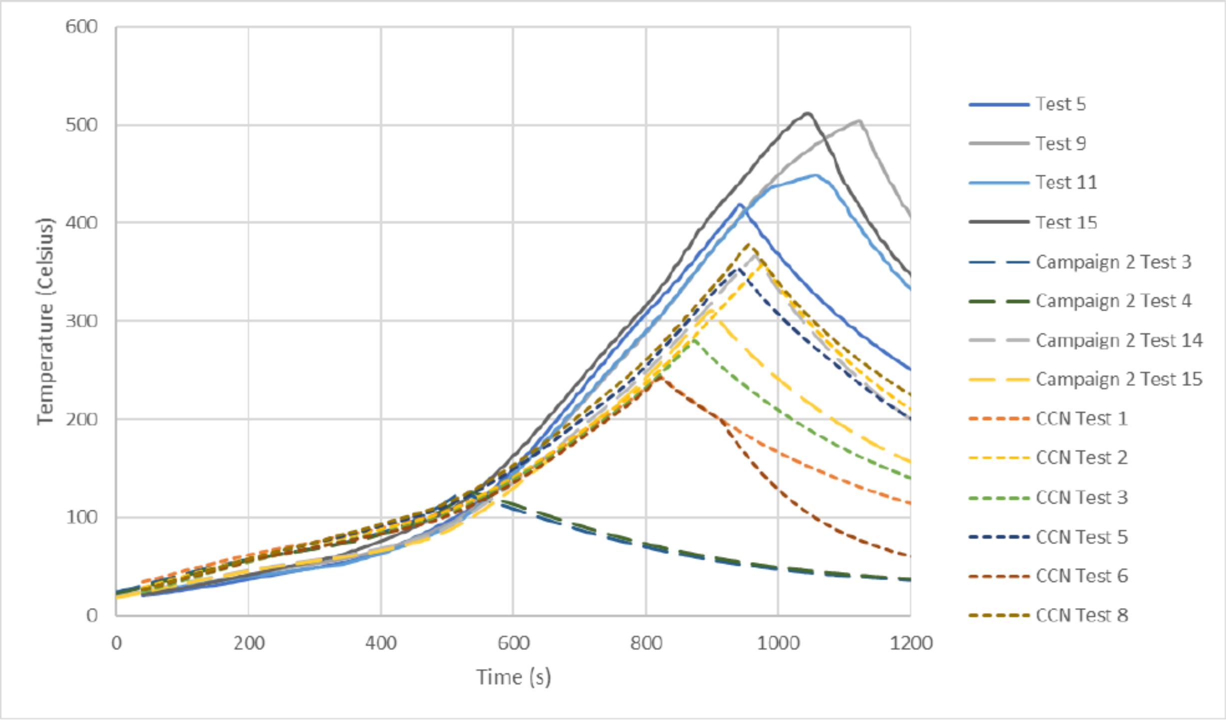


Dual “corner” panels

TEST RESULTS AND ANALYSIS – DEMISE

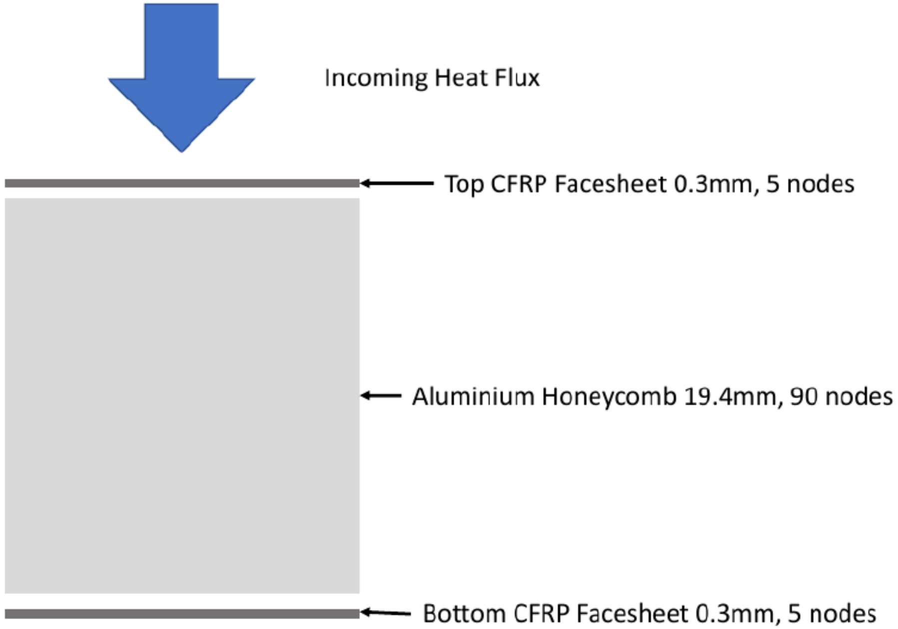
- Differences in Test Campaigns
  - Calibration Block
  - Heating in line with second campaign, below first campaign

