Long-Term Aging Performance of Fluoropolymer Heat-Shrink Films Used on UVC Lamps

Chris Rockett

Production/Applications Engineer

Light Sources Inc.

IUVA Americas Conference – Orlando, Florida – 10 Mar 2020

Project Motivation & Summary

- Many OEMs and end-users of low-pressure UVC lamps seek a way to protect lamps to mitigate the risk of glass shards in the event of lamp breakage, for example:
    - Food & beverage processing and packaging
    - Pharmaceutical manufacture
    - Healthcare
    - …or anywhere lamps may be handled or used around moving parts
- The challenge is that any material used for this purpose must be transparent in the UVC spectral range, which leaves very few options. Fortunately, we have fluoropolymers (often known by the genericized trademark Teflon) that meet several important criteria for this application.
- Due to the remarkable properties of the carbon-fluorine bond, fluoropolymers achieve outstanding engineering properties such as high melting & decomposition temperatures, high toughness, low friction coefficients, resistance to UV degradation, and UVC-transparency through thin sections.
- Light Sources Inc. & LightTech, among other lamp manufacturers, offer shatter-protective encapsulation of low-pressure UVC lamps

Project Motivation & Summary

- Fluoropolymer (FP) heat-shrink tubing, typically made of FEP* or PFA** is applied directly on low-pressure mercury & amalgam lamps where it is exposed to intense UVC radiation for thousands of hours

- The initial 254 nm transmission of these films (0.25-0.28 mm thickness) is known to be around 85-90% from manufacturer data or calculated by comparing radiometry of the same lamp with and without the film. But no manufacturer of FP films provides transmission data after long-term exposure to UVC and heat. The hypothesis is that they surely must degrade under these conditions.

- The objective of this project was therefore to characterize the long-term change in transmission for various FP heat-shrink films when applied on lamps of different power levels and operated for up to 8000 hours

* Fluorinated ethylene propylene
** Perfluoroalkoxy alkane

Experimental Matrix

Lamp Type / Material & Supplier	400 mA T5 (15 mm OD) lamp	800 mA T5 (15 mm OD) lamp	2.0 A T6 (19 mm OD) lamp
Manufacturer "A" T5 FEP **Thickness as-received = 0.22 mm** **Shrunk thickness = 0.26 mm**	0, 500, 1000, 2000, 4000, 6000, 8000 hrs Specimens L61-72	0, 500, 1000, 2000, 4000, 6000, 8000 hrs Specimens H37-48	
Manufacturer "C" T5 FEP **Thickness as-received = 0.42 mm** **Shrunk thickness = 0.49 mm**	0, 500, 1000, 2000, 4000, 6000, 8000 hrs Specimens L73-84	0, 500, 1000, 2000, 4000, 6000, 8000 hrs Specimens H49-60	
Manufacturer "A" T6 FEP **Thickness as-received = 0.225** **Shrunk thickness = 0.26 mm**			0, 500, 1000, 2000, 4000, 6000, 8000 hrs Specimens A1-12
Manufacturer "B" T6 FEP **Thickness as-received = 0.22 mm** **Shrunk thickness = 0.27 mm**			0, 500, 1000, 2000, 4000, 6000, 8000 hrs Specimens A13-24
Manufacturer "B" T6 PFA **Thickness as-received = 0.22 mm** **Shrunk thickness = 0.28 mm**			0, 500, 1000, 2000, 4000, 6000, 8000 hrs Specimens A25-36

Experimental Matrix

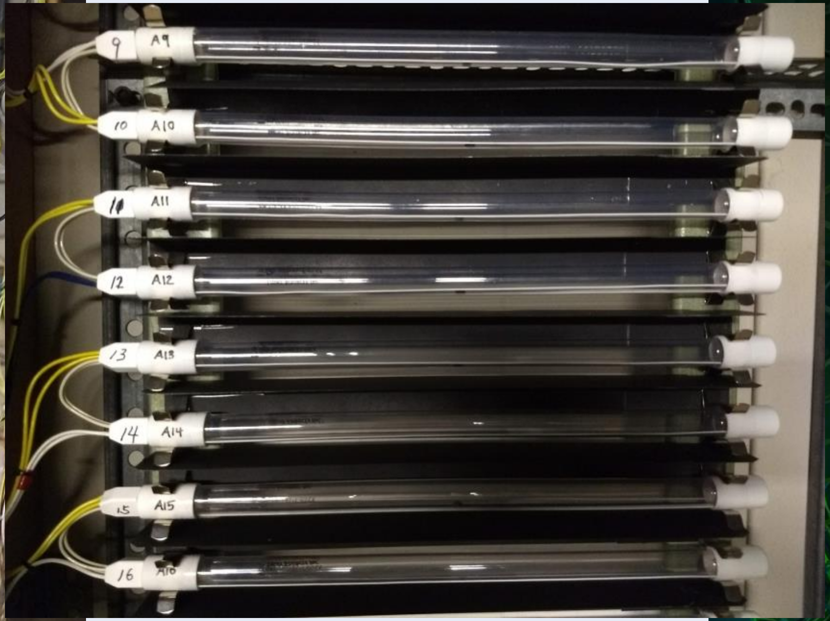
Lamp Physical & Electrical Data								
	Lamp Current (nominal)	Lamp Voltage	Lamp Power	Body Diameter	Overall length	Arc length	Power Density	Wall Loading
Description	**mA**	**V**	**W**	**mm**	**mm**	**mm**	**W/cm**	**W/cm^2**
GPH436T5L/4	400	48	19	15	436	347	0.55	0.116
GPH436T5L/HO/4	800	46	36	15	436	308	1.17	0.248
GPHHA436T6L/4	2000	40	88	19	436	368	2.39	0.401

- The 436 mm length was chosen as the best compromise between fitting in available aging cabinet space, energy efficiency, and ensuring that a good portion of the film was experiencing the full UVC output of the lamp (i.e. not dominated by end-effects near the electrodes)

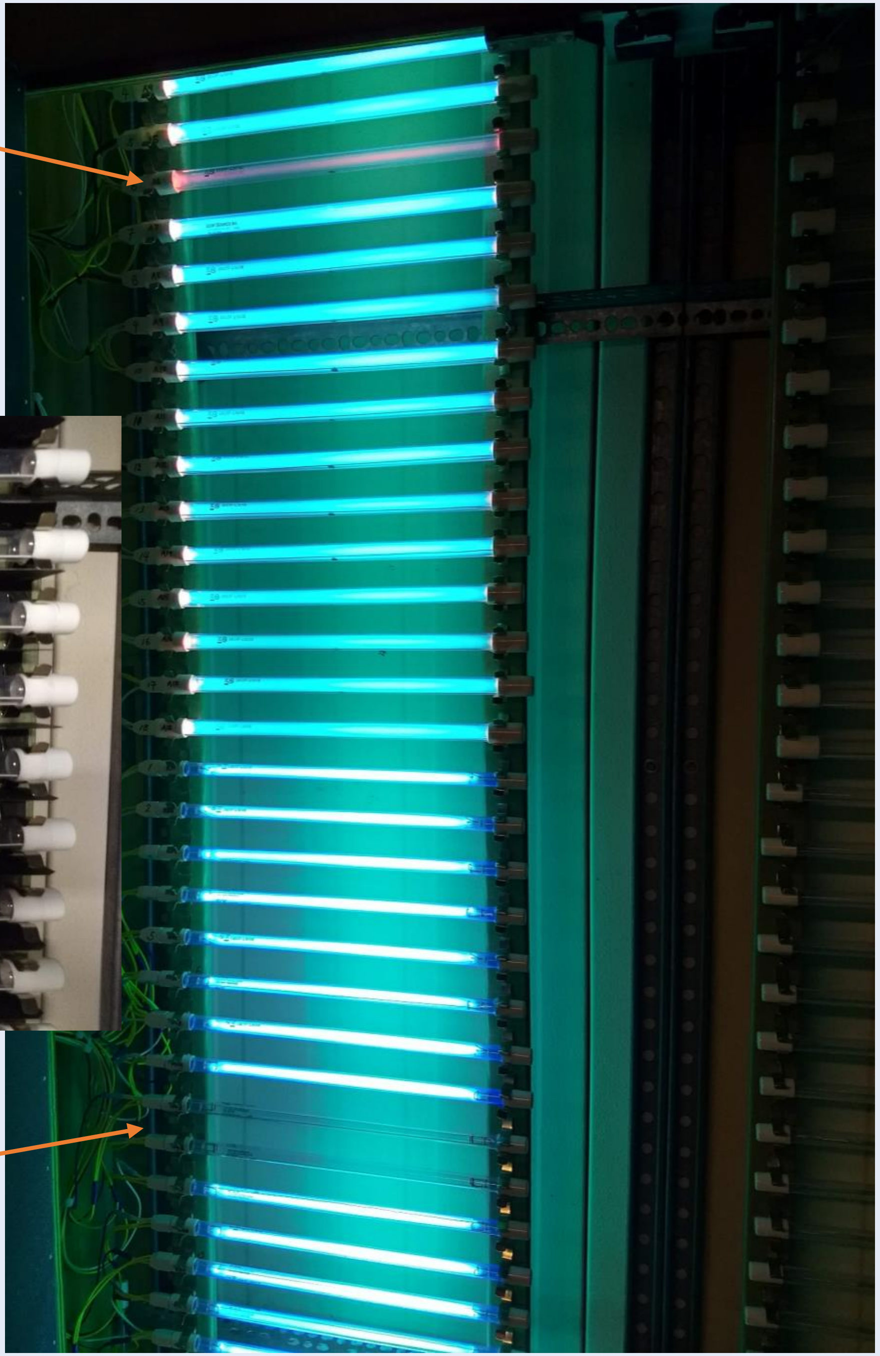
Experimental Procedure

1. Sample lamps 436 mm length at three different power levels prepared (standard-output, high-output, and amalgam), and five FP materials selected
2. Radiometry (peak irradiance) measured initially at 0 hrs on bare lamps and then again after the FP heat-shrink sleeves were applied
3. Lamps operated in a ventilated aging cabinet using shielding between each to avoid additional UVC exposure from their adjacent neighbors
4. Lamps removed from the cabinet at selected time intervals and peak irradiance again measured with and without the FP sleeves
5. Sample squares cut from each FP sleeve after aging and spectral transmission measured with a custom spectroradiometry setup
6. These two sets of transmission measurements – indirect & direct – are used to characterize the films' aging behavior

