NORTHROP GRUMMAN

THE AEROSPACE CORPORATION

"The 2nd ESA-NASA Working Meeting on Optoelectronics: Qualification of Technologies and Lessons Learned from Satellite LIDAR and Altimeter Missions"

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Fiber Laser Component Testing for Space Qualification Protocol Development

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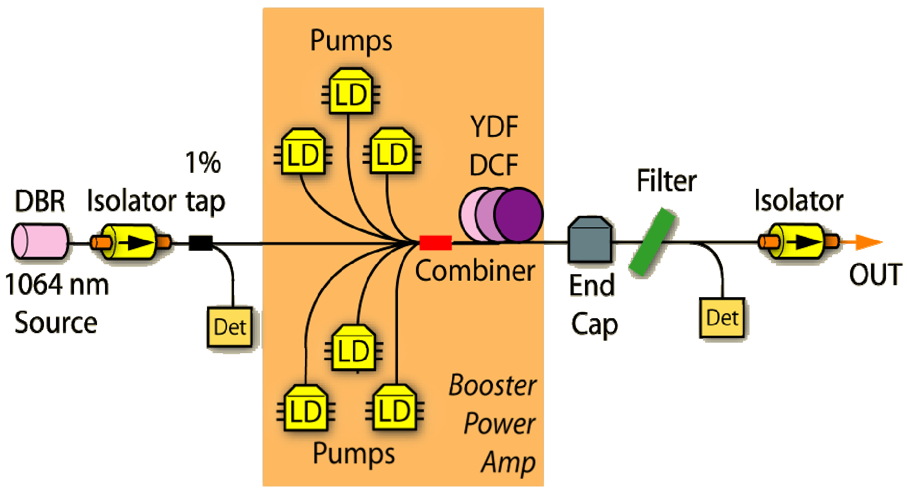
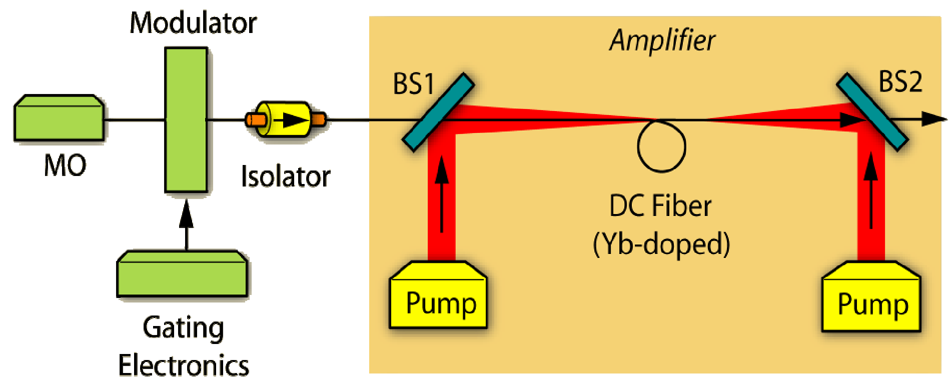
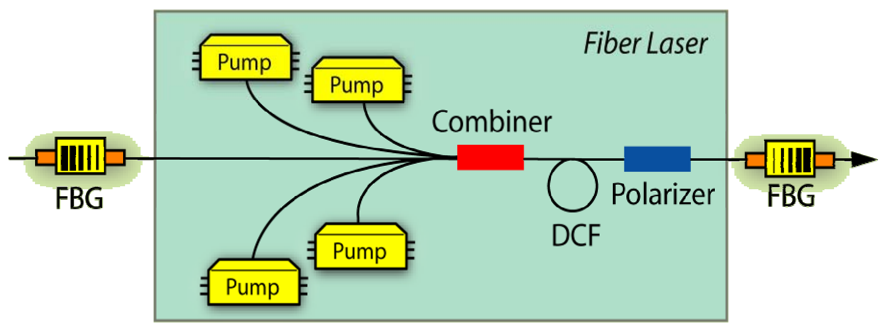
Background Remarks

- This work is the result of a task to establish a test protocol for application in markets where it is desired to take Commercial-off the-Shelf (COTS) photonics and apply them to space
- The testing results presented here was not the primary objective of the effort
  - Primary objective was to test the protocol and its procedures for space qualification of COTS fiber laser components
  - COTS test articles were selected for their nominal applicability to a notional system and not for their suitability for use in space
- The vendors were NOT informed that the parts would be screened for applicability to space
  - Site visits or materials analysis was not done prior to purchasing the test articles, but is desired for an actual space qualification program
- Data results presented here do not reflect on the vendors or their abilities to produce products for space applications