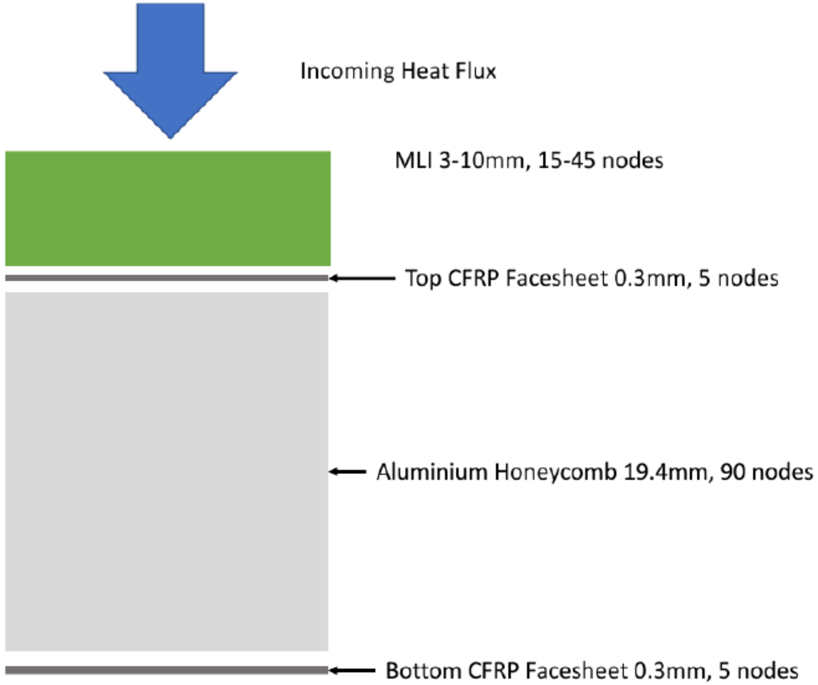
		Flux Scales		
Test Type	**Campaign**	**Initial Stage**	**Main**	**Final Stage**
Single Panel	1	0.6	1.0	0.8
Single Panel	2	0.5	0.7	0.6
Single Panel	CCN	0.7	0.7	0.7



TEST RESULTS AND ANALYSIS – DEMISE

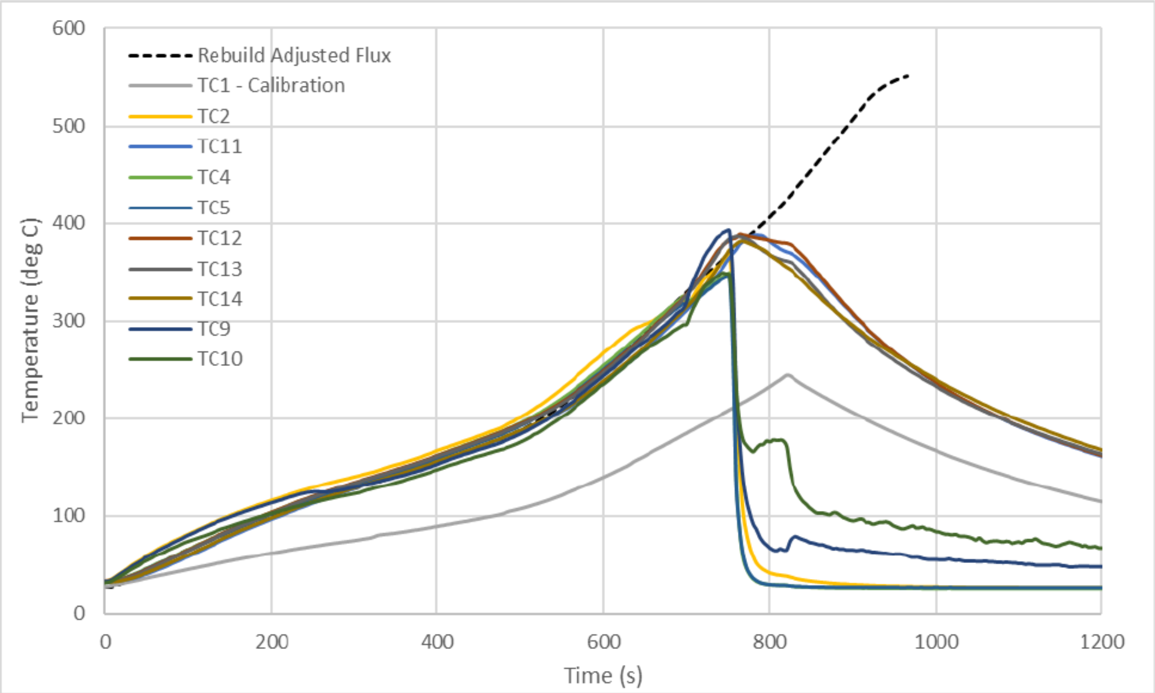
- SAMj Model - 1D layup used
  - Different layup with MLI present
  - MLI conductivity fit to data (consistent)





TEST RESULTS AND ANALYSIS – DEMISE

- Control Test (No MLI)
  - Good rebuild
  - Close to isothermal
  - Front facesheet off
  - Spare sample
    - Consistent