This lamp was replaced before aging commenced



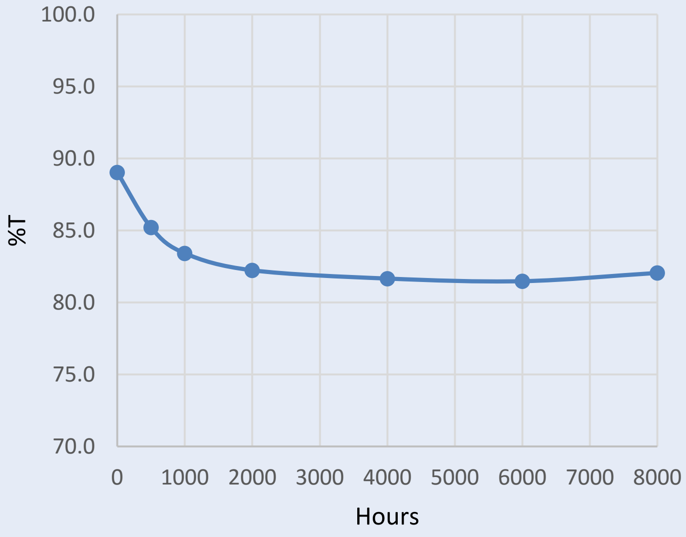
Ballast wiring problem - later fixed



Results – Calculated 254 nm film transmission from lamp radiometry

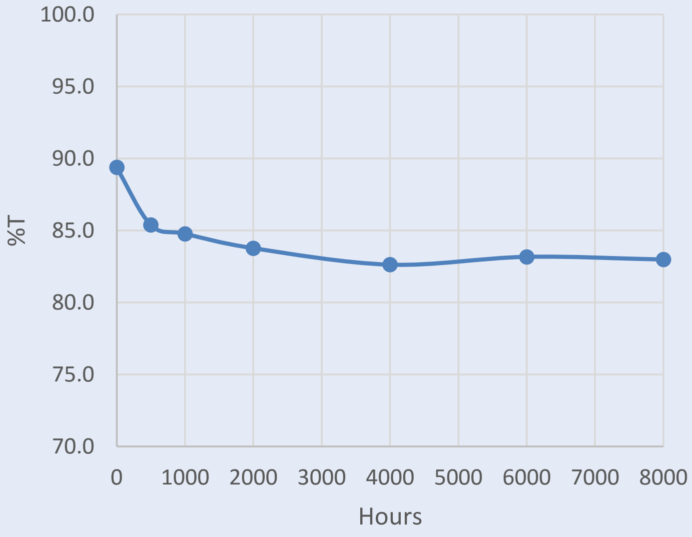
Mfr. "A" T6-FEP on 2.1 A amalgam lamps

Hours	Bare Lamps Avg. Irrad. [W/cm²]	Jacketed lamps Avg. Irrad. [W/cm²]	Film Transmission %
0	2.55E-04	2.27E-04	89.0
500	2.33E-04	1.99E-04	85.2
1000	2.38E-04	1.99E-04	83.4
2000	2.25E-04	1.85E-04	82.2
4000	2.13E-04	1.74E-04	81.6
6000	2.32E-04	1.89E-04	81.5
8000	2.26E-04	1.85E-04	82.0



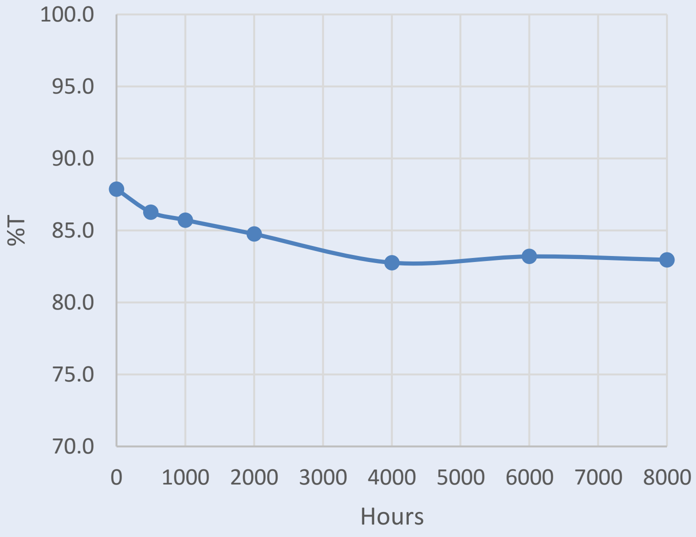
Mfr. "B" T6-FEP on 2.1 A amalgam lamps

Hours	Bare Lamps Avg. Irrad. [W/cm²]	Jacketed lamps Avg. Irrad. [W/cm²]	Film Transmission %
0	2.57E-04	2.30E-04	89.4
500	2.36E-04	2.02E-04	85.4
1000	2.40E-04	2.03E-04	84.8
2000	2.37E-04	1.99E-04	83.8
4000	2.19E-04	1.81E-04	82.6
6000	2.32E-04	1.93E-04	83.2
8000	2.29E-04	1.90E-04	83.0



Mfr. "B" T6-PFA on 2.1 A amalgam lamps

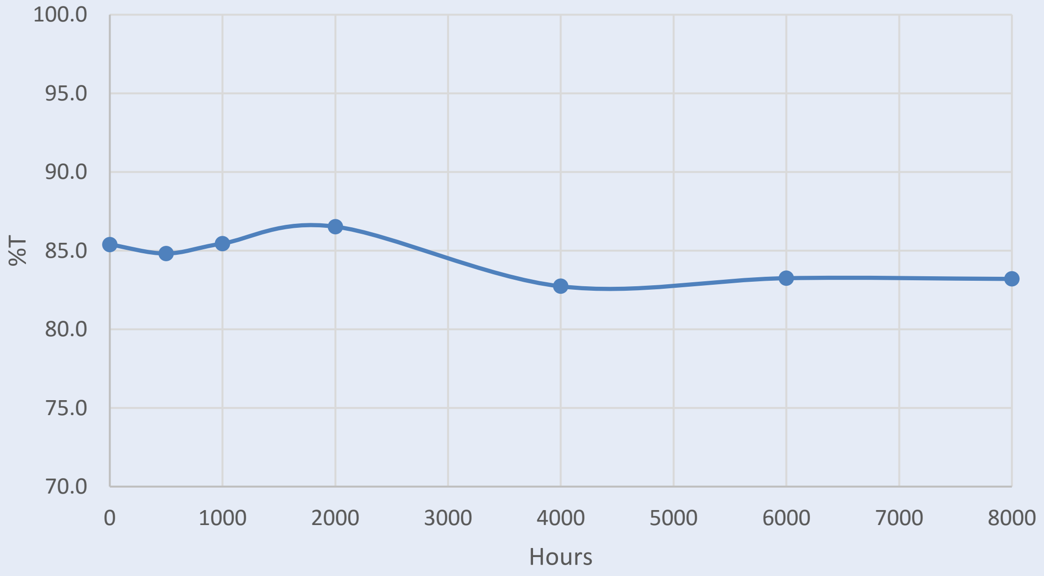
Hours	Bare Lamps Avg. Irrad. [W/cm²]	Jacketed lamps Avg. Irrad. [W/cm²]	Film Transmission %
0	2.53E-04	2.23E-04	87.9
500	2.33E-04	2.01E-04	86.3
1000	2.31E-04	1.98E-04	85.7
2000	2.36E-04	2.00E-04	84.7
4000	2.18E-04	1.80E-04	82.8
6000	2.29E-04	1.91E-04	83.2
8000	2.20E-04	1.83E-04	83.0