Generic Fiber Lasers – System Architecture*



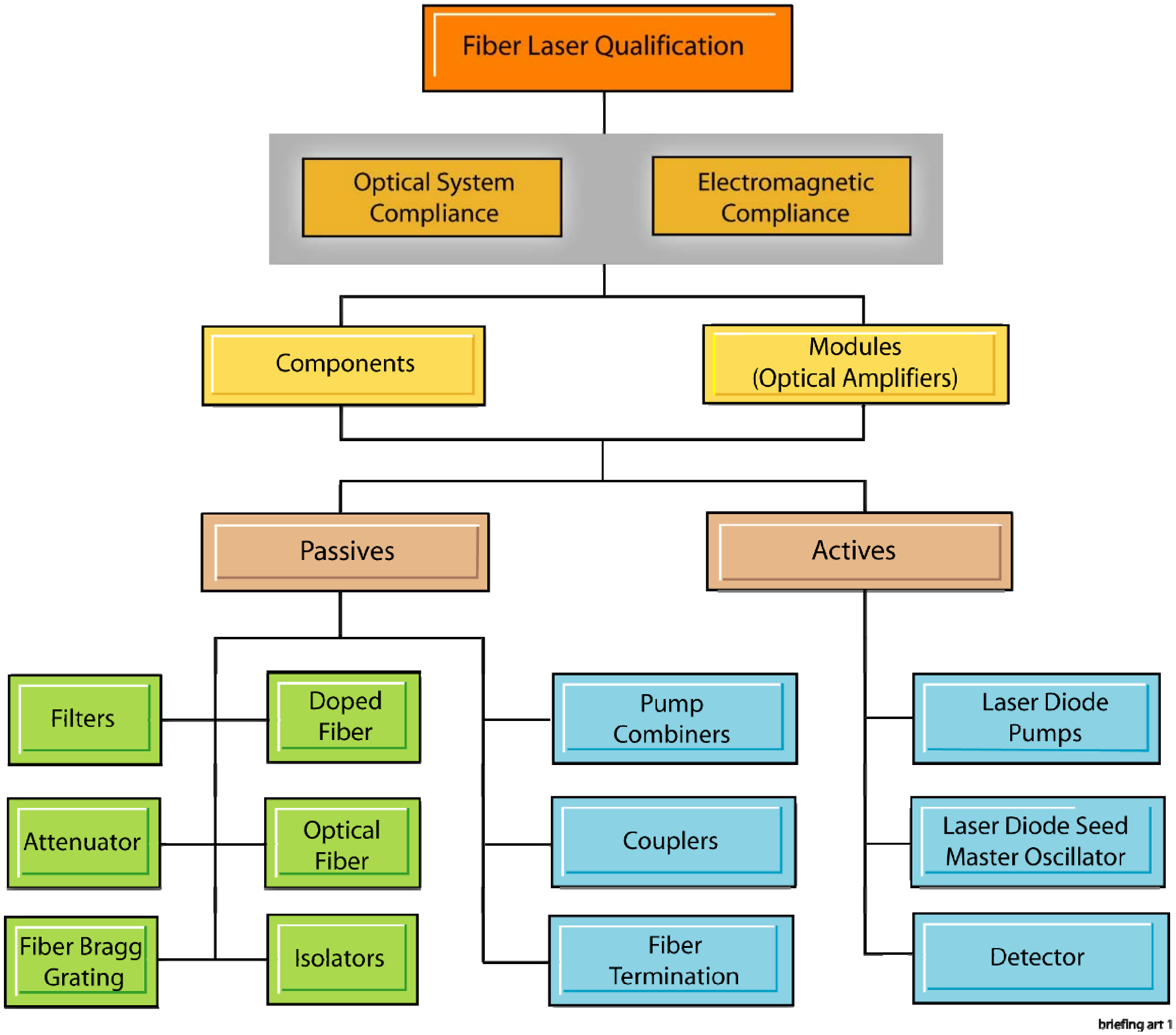




briefing art 3

* *Qualification of Fiber Lasers and Fiber Optic Components for Space Applications*, S. Hendow, S. Falvey, B. Nelson, L. Thienel, Maj. T. Drape, SPIE LASE 2006, 6102-59.