TEST RESULTS AND ANALYSIS – DEMISE

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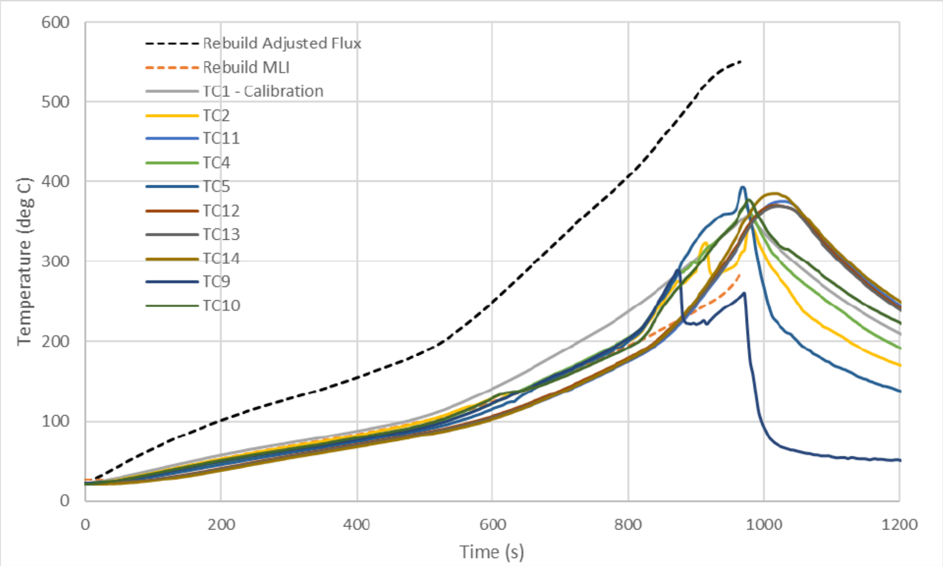
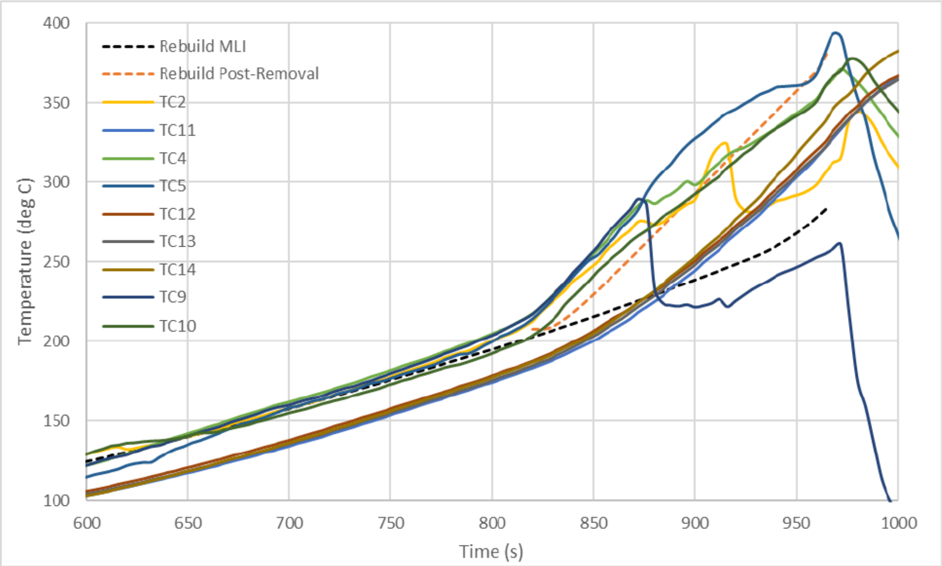
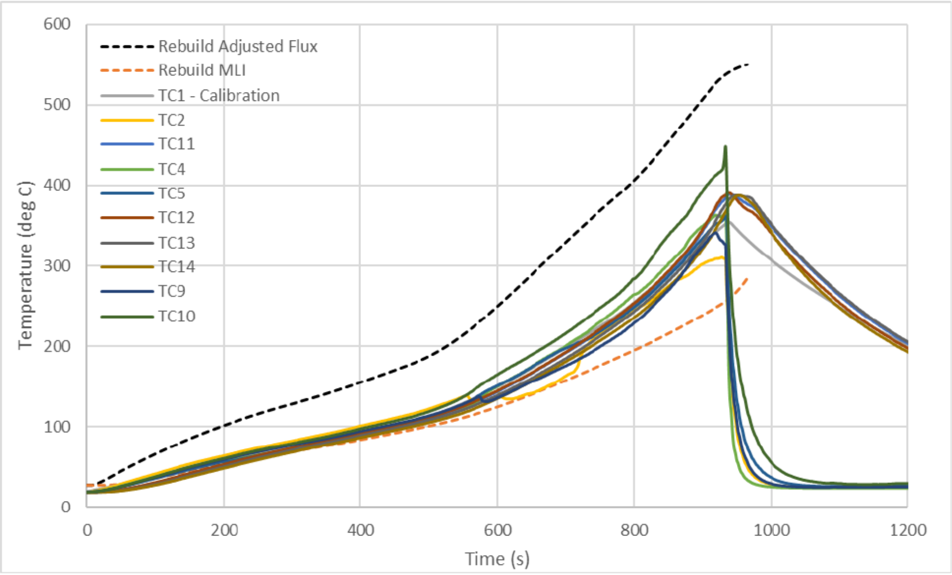
- Baseline MLI with Standoffs
  - Clear reduction in heating from MLI presence
  - Warping of MLI at 200^{0}C, increased flux
  - Front sheet removal at 350^{0}C, panel collapse soon after
  - Heating captured by model after panel release