Results – Calculated 254 nm film transmission from lamp radiometry

Mfr. "A" T5-FEP on 800 mA lamps

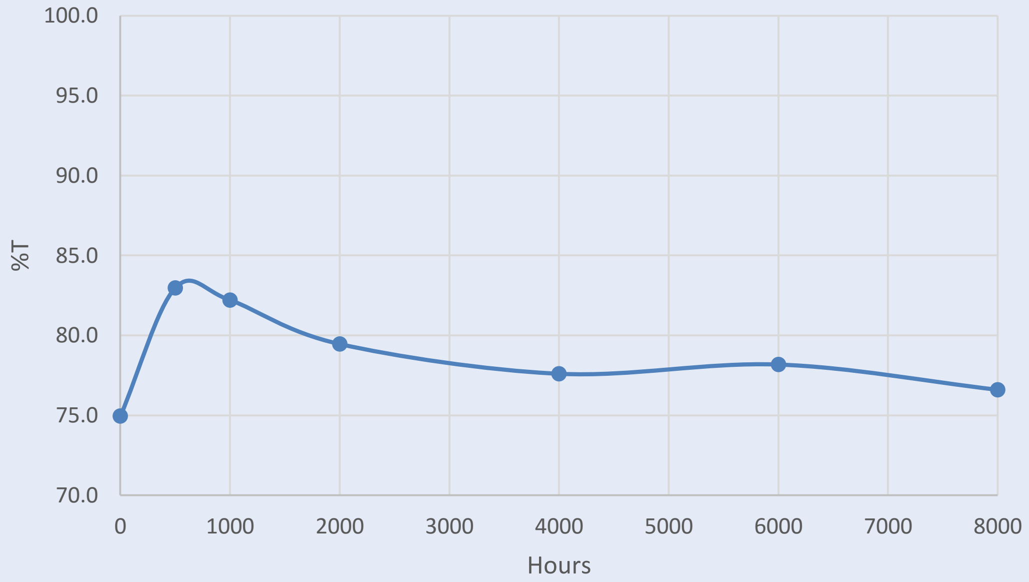
Hours	Bare Lamps Avg. Irrad.	Jacketed lamps Avg. Irrad.	Film Transmission
	[W/cm²]	*[W/cm²]*	%
0	1.15E-04	9.79E-05	85.4
500	1.12E-04	9.50E-05	84.8
1000	1.06E-04	9.02E-05	85.5
2000	1.04E-04	8.96E-05	86.5
4000	9.91E-05	8.20E-05	82.7
6000	1.03E-04	8.58E-05	83.3
8000	1.05E-04	8.70E-05	83.2



Mfr. "C" T5-FEP on 800 mA lamps

Hours	Bare Lamps Avg. Irrad.	Jacketed lamps Avg. Irrad.	Film Transmission
	[W/cm²]	*[W/cm²]*	%
0	1.12E-04	8.38E-05	74.9
500	1.03E-04	8.55E-05	83.0
1000	1.00E-04	8.25E-05	82.2
2000	1.02E-04	8.11E-05	79.5
4000	9.51E-05	7.38E-05	77.6
6000	9.95E-05	7.78E-05	78.2
8000	9.83E-05	7.53E-05	76.6

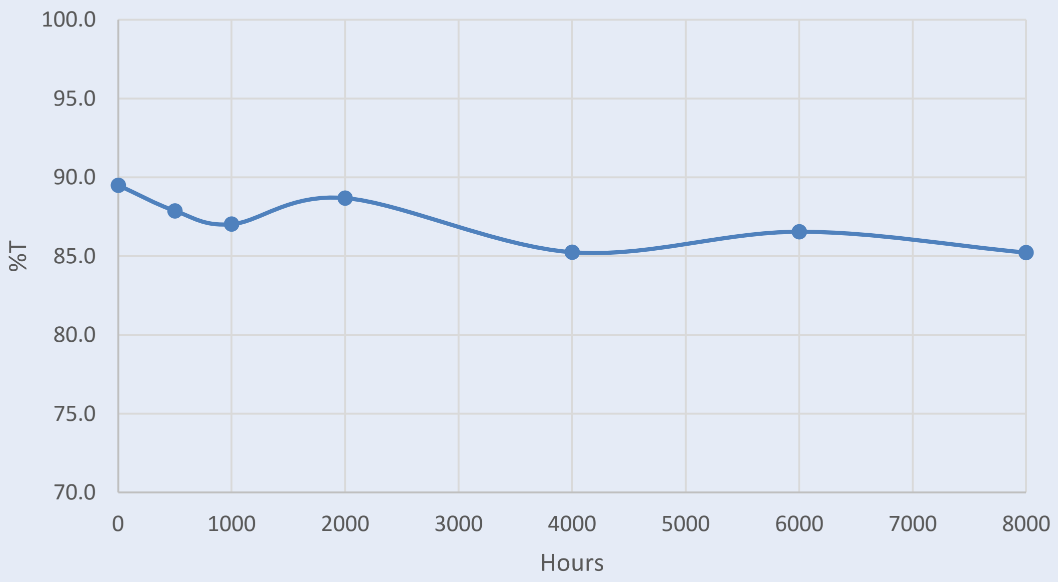
Note: Mfr. C's film is 0.49 mm thick versus 0.26 mm for others



Results – Calculated 254 nm film transmission from lamp radiometry

Mfr. "A" T5-FEP on 400 mA lamps

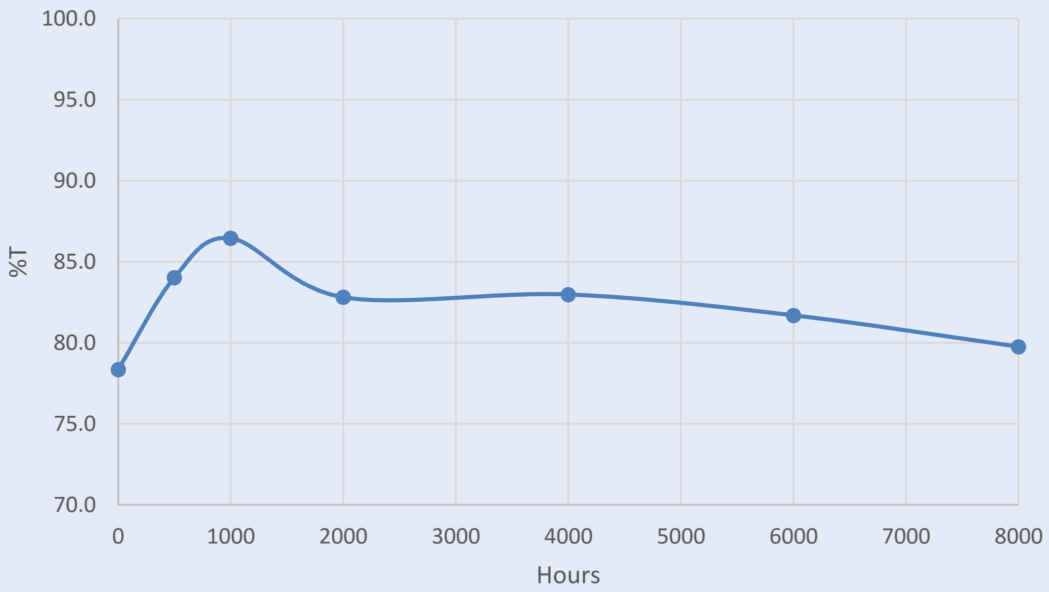
Hours	Bare Lamps Avg. Irrad. [W/cm²]	Jacketed lamps Avg. Irrad. [W/cm²]	Film Transmission %
0	8.64E-05	7.73E-05	89.5
500	7.96E-05	6.99E-05	87.9
1000	7.75E-05	6.74E-05	87.0
2000	7.64E-05	6.78E-05	88.7
4000	7.05E-05	6.01E-05	85.2
6000	7.47E-05	6.47E-05	86.5
8000	7.45E-05	6.35E-05	85.2