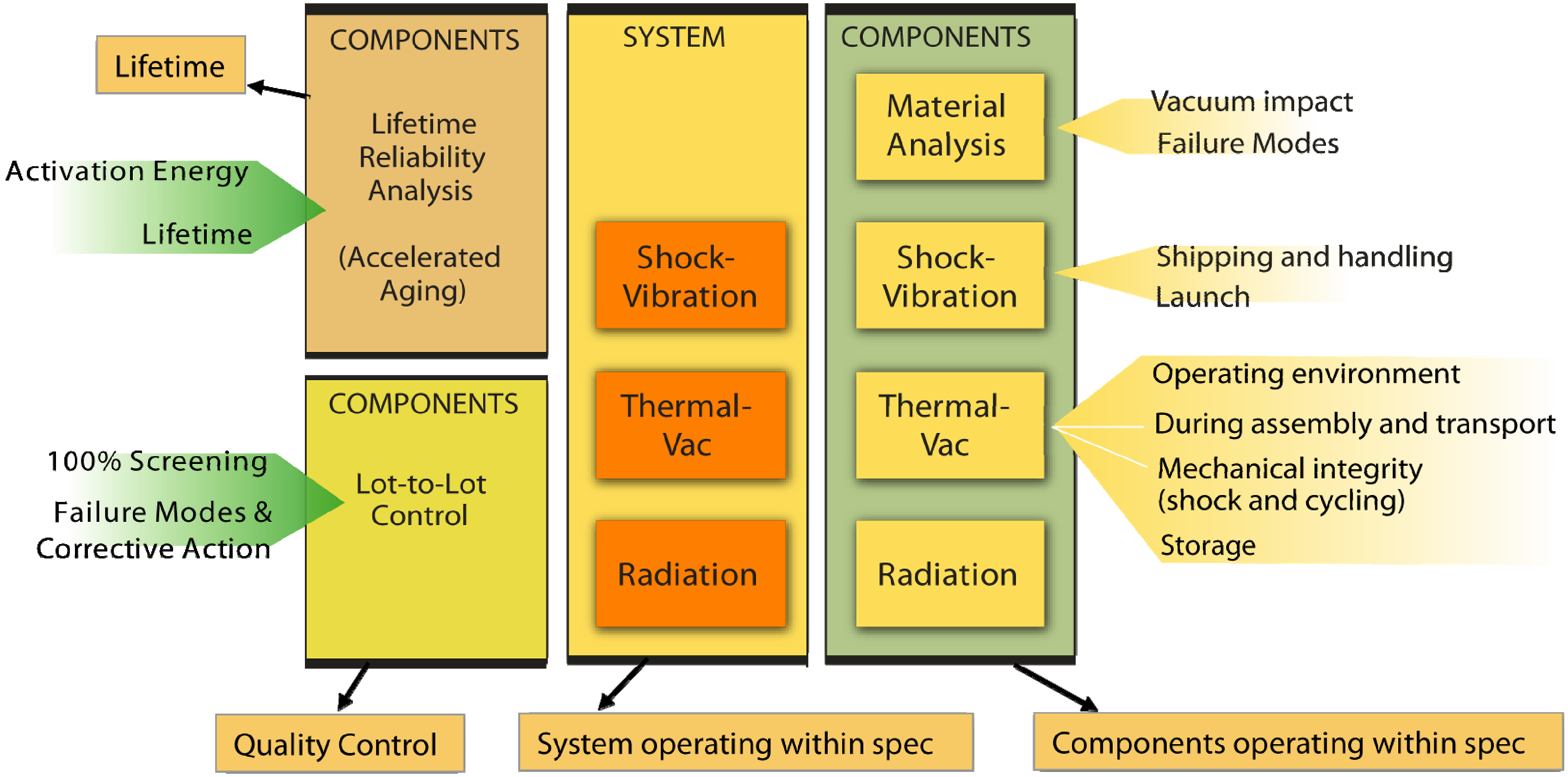
Taxonomy of Test Protocol*



* *Qualification of Fiber Lasers and Fiber Optic Components for Space Applications*, S. Hendow, S. Falvey, B. Nelson, L. Thienel, Maj. T. Drape, SPIE LASE 2006, 6102-59.

Space Flight Qualification Process of a Fiber System*

- **'Integration' of NASA and Telcordia Qualifications**



briefing art 4

* *Qualification of Fiber Lasers and Fiber Optic Components for Space Applications*, S. Hendow, S. Falvey, B. Nelson, L. Thienel, Maj. T. Drape, SPIE LASE 2006, 6102-59.

Components Selected for Qualifying the Process

Component or Part	Description
Double-Clad Ytterbium-doped Fibers	▪ Wide-mode area ▪ Photonic crystal ▪ Various doping concentration ▪ Various manufacturers
Combiners	▪ 6+1 : 1 ▪ 16 : 1
Fiber Bragg Gratings	▪ ASE Filter ▪ Custom
Isolators	▪ Fiber pigtailed unit ▪ High power bulk unit
Pump Laser Diodes	▪ 915 and 976 nm ▪ Pigtailed, multimode, no TEC, and high power
Laser Diode Seed Sources	▪ Distributed Bragg reflector, with TEC, pigtailed
Pump-Combiner Modules	▪ Integrated module using OFS combiner, has 6 laser diodes, 7:1 combiner, with TEC

Selection is based on relevance to high-power fiber lasers in space application at 106x nm.

Tests Performed are a Function of the Dominant Component Failure Modes

Item	Parameter to Monitor	Type of Measurement	Dominant Failure Modes
Fibers	Insertion loss of core	Active	• Increase in IL leading to optical damage during operation at peak power (catastrophic)
	Absorption rate of clad at pump λ	Before and after	
	Absorption and emission spectra	Occasional	
Combiners	Insertion loss, thru fiber	Active	• Decrease in transfer efficiency from the pump arm to output cladding and overheating of combiner.
	Insertion loss, 3 multimode ends	Before and after	
Pump Laser Diodes	Output Power	Active	• Gradual degradation or sudden failure with radiation exposure. • High environmental temp may lead to wavelength drift
	Wavelength & spectrum	Active	
	Threshold	Before and after	
Pump-Combiner Modules	Output power at max current	Active	• Gradual degradation with radiation. • Overheating at high environmental temp may lead to wavelength drift. • Combiner may have thermal drift.
	λ and spectrum at max current	Active	
	TEC current at 20°C	Before and after	
	Power vs. current	Before and after	
	Isolation	Before and after	
Fiber Bragg Gratings	Reflectivity	Occasional	• Athermal property may get damaged leading to wavelength drift (catastrophic). • IL degradation with radiation damage.
	Reflectivity spectrum	Occasional	
	Sideband reflectivity	Before and after	
Laser Seed Source	Output power at max current	Active	• Wavelength drift. • Gradual or sudden failure due to high thermal operation or radiation exposure.
	Output spectra	Occasional	
	Output power vs. current	Before and after test	
	TEC current at 20°C	Before and after	
Isolators, Fiber Pigtailed	Insertion Loss	Active	• Increase in IL with vibration, thermal or radiation exposure.
	Isolation	Before and after test	
Isolators, Free Space	Insertion Loss	Before and after test	• Increase in IL with radiation. • Degradation of isolation. • Misalignment with vibration.
	Isolation	Before and after test	

Optical Properties were Measured for Performance Metrics

Component	Test Performance Metrics	Test Type
Ytterbium Fibers	Insertion Loss	Passive, before and after
Combiners	Insertion Loss	Passive, before and after
Fiber Bragg Gratings	Insertion Loss, Isolation	Passive, before and after
	Spectrum	Active thermal testing
Isolators	Insertion Loss, Isolation	Passive, before and after
Laser Diode Pumps	Light-Current Curve	Passive, before and after
	Light-Current Curve, Spectrum	Active thermal testing
Pump-Combiner Modules	Light-Current Curve, Isolation	Passive, before and after
	Light-Current Curve, Spectrum*	Active thermal testing
Laser Seed Sources	Light-Current Curve	Passive, before and after
	Spectrum	Active thermal testing