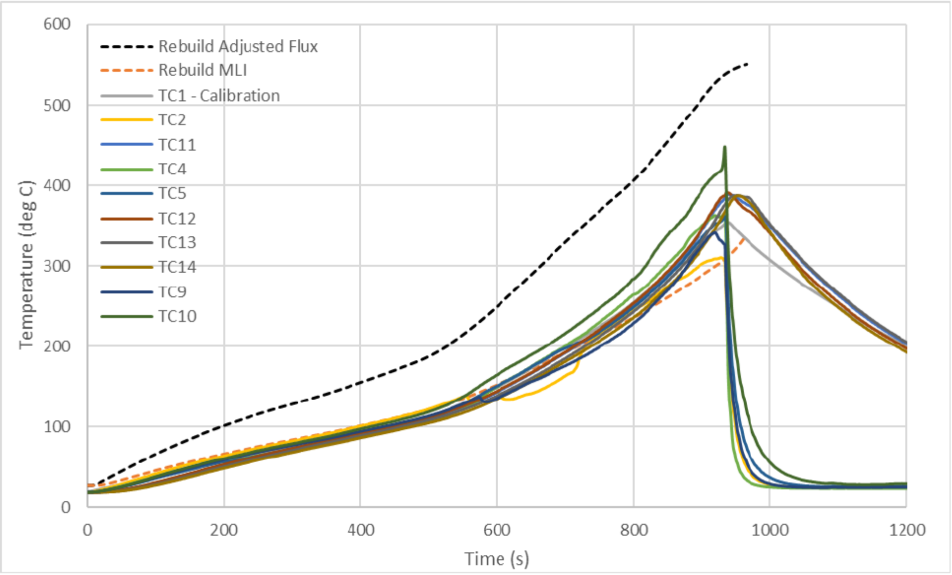




TEST RESULTS AND ANALYSIS – DEMISE

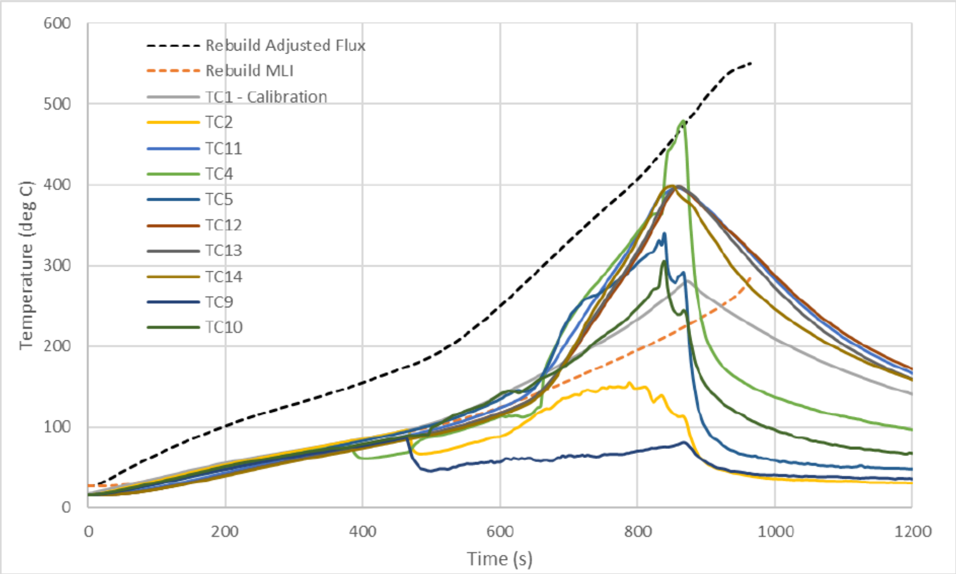
- Alternative MLI Materials (Kapton Black) with Standoffs
  – Slightly less insulation effect
  – Baseline model (left), adjusted model (right)
  – Same temperature thresholds for warping, frontsheet release
  – Standoffs are not removed – released with frontsheet

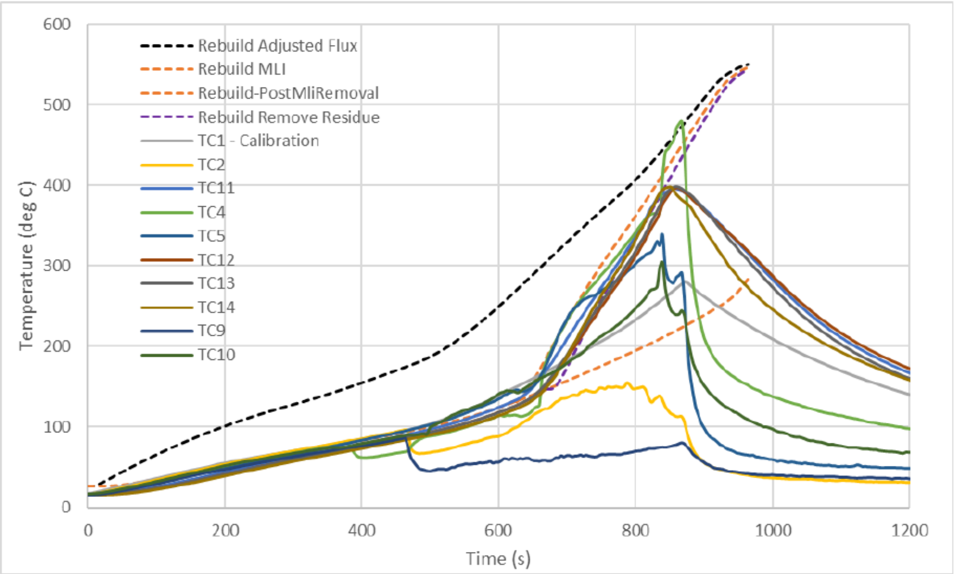




TEST RESULTS AND ANALYSIS – DEMISE

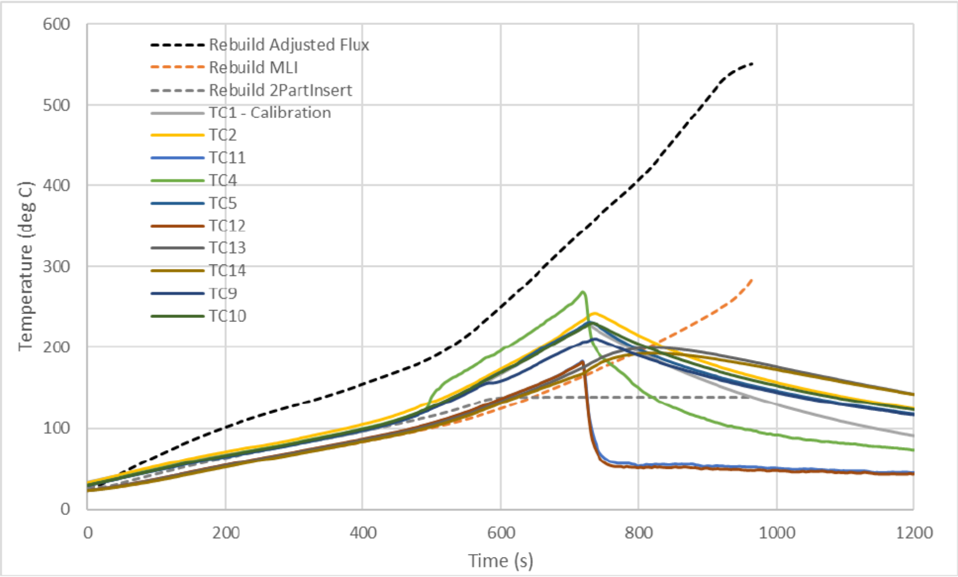
- Baseline MLI with Velcro
  - Same MLI insulation model – consistent behaviour
  - Much earlier release of MLI, Velcro melt <150^{0}C
  - CFRP Frontsheet remains in place, removed at 350^{0}C
  - Again, model captures heat rise after removal