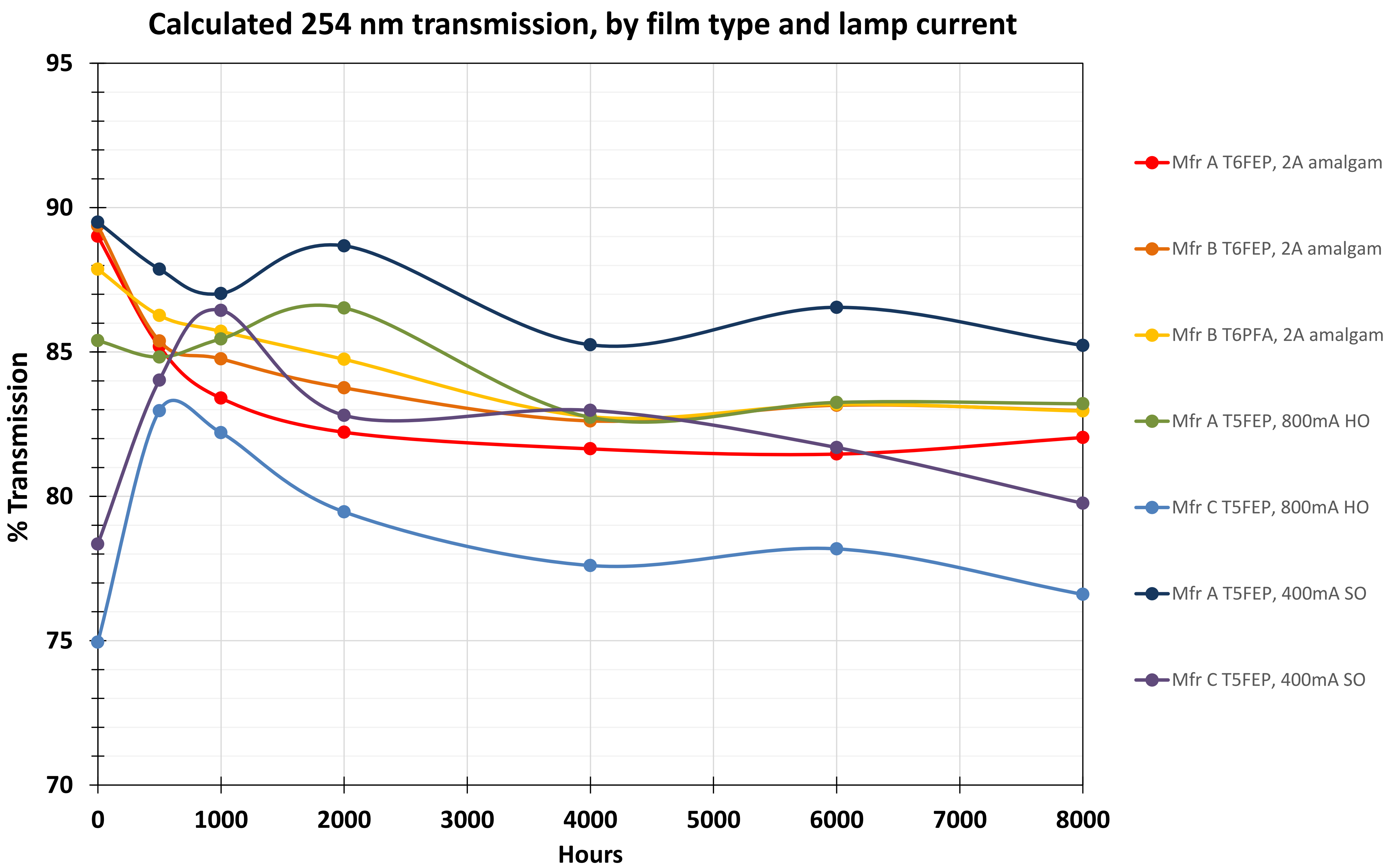


Mfr. "C" T5-FEP on 400 mA lamps

Hours	Bare Lamps Avg. Irrad. [W/cm²]	Jacketed lamps Avg. Irrad. [W/cm²]	Film Transmission %
0	8.50E-05	6.66E-05	78.3
500	7.51E-05	6.31E-05	84.0
1000	7.75E-05	6.70E-05	86.4
2000	6.95E-05	5.76E-05	82.8
4000	6.79E-05	5.63E-05	83.0
6000	6.80E-05	5.56E-05	81.7
8000	7.04E-05	5.62E-05	79.8

Note: Mfr. C's film is 0.49 mm thick versus 0.26 mm for others

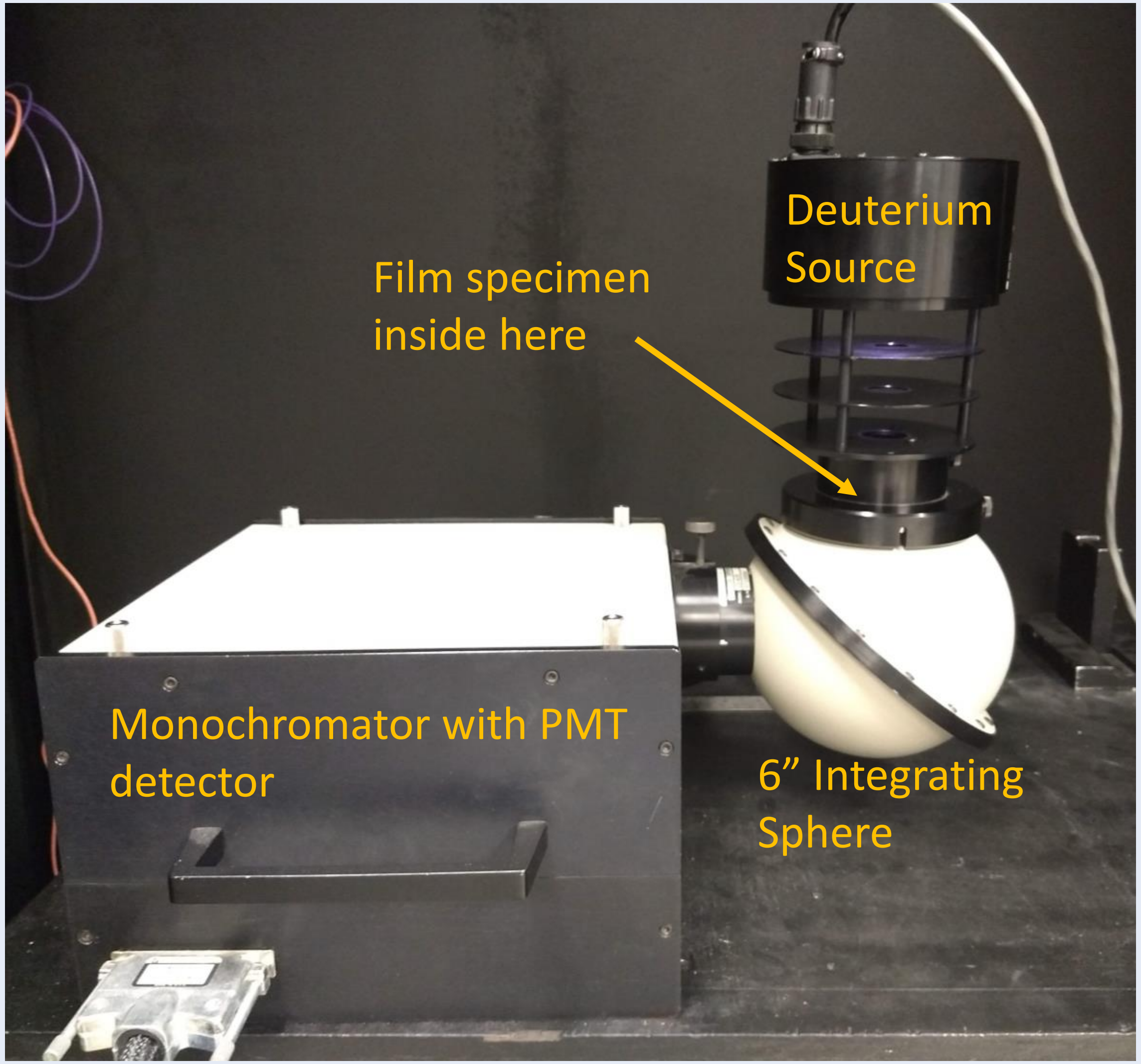


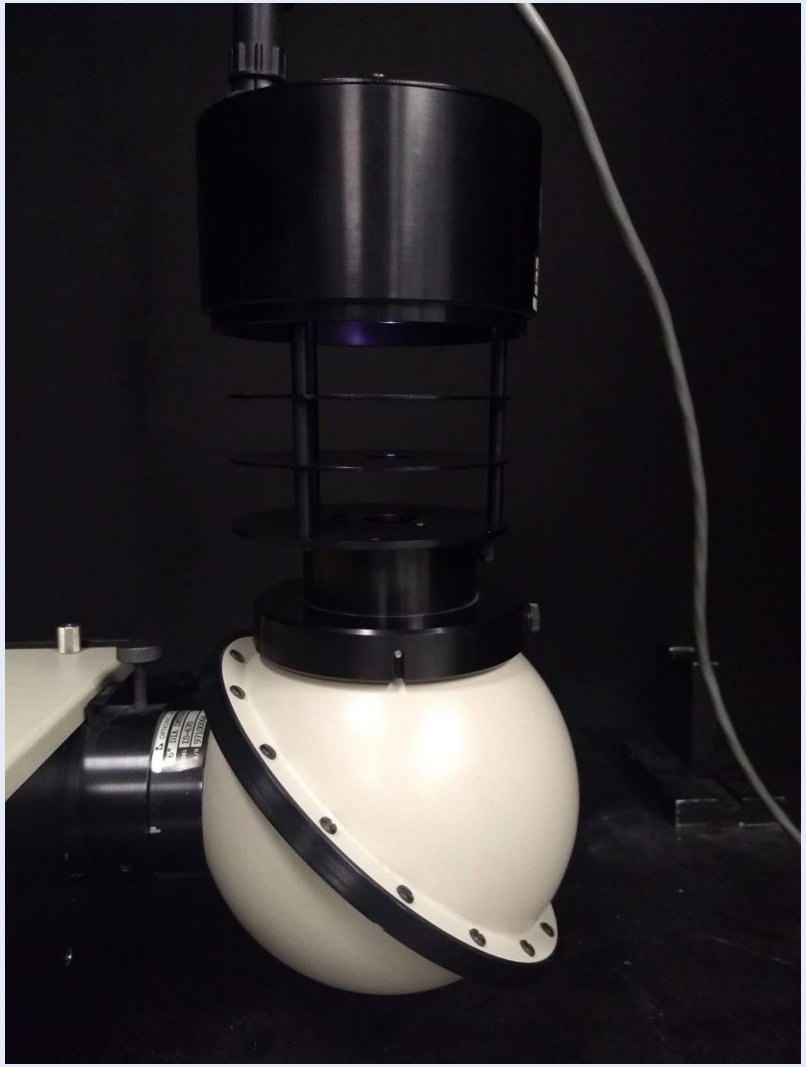


Calculated 254 nm transmission, by film type and lamp current
% Transmission
95
90
85
80
75
70
0
1000
2000
3000
4000
5000
6000
7000
8000
Hours
Mfr A T6FEP, 2A amalgam
Mfr B T6FEP, 2A amalgam
Mfr B T6PFA, 2A amalgam
Mfr A T5FEP, 800mA HO
Mfr C T5FEP, 800mA HO
Mfr A T5FEP, 400mA SO
Mfr C T5FEP, 400mA SO