* Not tested due to complexity of splice to connect with OSA

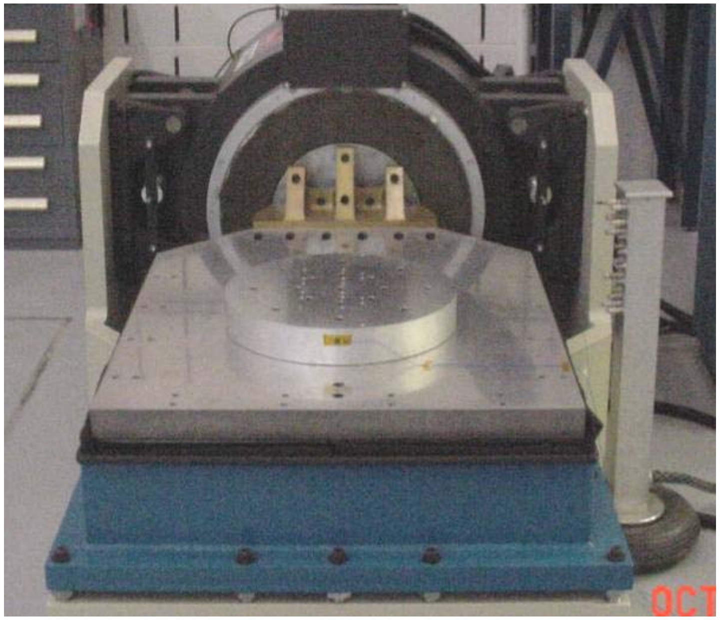
Tests were Performed in Batches

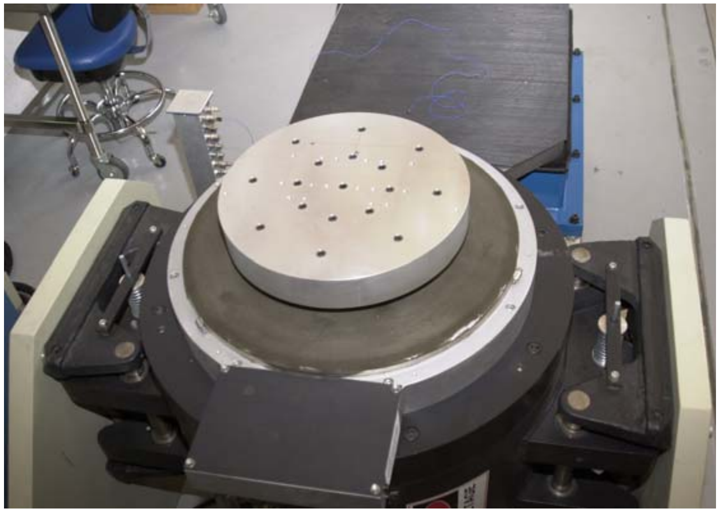
<table>
<tr><th colspan="4">Component Testing Grouping and Sequencing</th></tr>
<tr><th>Test / Batch</th><th>Vibration</th><th>Thermal†</th><th>Radiation†</th></tr>
<tr><td>1</td><td>▪ Isolator A
▪ Combiner B</td><td>▪ Fiber A
▪ Fiber B
▪ Combiner A
▪ Combiner B</td><td rowspan="6">▪ Fiber A
▪ Combiner A
▪ Fiber B
▪ Isolator A
▪ FBG B
▪ FBG A
▪ Combiner B
▪ Fiber C
▪ Fiber D</td></tr>
<tr><td>2</td><td>▪ Fiber Bragg Grating A
▪ Combiner A</td><td>▪ Isolator A
▪ Fiber E (non-active)</td></tr>
<tr><td>3</td><td>▪ Laser Diode A (Pump)
▪ Fiber Bragg Grating B</td><td>▪ Fiber Bragg Grating A
▪ Fiber Bragg Grating B</td></tr>
<tr><td>4</td><td>▪ Laser Diode C (PCM)</td><td>▪ Fiber C
▪ Fiber D</td></tr>
<tr><td>5</td><td>▪ Laser Diode B (Seed)</td><td>▪ Laser Diode A (Pump)
▪ Laser Diode B (Seed)
▪ Laser Diode C (PCM)</td></tr>
<tr><td>6</td><td>▪ Isolator B</td><td>▪ Isolator B (non-active)</td></tr>
</table>

† Active measurements were conducted, unless otherwise noted

Environmental Test Facilities - Vibration

- **Aerospace Engineering Facility on Kirtland AFB, NM**
- **Mounting fixture machined and tested to our subsystem testing levels**





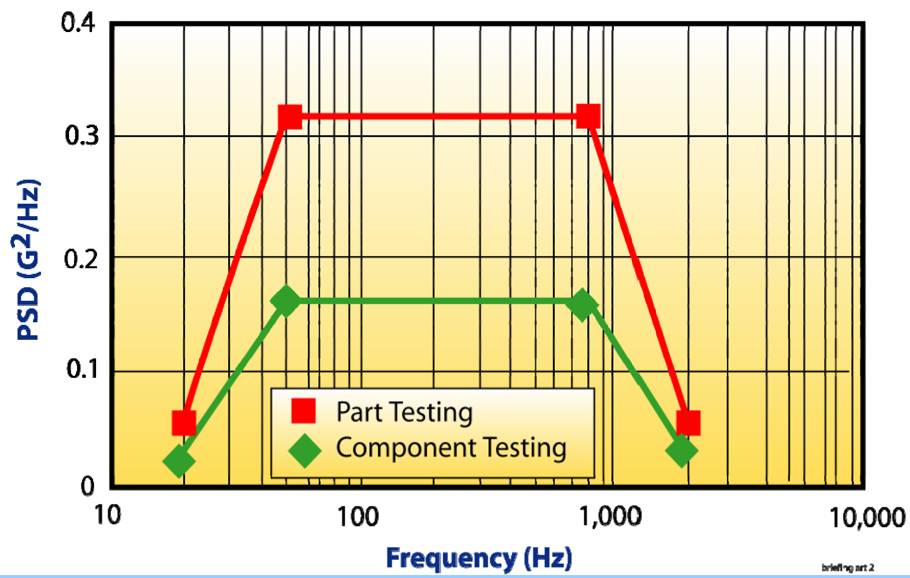
Vibration Testing Parameters

- Only component level testing was performed
- Test range 20 to 2000 Hz
- Test in X, Y, and Z
- Order of sweeps for any one axis is SINE-RANDOM-SINE
  - Sine sweeps are ¼G pre- and post-random runs
- Sine sweep parameters
  - 1:3 octaves per minute
  - BB RMS 318 mcyc
- Random sweep parameters
  - 4 minutes
  - RMS 14 G