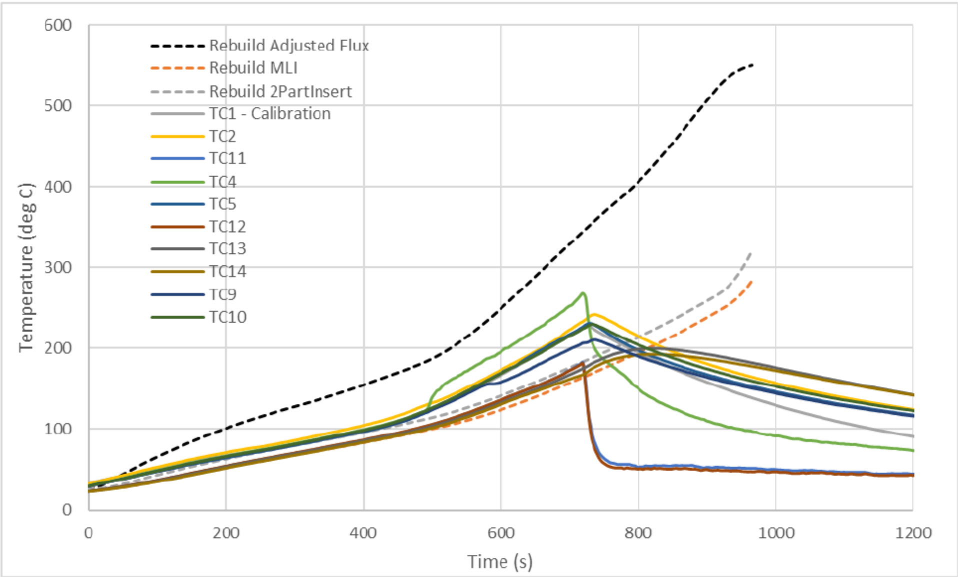




TEST RESULTS AND ANALYSIS – DEMISE

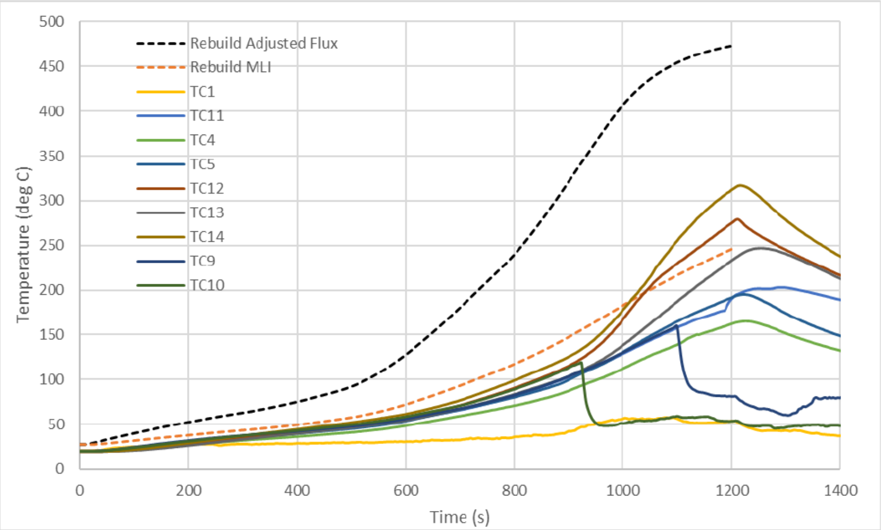
- Baseline MLI with Standoffs and Demisable Joint
  - Slightly lower thermal inertia
    - Higher mass, lower heat capacity
  - Failure before 200⁰C, but later than nominal 140⁰C (latent heat)
    - Concept shown to work well – failure is before warping





TEST RESULTS AND ANALYSIS – DEMISE

- Two-Panel Test
  - High heat flux gradient across panel
  - Confirms warping of material
  - Fluxes too low to remove material
  - Confirms standoffs removed with frontsheet
    - MLI removal needs CFRP facesheet removal
  - Rebuilds less good
    - Model at insert location



TEST RESULTS AND ANALYSIS – DEMISE

- Stripe Tests
  - Thermocouples Release Early
  - Clearly seen in video data
  - Qualitative only
  - Velcro failure at ~150^{0}C confirmed
  - No release of standoffs from frontsheet confirmed

FLIGHT EXTRAPOLATION

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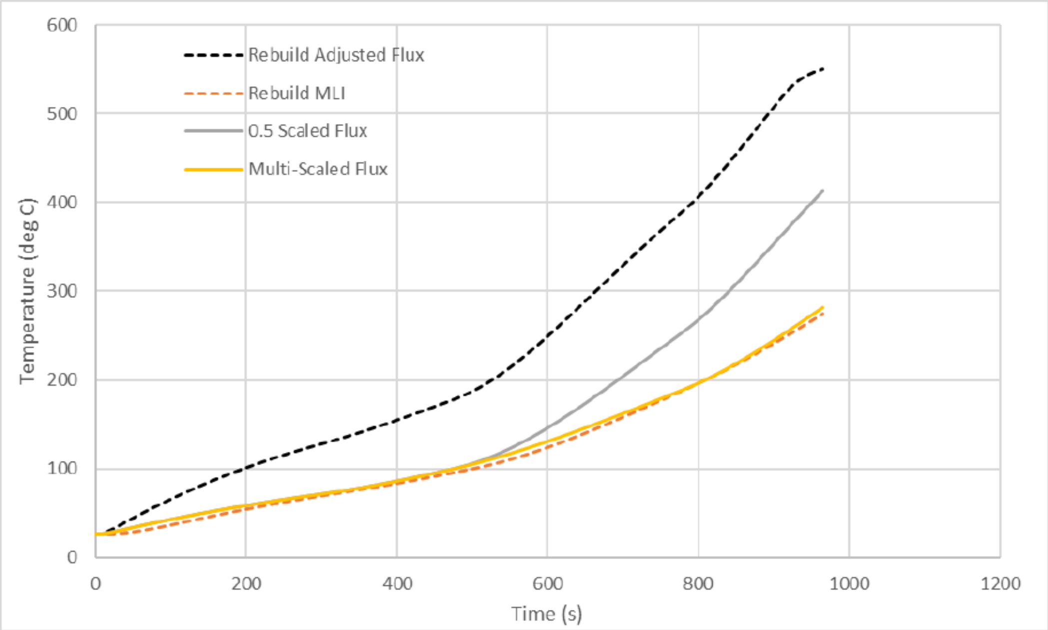
- Proxy Scale for Input Heat Flux
  - Models for MLI removal
  - Velcro
    - Fail at 150^0C
  - Standoffs
    - Warping at 200^0C