Spectroradiometry Setup

- Optronics OL-754-O-PMT double-monochromator with photomultiplier tube detector
- Optronics IS-670 6-inch diameter integrating sphere with PTFE internal coating (200-2500 nm range)
- Optronics OL-752-12 deuterium lamp calibration source

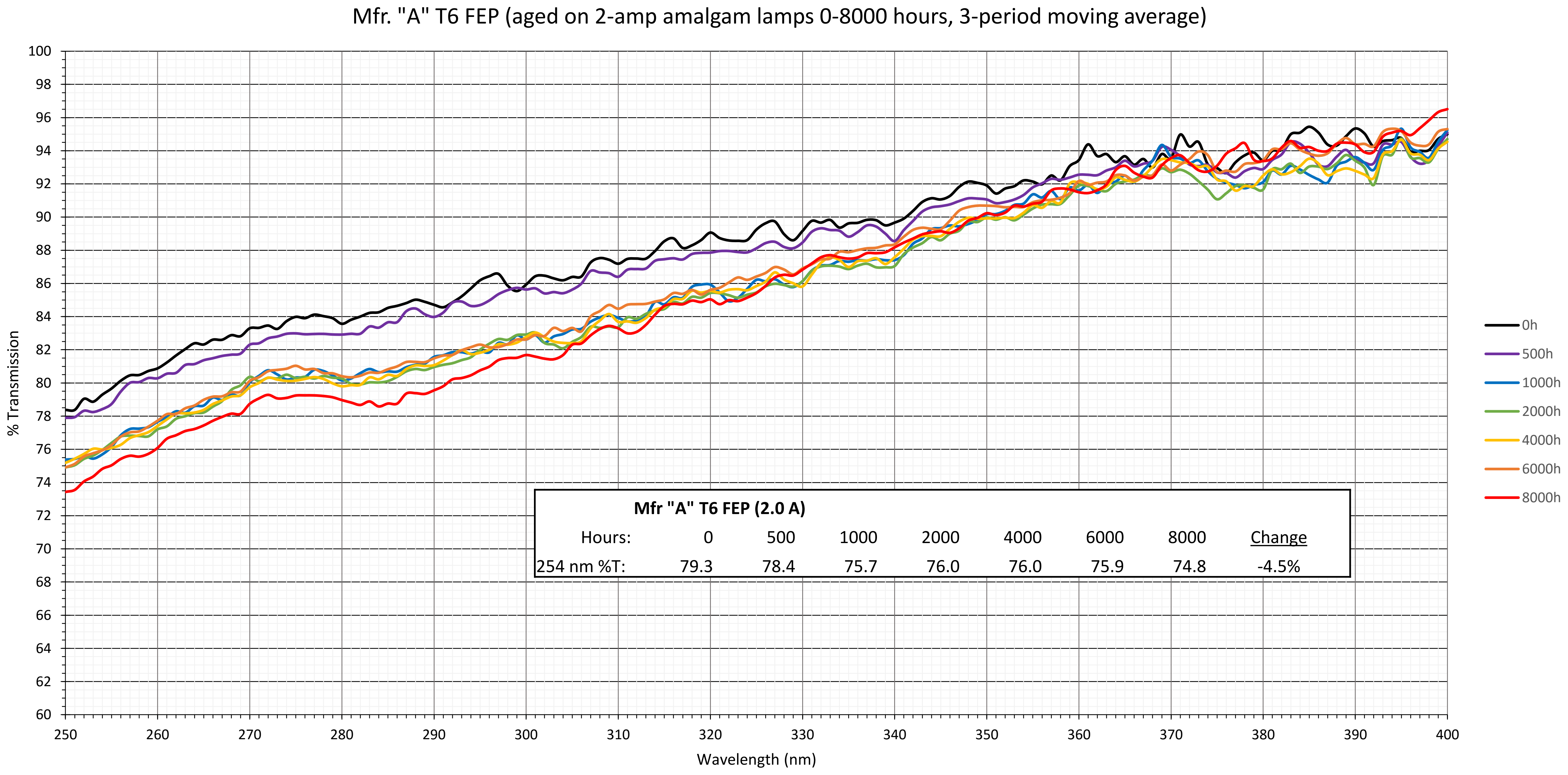




Spectroradiometry Procedure

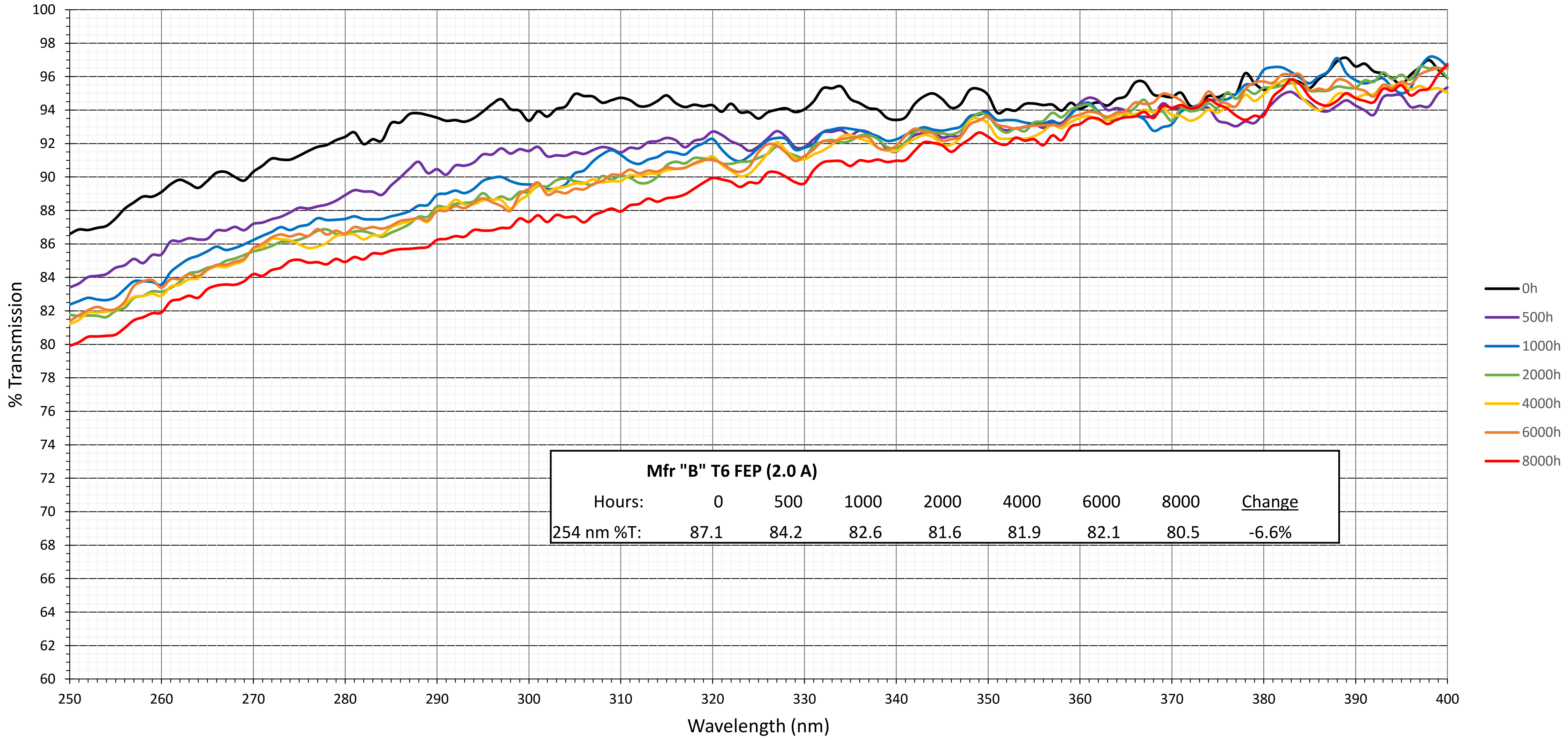
1. Turn on deuterium lamp and allow to warm up for at least 20 minutes before placing it into its adaptor collar atop the integrating sphere
2. Run blank baseline scan 200-400 nm with no test specimen
3. Cut film specimen (approximately 50 mm square) from middle of sample lamp and clean with alcohol
4. Lay film specimen flat, sandwiching it between the integrating sphere's adaptor collar and a custom-made "washer" plate, which holds the film just in front of the entrance port of the sphere
5. Run scan 200-400 nm with film specimen in place, then remove film specimen
6. Repeat above steps #3-5 for each film specimen in a series
7. After the last specimen of a series is measured, remove it and again run the blank baseline scan per step #2 above. It is recommended to run baseline scans every 10-12 specimen measurements.
8. To calculate spectral transmission, spectral irradiance for each specimen is divided into spectral irradiance of blank baseline scan that occurred nearest in time to the specimen measurement. Spectral irradiance curves are smoothed somewhat by using a three-period moving average.