Vibration Profile Levels*

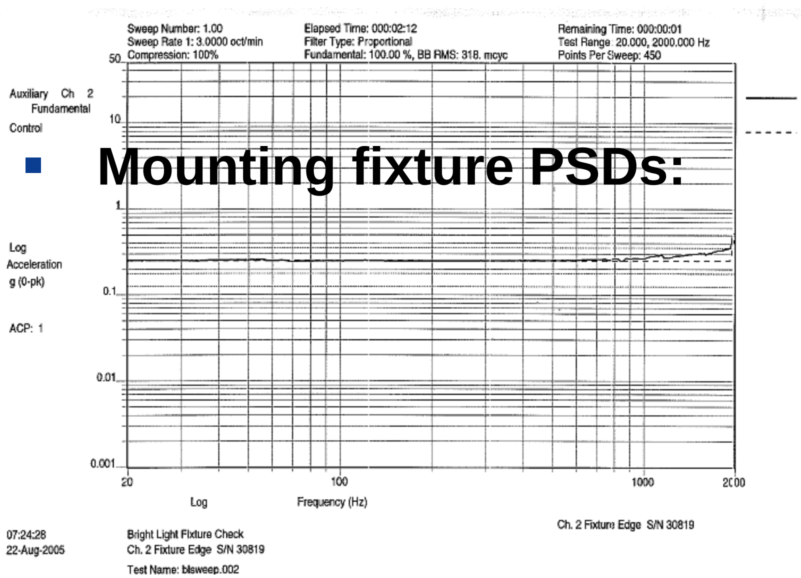
Frequency (Hz)	Component Testing	Part Testing	Units
20	0.026	0.052	G^2/Hz
20-50	+6	+6	dB/octave
50-800	0.16	0.32	G^2/Hz
800-2000	-6	-6	dB/octave
2000	0.026	0.052	G^2/Hz
Overall	14.1	20.0	G_{rms}

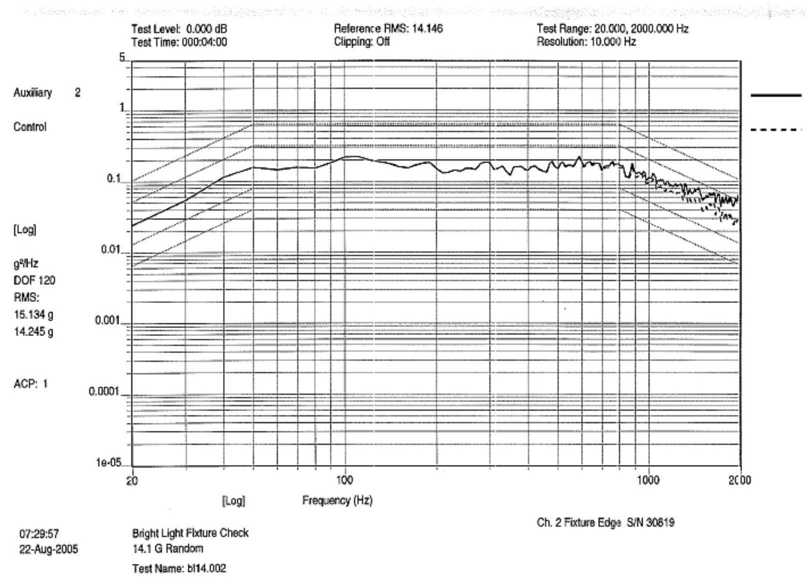
*3 minutes per axis, tested in x,y, and z.