1. Increased flux
    - Removal at 350^0C

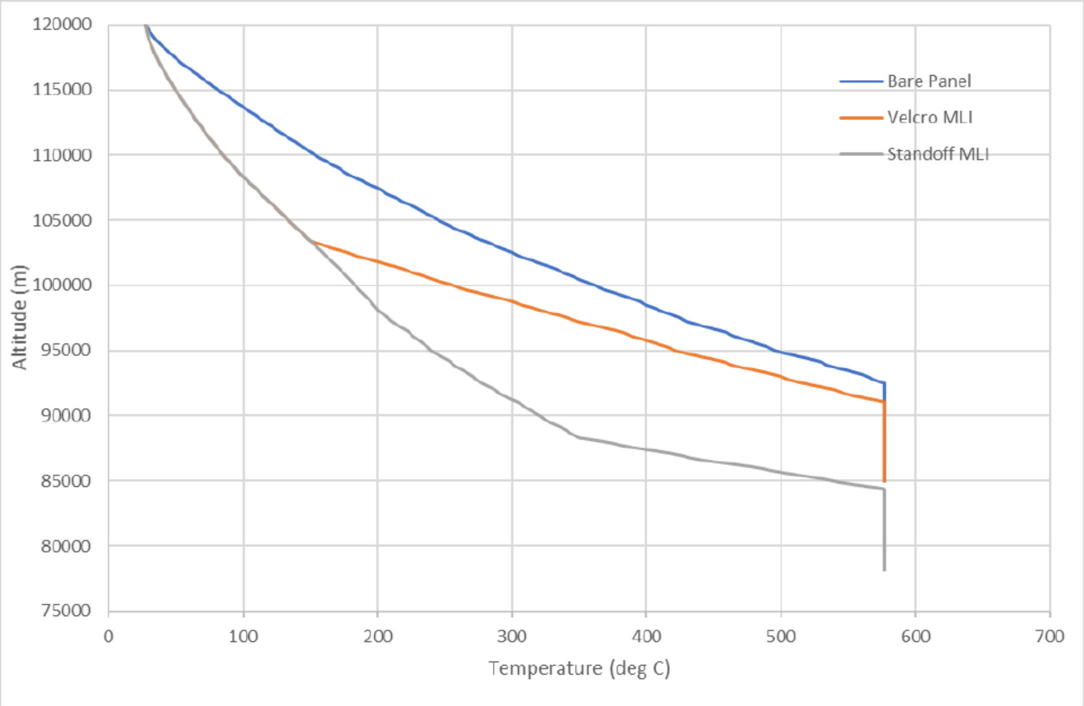
- Bulk Heating Model
  - Verified on test data
  - Applicable to flight



Heat Flux (kW/m^2) Nominal	Heat Flux (kW/m^2) Calibrated	Scale Factor
<5000	<3500	0.5
5000	3500	0.5
20000	14000	0.27
50000	35000	0.23

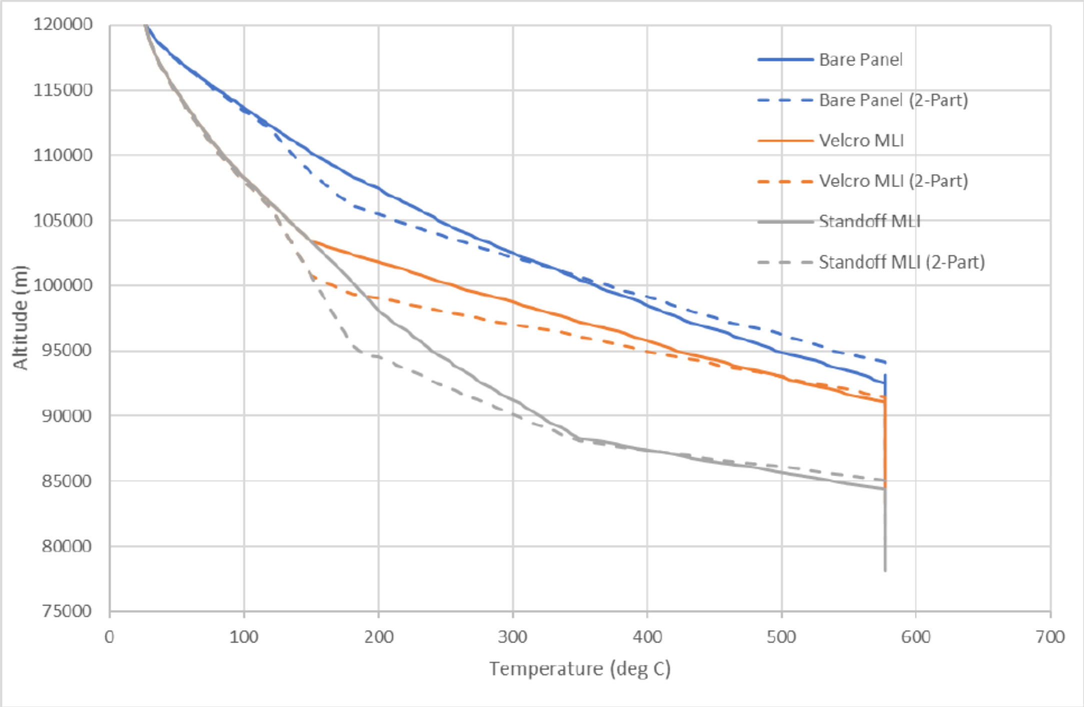
FLIGHT EXTRAPOLATION

- Trajectory of 2m Cube
  - Assess behaviour of external panels
- MLI Insulation Effect
  - Clearly observed
  - Standoffs significant
- Closer to Observation?
  - Open question
  - Sensible result
    - 85km still reasonable



FLIGHT EXTRAPOLATION

- Demisable Insert
  - Appropriate sandwich panel proxy model with 2-part inserts
  - Similar thermal inertia (higher mass, lower specific heat)
  - Account for latent heat
  - Failure at 185^{0}C
  - After Velcro removed
  - Before Standoffs
- Clear Impact
  - Inhibited by MLI?
    - If standoffs?