Results – Spectral Transmission Measurements



Results – Spectral Transmission Measurements

Mfr "B" T6 FEP (3-period moving average), aged on 2-amp amalgam lamps 0-8000 hours

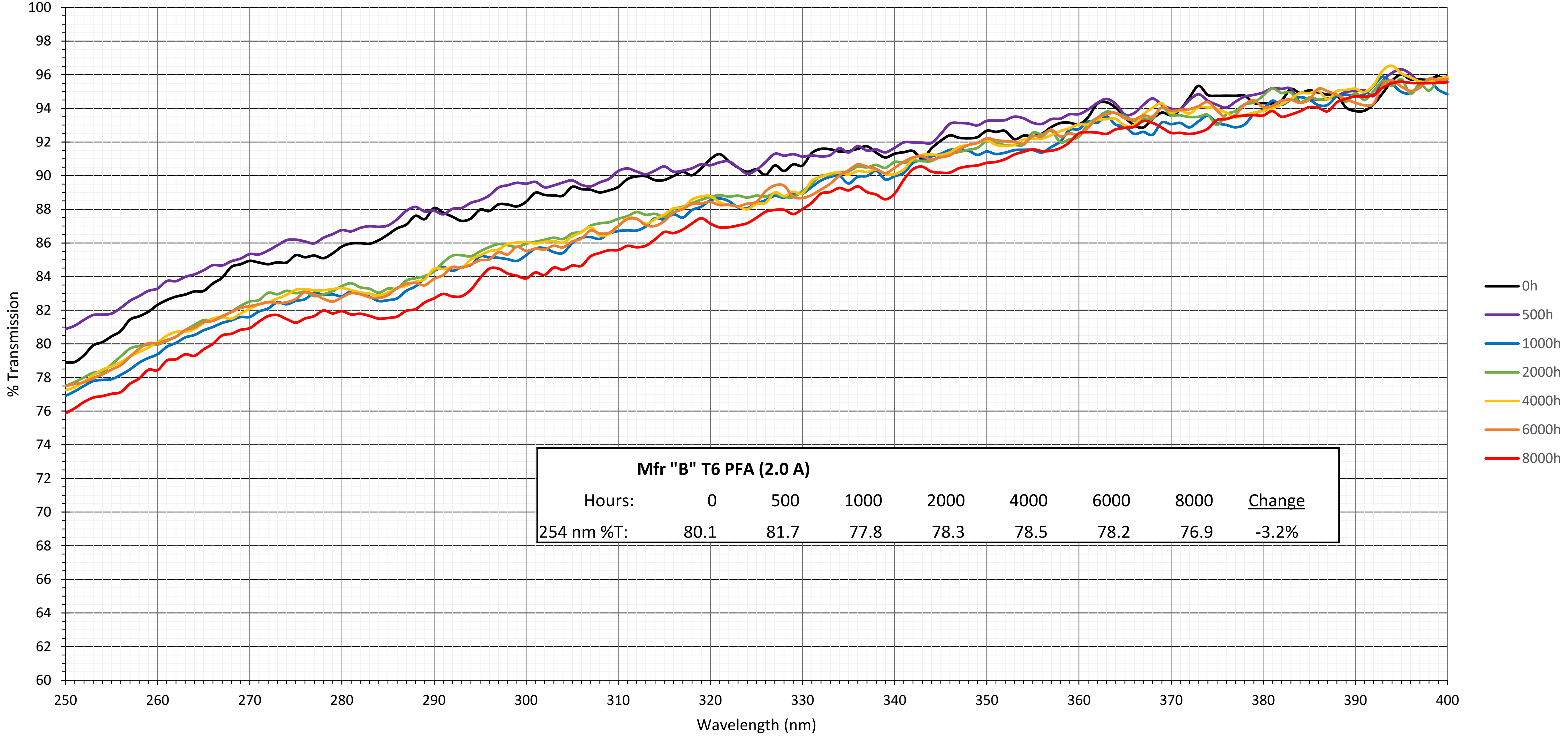


Mfr "B" T6 FEP (2.0 A)

Hours:	0	500	1000	2000	4000	6000	8000	Change
254 nm %T:	87.1	84.2	82.6	81.6	81.9	82.1	80.5	-6.6%

Results – Spectral Transmission Measurements

Mfr “B” T6 PFA (aged on 2-amp amalgam lamps 0-8000 hours, 3-period moving average)

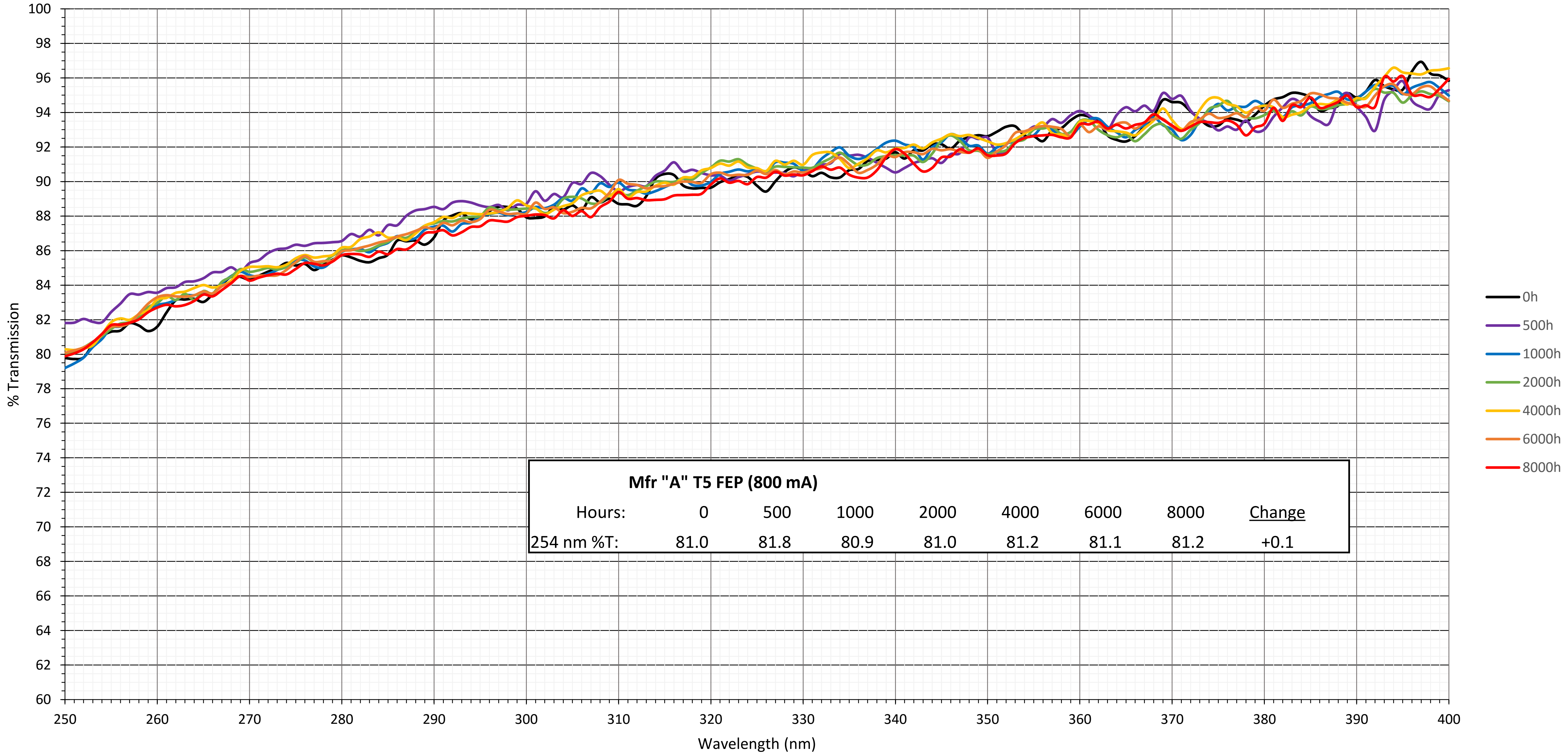


Mfr "B" T6 PFA (2.0 A)

Hours:	0	500	1000	2000	4000	6000	8000	<u>Change</u>
254 nm %T:	80.1	81.7	77.8	78.3	78.5	78.2	76.9	-3.2%