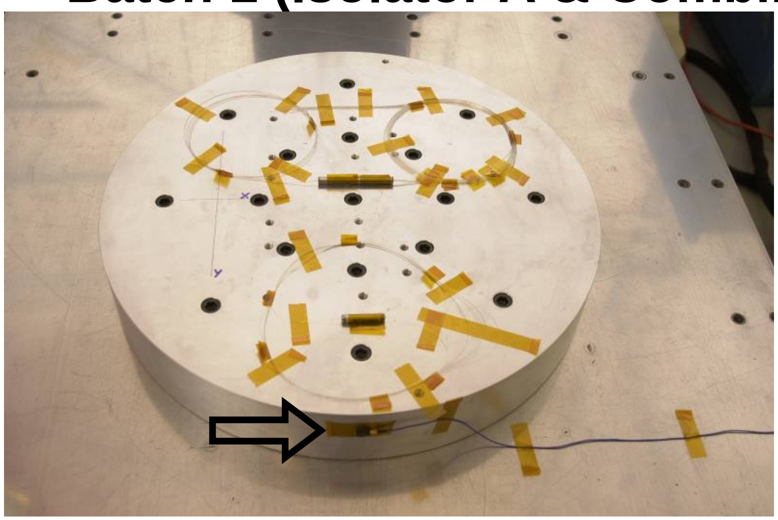
Typical Vibration Testing

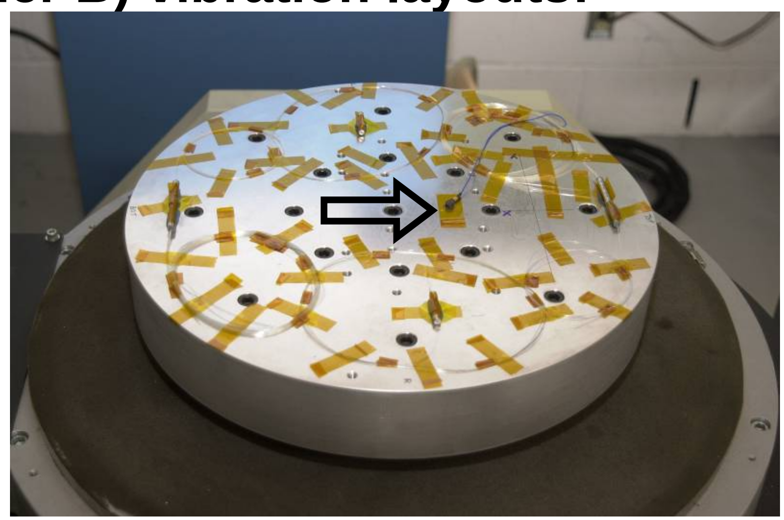
- **Mounting fixture PSDs:**





- **Batch 1 (Isolator A & Combiner B) vibration layouts:**





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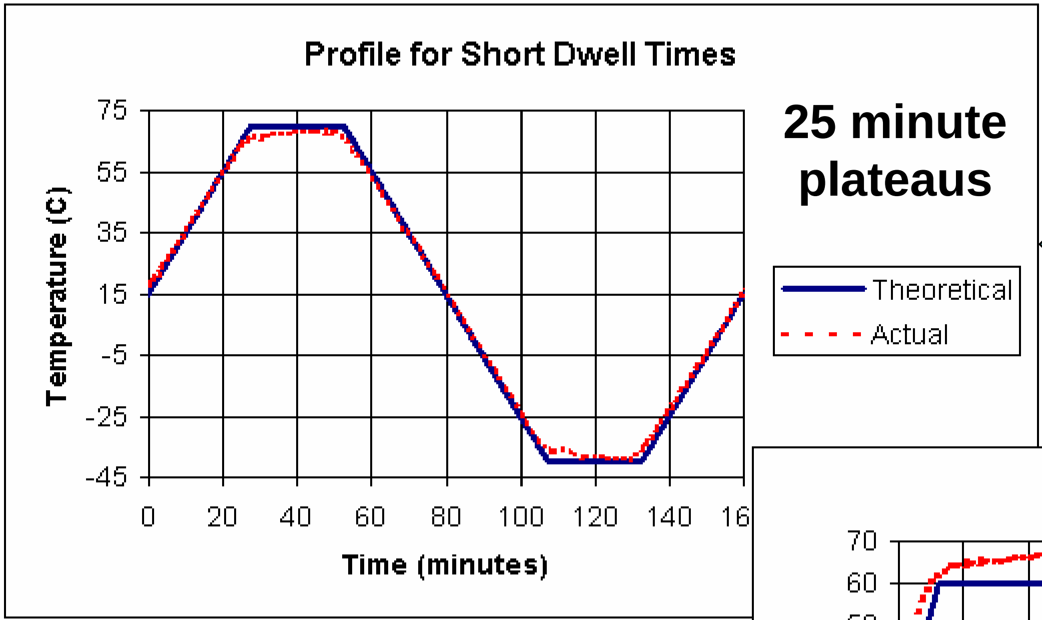
Environmental Test Facilities - Thermal

- **Aerospace Engineering Facility on Kirtland AFB, NM**

Thermal Testing Conditions

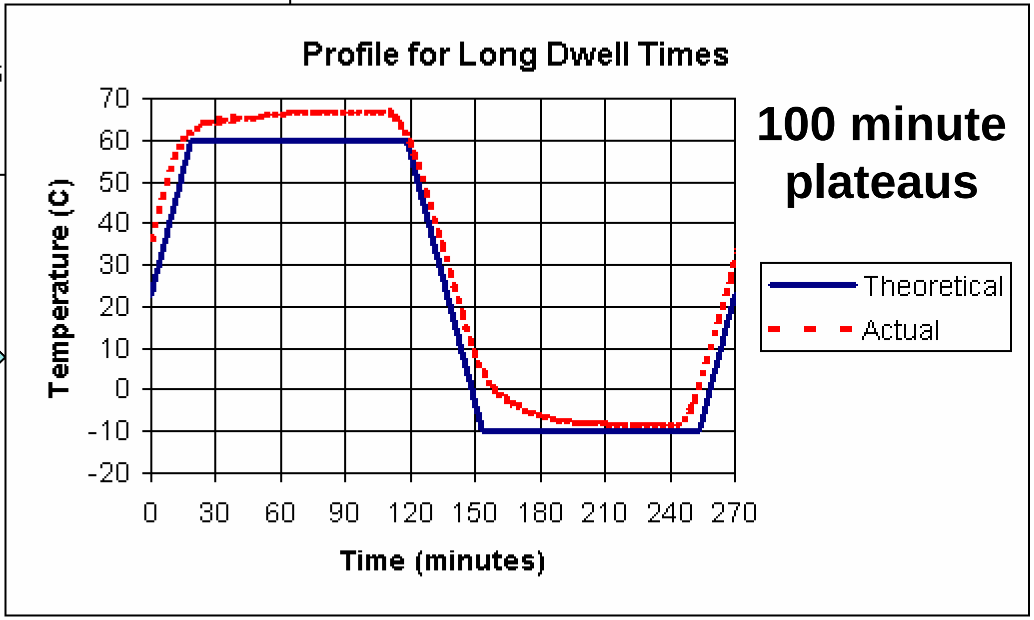
- Most components were continuously monitored and data recorded during tests
  - Exception is Fibers E and Isolators B
- Temperature range
  - -40 °C to +70 °C for Batches 1 through 4, and 6
  - -10 °C to +60 °C for Batch 5 (Laser Diodes)
- Ramp rate was 2°C per minute
- Dwell (plateau) time is based on mass of component to allow article to reach thermal equilibrium
- Test duration was approximately 11 days
  - Approximately 8 days for Batch 5
- Interrupted (paused) thermal cycles to insert more components
  - Batches 1, 2 & 4
  - Enabled schedule compression (make up time)

Thermal Testing Parameters



Batches 1, 2, 3, 4
100 cycles

Batch 5 (LDs)
40 cycles



Batch 6 (Isolator B) underwent 50 cycles from -40 to +70°C with 100 min plateaus.