	MLI Warp	MLI Removal	Joint Failure	Demisable Joint Failure
Bare Panel			96km	106km
MLI (Velcro)		102.5km	94km	99km
MLI (Standoffs)	97.5km	87.5km	82km	95km

DEMISE TESTING CONCLUSIONS

- Clear Impact of MLI
  - Insulation is real
  - MLI likely to stay in place until Velcro melt / front facesheet goes
  - Model constructed to account for this
    - Proxy model, applicable to DRAMA (needs code change)
- Reduction of Joint Failure Altitude
  - Towards observed data (which is on steeper trajectories)
  - Fragmentation still suggested to be clearly higher than 78km
- Demisable Joint Effective
  - Expected to have significant impact
  - Fragmentation could be slightly inhibited by remaining MLI

LESSONS LEARNED & CONCLUSIONS

LESSONS LEARNED

- Atomic Oxygen Exposure has Limited Effect
  – The MLI at re-entry can be considered undamaged for demise assessments
- MLI has a Clear Insulating Effect
  – The heat to the spacecraft structure is clearly reduced until the MLI is removed
- MLI Removal Depends on Attachment Methodology
  – Velcro melts early and is quickly removed
  – Standoffs do not fail and are removed with front facesheet
- Demisable Joint is Effective
  – Removal of insert occurs even with MLI in place
  – Significant increase in expected altitude of failure

CONCLUSION

- Impact of MLI on Re-entry is Real
  - Minimal effect of ATOX
  - Heating to the spacecraft will be reduced
  - More test data would be desirable to increase confidence in modelling
- Reduction of Joint Failure Altitude
  - Closer to observation data (which is on steeper trajectories)
  - Fragmentation still above 78km in predictions
    - No immediate need to adjust risk analyses where 78km is used
- Demisable Joint Effective
  - Significant impact
  - Possible inhibition by remaining MLI

THANK YOU!

ATOX SAMPLE PICTURES

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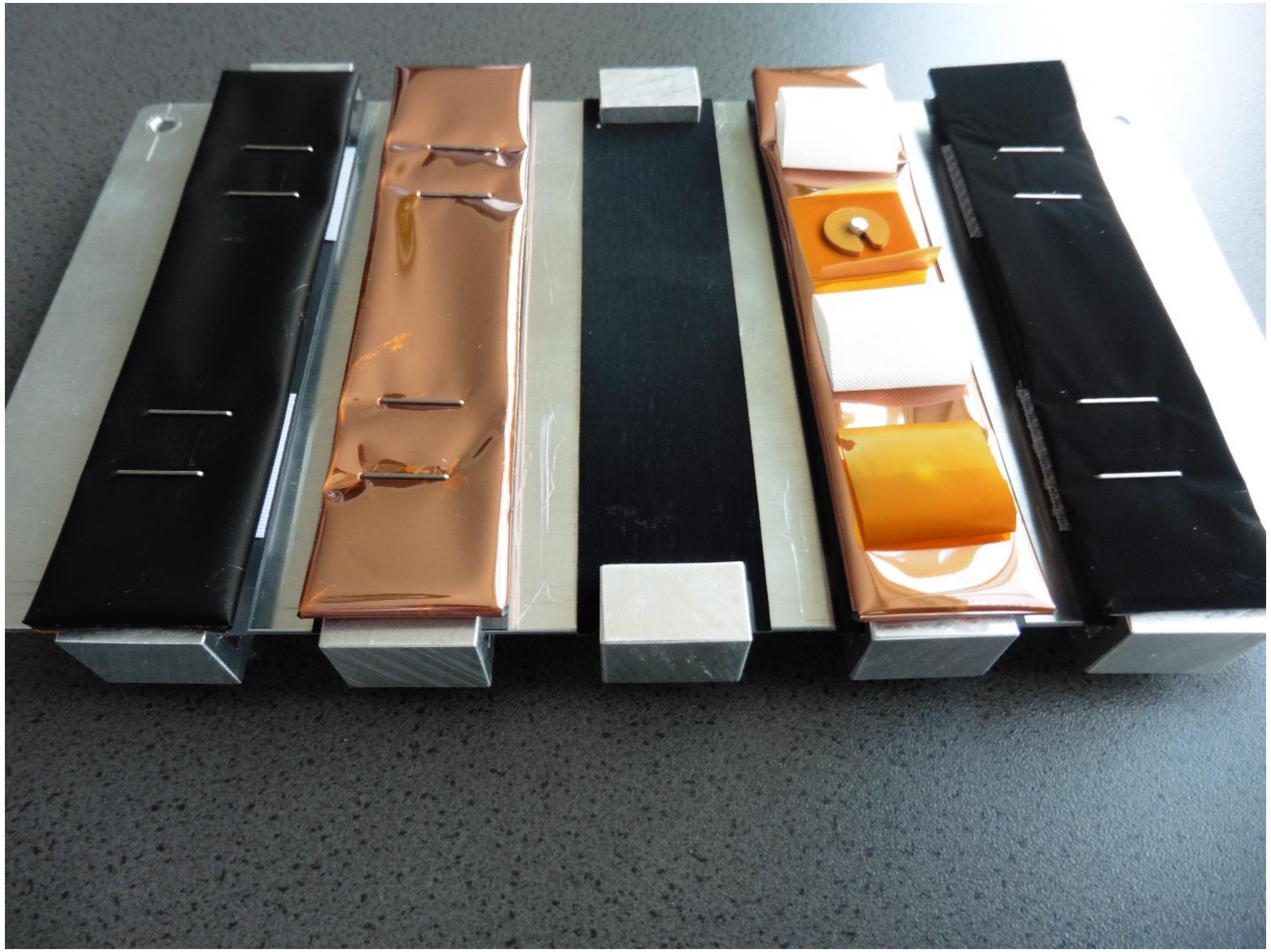