Results – Spectral Transmission Measurements

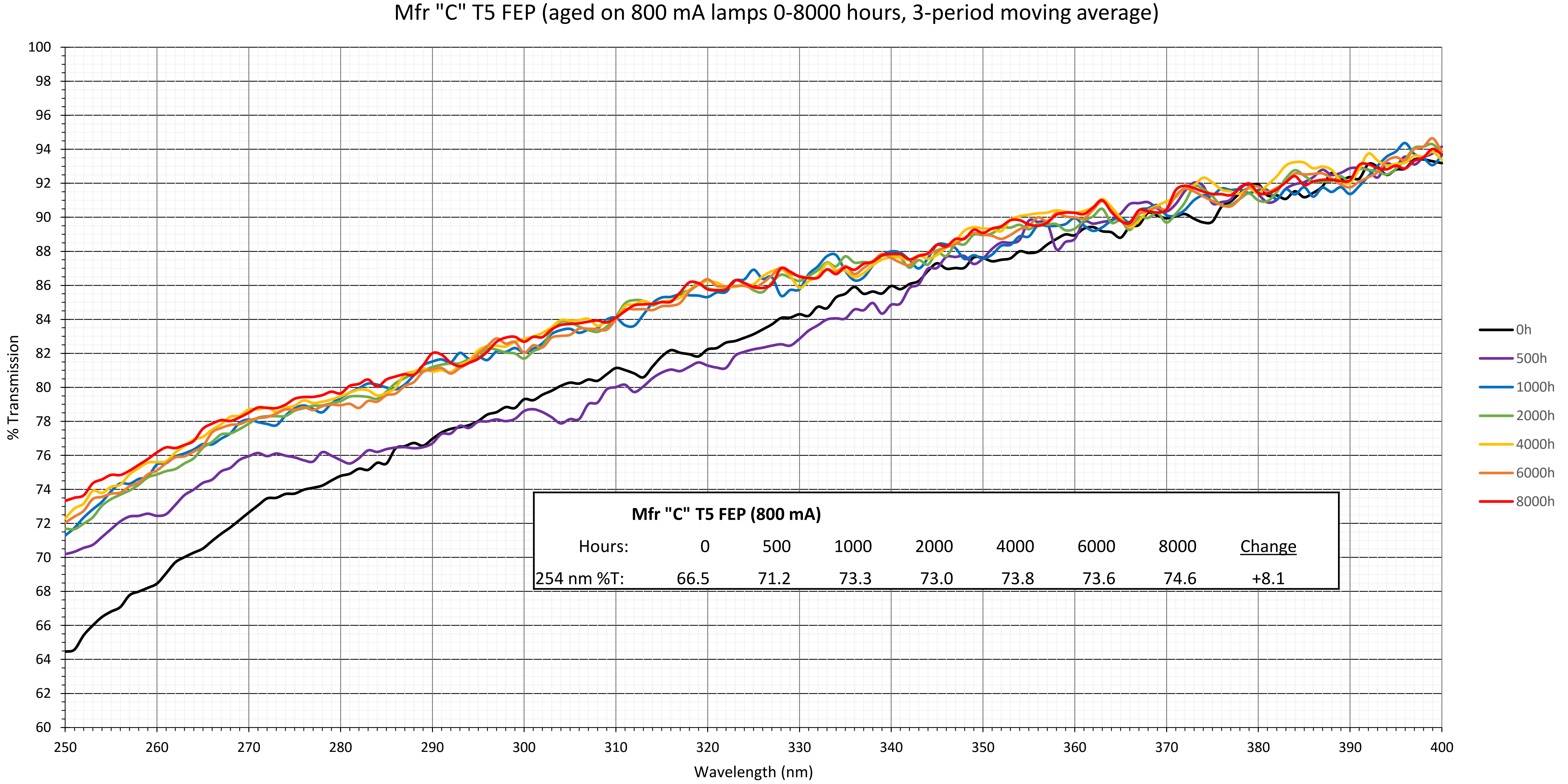
Mfr “A” T5 FEP (aged on 800 mA lamps 0-8000 hours, 3-period moving average)



Mfr "A" T5 FEP (800 mA)

Hours:	0	500	1000	2000	4000	6000	8000	Change
254 nm %T:	81.0	81.8	80.9	81.0	81.2	81.1	81.2	+0.1

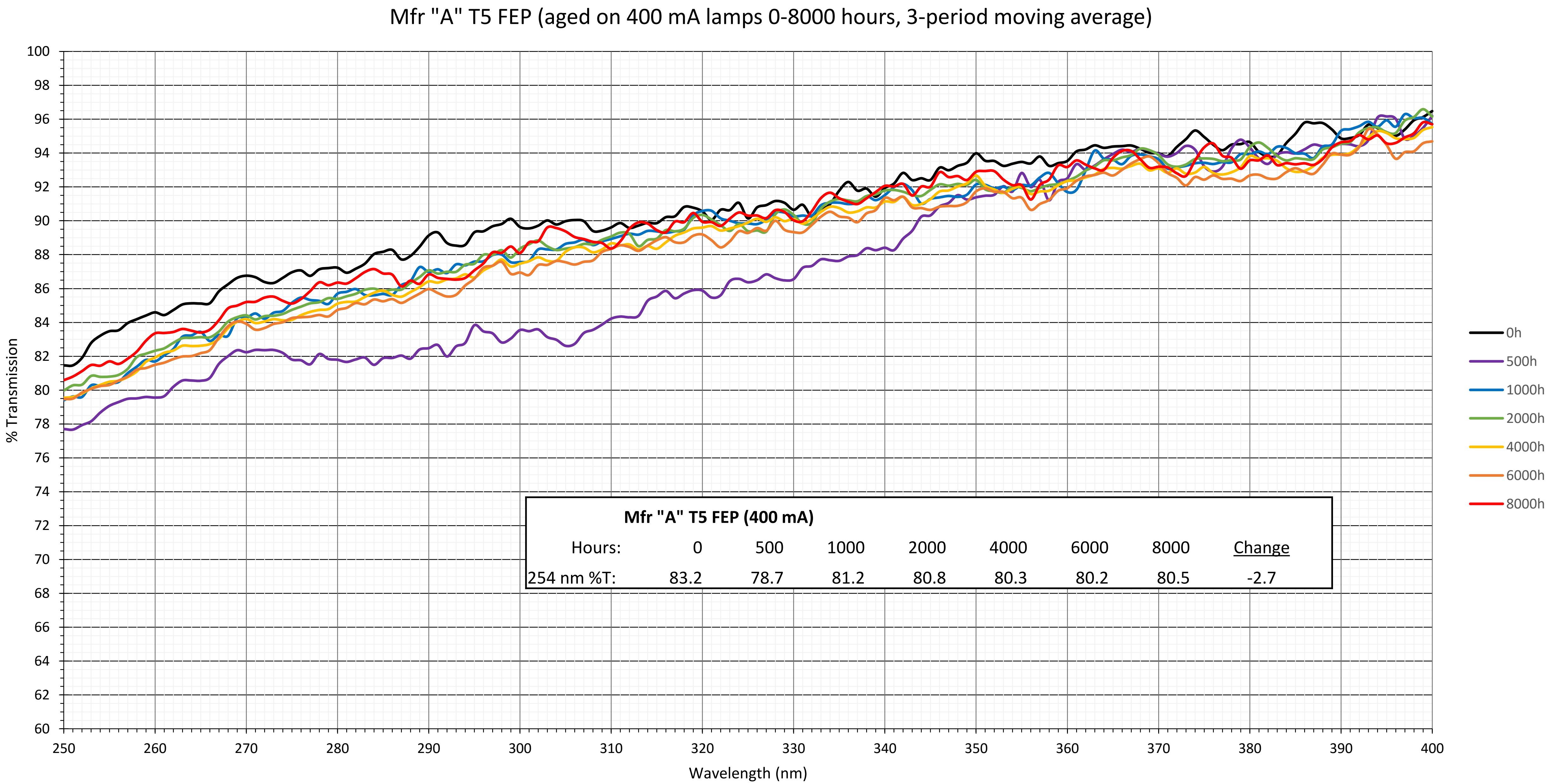
Results – Spectral Transmission Measurements



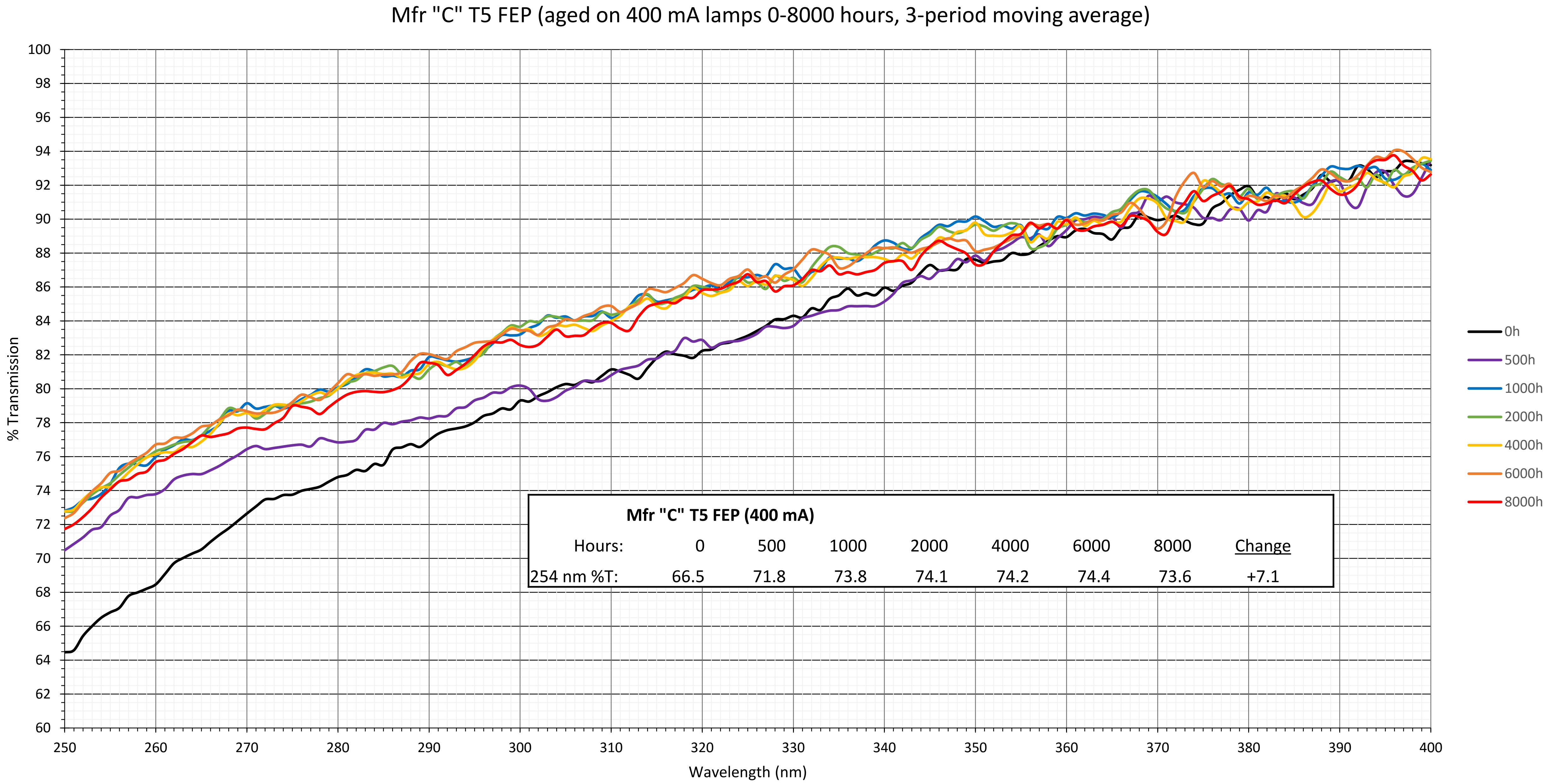
Mfr "C" T5 FEP (800 mA)