Vibration and Thermal Testing Results Overview

Component	Description	Item #	Degradation (D) or Failure (F) Observed		
			Vibration	Thermal	Handling
Fiber A	PM SMF 5/125/250µm	1			
		2	N/A		
		3			D
Fiber B	30/250µm DCF with FC/PC connectors	1			
		2	N/A	F	
		3			
Fiber C	30/250/400µm large mode area fiber	1			
		2	N/A		
		3			
Fiber D	45/49/250µm fiber under development	1			
		2	N/A		
		3			
Fiber E	40/170/650µm high NA fiber, with ends sealed	1			
		2	N/A	N/A	
		3			
Isolator A	1064nm, PM, single stage, pigtailed	1			
		2			
		3			
Isolator B	Bulk unit	1	N/A	D	
		2	F	N/A	

Component	Description	Item #	Degradation (D) or Failure (F) Observed		
			Vibration	Thermal	Handling
Combiner A	6+1 : 1 SMF core fiber MMF port fibers	1			
		2	D	F	
		3			
Combiner B	16 : 1 MMF input fibers DCF output fibers	1	D	D	
		2			
		3			
FBG A	Custom, ASE Filter, 1064 nm, Athermal Package	1			D
		2			
		3			
FBG B	ASE Filter, 1062 nm, Demonstrator	1			
		2			
		3			
Laser Diode A	Pump, Pigtailed, multimode, no TEC, high power	1			
		2			
		3			D
Laser Diode B	Seed Source, DBR with TEC, pigtailed, low power	1			
		2			
		3		D	
Laser Diode C	PCM, integrated using 7:1 combiner & 6 LDs, with TEC	1		D	
		2	D	D	
		3		D	

Vibration and Thermal Testing Summary

- Vibration Component Failures or Degradations:
  - Combiner A #2 saw 2.2 dB degradation
  - Combiner B #1 saw 1.4 dB degradation
  - Laser Diode C (PCM) #2 saw 8% degradation in max output power
  - Isolator B physically shook apart
- Thermal Component Failures or Degradations:
  - Fiber B #2 had immediate damage when fiber snapped at start of cycle, possibly due to air flow in chamber
  - Combiner A #2 failed after one cycle
  - Combiner B #1 degraded by 1.5 dB after 80 cycles
  - Laser Diode B (seed) #3 showed ~25% degradation
  - Laser Diodes C (PCM) showed ~10% degradation
  - Isolator B (Bulk) isolation degraded by ~20%
- Handling Degradations:
  - Fiber A #3 was degraded by 0.6 dB when inserted into its vinyl bag
  - FBG A #3 fiber pigtails broke easily, but recovered when re-spliced
  - LD A (pump) #3 slope efficiency decreased by ~10% when unsoldered from thermal setup

Environmental Test Facilities - Radiation

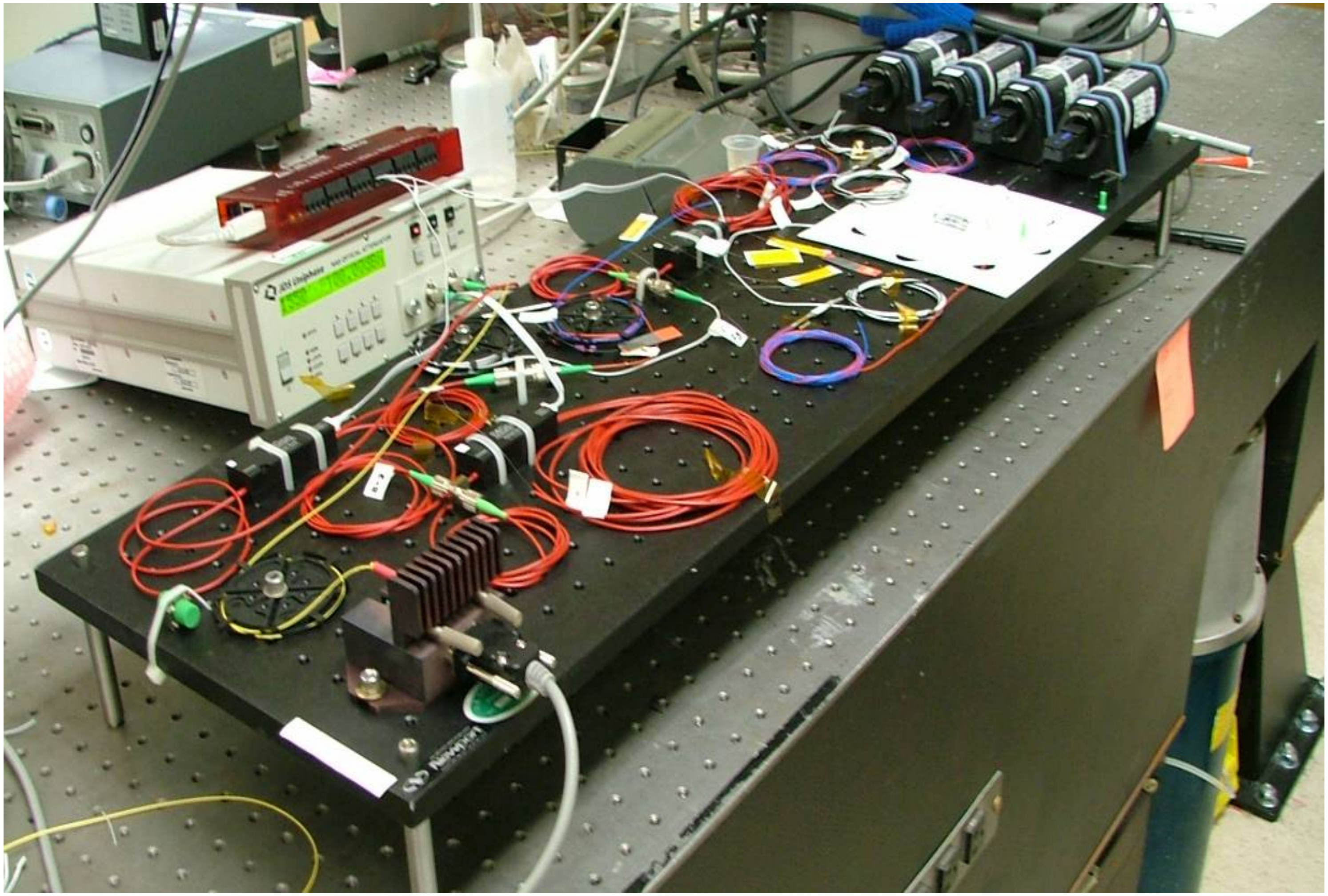
- **Aerospace Corporation, El Segundo, CA**
- **Cobalt-60 source**
- **Chamber dimensions ~10.5” x 10.5” x 42”**