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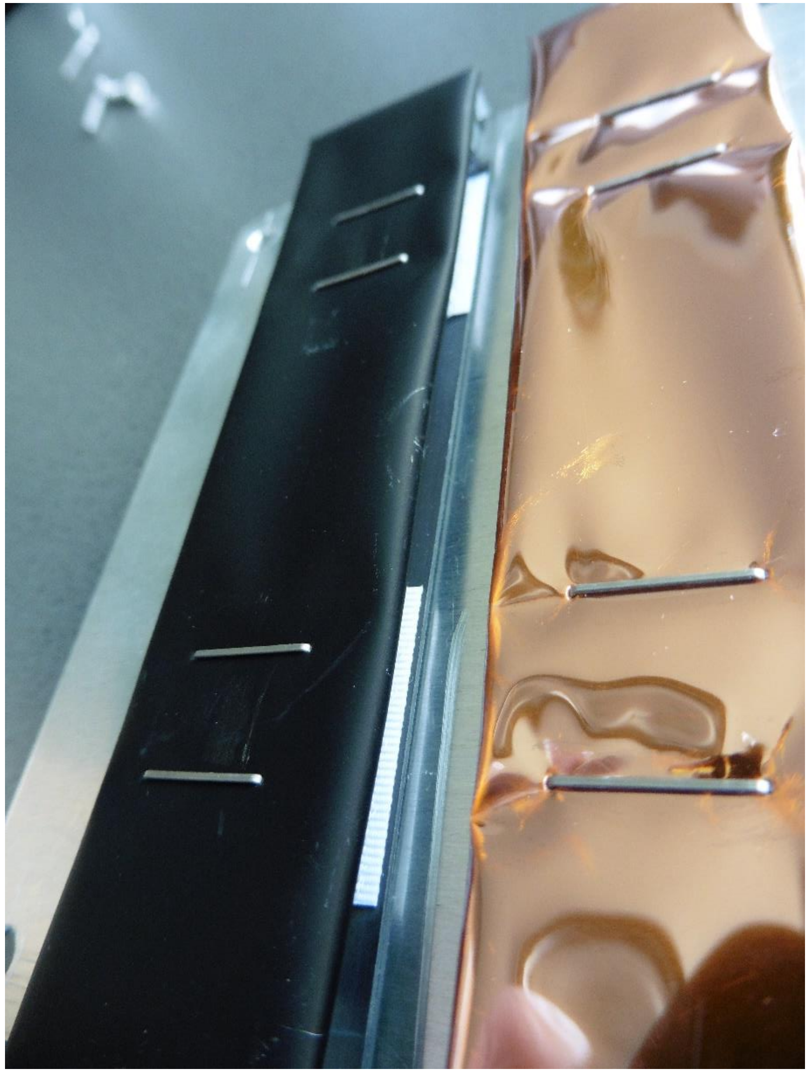

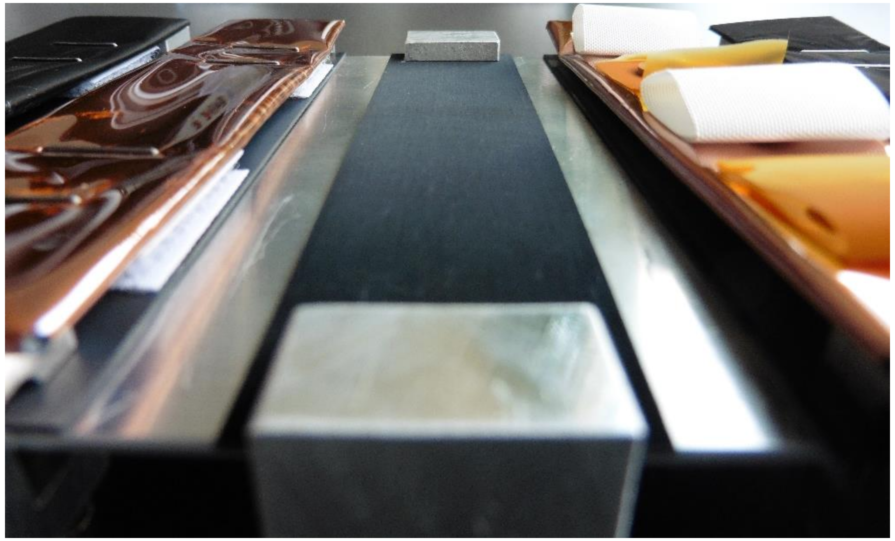

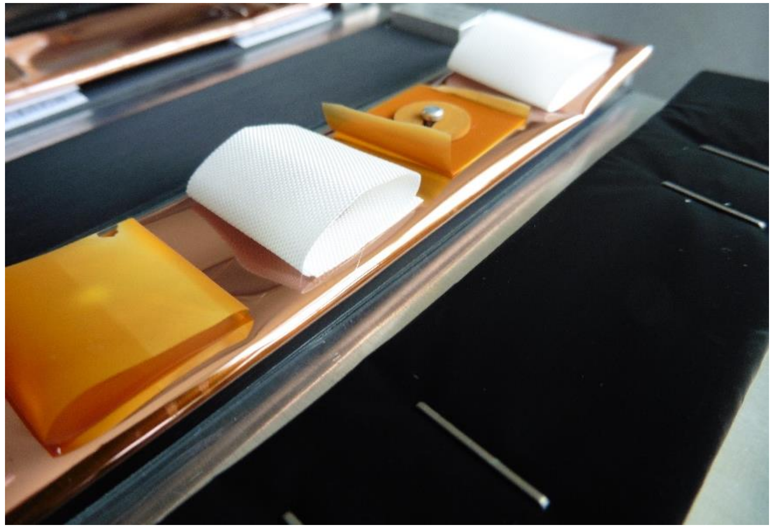

ATOX SAMPLE PICTURES