Hours:	0	500	1000	2000	4000	6000	8000	Change
254 nm %T:	66.5	71.2	73.3	73.0	73.8	73.6	74.6	+8.1

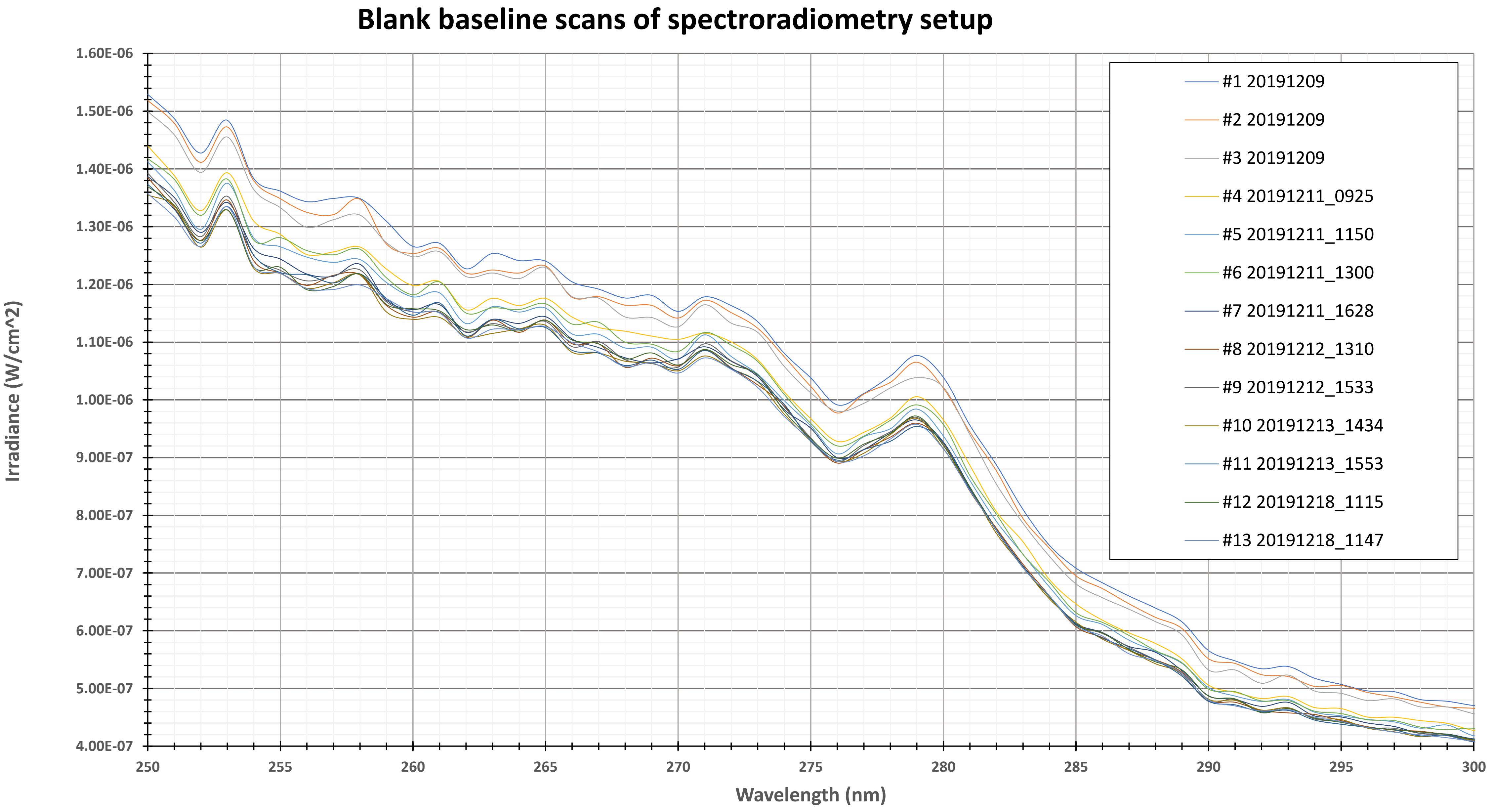
Results – Spectral Transmission Measurements



Results – Spectral Transmission Measurements



Results – Spectral Transmission Measurements



Discussion of Results

- Films experience degradation in UVC transmittance as expected, though the magnitude of this change after 8000 hours is surprisingly small: 5-7% on the amalgam lamps and just a few percent (perhaps) on the lower-powered standard- & high-output lamps.
- No substantial difference between FEP and PFA material types was observed. It could be argued that PFA degradation was worse and it is the more expensive of the two, so FEP seems to be the winner.
- Also no clear winner between the different manufacturers, so decision could probably be made on price alone. Not entirely fair to compare two manufacturers with different film thicknesses, but also not much reason to use the thicker film since it only results in more absorption
- Mfr. “C” films (the thicker FEP) appear to have experienced an improvement in transmittance over the aging time, which is counter to expectations but happened with both sets of samples and appears in both measurement procedures. Perhaps heat effects are causing beneficial changes in microstructure initially.
- Power density (i.e. wall loading) appears to make a substantial difference, as all samples aged on amalgam lamps showed the highest degradation. Degradation is likely accelerated by additional heat along with increased UVC.
- A realistic lifetime for lamps is 16,000 hours and this test was only half of that. However, the degradation seems to level off to an approximately linear rate after 2000 hours (similar to the lamps themselves) and one would not expect a significant deviation from this linear rate for the remainder of lamp lifetime.
- Happy to receive some >12,000-hour lamps from the field and measure film transmittance! This would require 0-hr film spectrometry and/or lamp radiometry measurements to compare as baseline

Discussion of Results

- Probable sources of error:
  - Inconsistency in applying heat-shrink film
  - Standard uncertainty of the detector alone is at least 5%, which can be as large as the observed change in transmittance!
  - Poor signal strength in spectroradiometry setup due to weak output of deuterium source (especially above 280 nm)
  - Rapid depreciation of deuterium lamp output in spectroradiometry setup means baseline constantly shifting – very important to make frequent blank baseline scans and correlate all measurements to the baseline nearest in time! This was learned in hindsight.
- A dual-beam benchtop spectrometer with a film holder would give more accurate transmission spectrometry results, but the films scatter light considerably so an integrating sphere accessory is necessary, which LSI does not have for our Perkin Elmer Lambda 365 instrument
- Using a digital caliper with 0.01 mm resolution, no change in film thickness was measured. A more sensitive instrument might tell a different story.
- Polymer analysis tools such as FTIR and Raman spectroscopy could give better insight into the actual degradation mechanisms.

Energy Consumption and CO_2 Emission Calculations

		Hours:	500 h	1000 h	2000 h	4000 h	6000 h	8000 h
	Watts		#	#	#	#	#	#
Am	88.5		6	6	6	6	6	6
HO	36		4	4	4	4	4	4
SO	19		4	4	4	4	4	4

	W	W	W	W	W	W
	531	531	531	531	531	531
	144	144	144	144	144	144
	76	76	76	76	76	76
Hours:	500	1000	2000	4000	6000	8000
Subtotal W·h	375500	751000	1502000	3004000	4506000	6008000

Grand total W·h = 16,146,500

Connecticut CO2 emission by electrical generation = 243 kg/MWh

16.1465 * 243 = **~3924 kg of CO2 produced by this experiment**

Car commute = 14.2 mi round-trip 1 gal gasoline produces ~ 8.9 kg CO2

My car: ~29 MPG **0.49 gal gasoline = 4.35 kg CO2 per round-trip in car**

Bicycle commute = 10.6 mi round-trip Bicycling average is about 60 g CO2 per mile.

10.6 * 60 = 0.636 kg CO2 per round-trip on bicycle

CO2 savings by bicycle = 3.714 kg per round-trip

3924/3.714 = 1057 commutes on bicycle needed to compensate

My average is around 120-150 bicycle commutes per year… 7-9 years of bicycle commuting at this rate

Sources:

https://www.eia.gov/electricity/state/connecticut/

https://www.theguardian.com/environment/2010/jun/08/carbon-footprint-cycling

Acknowledgements

LightTech LightSources

- Hector Ramos – radiometry lab technician
  - Made more than 250 lamp measurements for this experiment!
- An Rui "Andy" Zhu – electrician
  - Built out and wired the aging cabinet with 38 ballasts for 84 lamp positions, much of the work done in June-July when it was over 90°F (32°C) in the life test area!
- Mohamed Maklad – CFO
  - Approved the expenditure of time, manpower, and money on this project