Radiation Testing Overview

- Gamma-ray testing of components for current effort
  - Devices include
    - Ytterbium fibers
    - Isolators
    - Fiber-Bragg gratings
    - Combiners
  - Laser diode seed and pump are susceptible to displacement damage, radiation testing not planned
  - Total dose planned
    - 100 kRad (“high” rate) for most components
    - 10 kRad (“low” rate) for Ytterbium fibers

Component	Dose (kRad)
Fibers A	10 & 100
Fibers B	10 & 100
Fibers C	10 & 100
Fibers D	10 & 100
FBGs A	100
FBGs B	100
Isolators A	100
Combiners A	100
Combiners B	100

Radiation Testing Setup



Radiation Testing Results Overview

Component	Item Number	Degradation (D) or Failure (F) Observed — Radiation
Fiber A	1	100kRad, dark (D)
	2	100kRad, pumped (D)
	3	10kRad, dark (D)
Fiber B	1	100kRad, dark (D)
	2	100kRad, pumped (D)
	3	10kRad, dark (D)
Fiber C	1	100kRad, dark (D)
	2	100kRad, pumped (D)
	3	10kRad, dark (D)
Fiber D	1	100kRad, dark (D)
	2	100kRad, pumped (D)
	3	10kRad, dark (D)
Fiber E	1	
	2	
	3	
Isolator A	1	100kRad
	2	100kRad
	3	100kRad
Isolator B	1	Units arrived late and were not subjected to radiation testing
	2	

Component	Item Number	Degradation (D) or Failure (F) Observed — Radiation
Combiner A	1	100kRad
	2	100kRad
	3	
Combiner B	1	100kRad
	2	100kRad
	3	100kRad
Fiber Bragg Grating A	1	100kRad
	2	100kRad
	3	100kRad
Fiber Bragg Grating B	1	100kRad
	2	100kRad
	3	100kRad
Laser Diode A	1	These units were not subjected to Gamma Radiation testing as their failure modes would not be seen. The decision was made early on that for the purposes of this activity the cost to perform particle radiation testing was prohibitive.
	2	
	3	
Laser Diode B	1	
	2	
	3	
Laser Diode C	1	
	2	
	3	

Green: No degradation or failure observed
Yellow: Limited degradation or failure observed
Red: Unacceptable degradation or failure observed

Radiation Testing Summary

- Passive components like the isolators, FBGs, and combiners show only insignificant radiation sensitivity
  - < 0.1 dB change over 100 kRad
- Active fiber will fail within 100 kRad if not pumped
- Laser diode seed and pump are susceptible to displacement damage, so no gamma radiation testing performed on these components

Lessons Learned

- The lessons learned can be categorized:
  - Fiber Handling
  - Test Equipment
  - Component Testing
  - Data Acquisition
  - Safety Issues

☆ The lessons learned will aid in future assessments and definition of space qualification protocols, and provide recommendations for areas of improvement

Test Protocol was Updated as a Result of This Effort

- Performed testing to improve the fidelity of the draft test protocol
  - Documents appropriate tests that are performed at the part, component, and subsystem level to increase probability of success on orbit
- The Lessons Learned are being incorporated into the protocol
- Revising the protocol to have more of a bottoms up view, including a utilitarian approach
  - Attach the actual test procedures that we ran
- Improvements to the protocol document also include discussions on
  - COTS Vendor interaction and involvement
    - Engineering issues
    - Survivability and reliability
  - Materials analysis at process start
  - Expanded fiber splicing section
    - Handling and issues

Component Testing Summary/Conclusions

- **Primary objective of this effort was to test the protocol and its procedures for space qualification of COTS fiber laser components**
- **Data results presented here do not reflect on the vendors or their abilities to produce products for space applications**
- **Subjective judgment for space qualification of components is summarized here:**

Key:

Acceptable Results
Caution, more data needed
Unacceptable Results
TBD

Component	Space Qualification			
	DPA	Vibration	Thermal	Radiation
Fiber A	Acceptable	Acceptable	Acceptable	Unacceptable
Fiber B	Acceptable	Acceptable	Unacceptable	Unacceptable
Fiber C	Acceptable	Acceptable	Acceptable	Caution
Fiber D	Acceptable	Acceptable	Acceptable	Unacceptable
Fiber E	Acceptable	Acceptable	Acceptable	TBD
Isolator A	Caution	Acceptable	Acceptable	Acceptable
Isolator B	Unacceptable	Unacceptable	Caution	TBD
Combiner A	TBD	Caution	Unacceptable	Acceptable
Combiner B	TBD	Caution	Caution	Acceptable
FBG A	Acceptable	Acceptable	Acceptable	Acceptable
FBG B	Caution	Acceptable	Acceptable	Acceptable
Laser Diode A	Acceptable	Acceptable	Acceptable	TBD
Laser Diode B	Caution	Acceptable	Caution	TBD
Laser Diode C	Caution	Caution	Caution	TBD

Acknowledgements

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  - **Colonel Norman Anderson**

Detailed final report will be submitted to DTIC 30 June 2006
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