Spectroscopic In-Situ Non-Destructive Evaluation to Monitor the Health of Thermal Barrier Coatings

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Project Awarded (07/01/03, 36 Month Duration)

$391,615 Total Contract Value ($391,615 DOE)

Gas Turbine Needs

- Early detection of TBC degradation and failure is critical to prevent catastrophic engine failure as advanced gas turbine engines depend on TBC for higher operating temperature
- TBC inspection is costly because it requires skilled labor and interruption of service
- An in-situ non-destructive evaluation of TBC health will provide significant savings in engine maintenance

Objective

- Develop in-situ non-destructive evaluation method to monitor the health of TBC using emission spectroscopic analysis

Approach

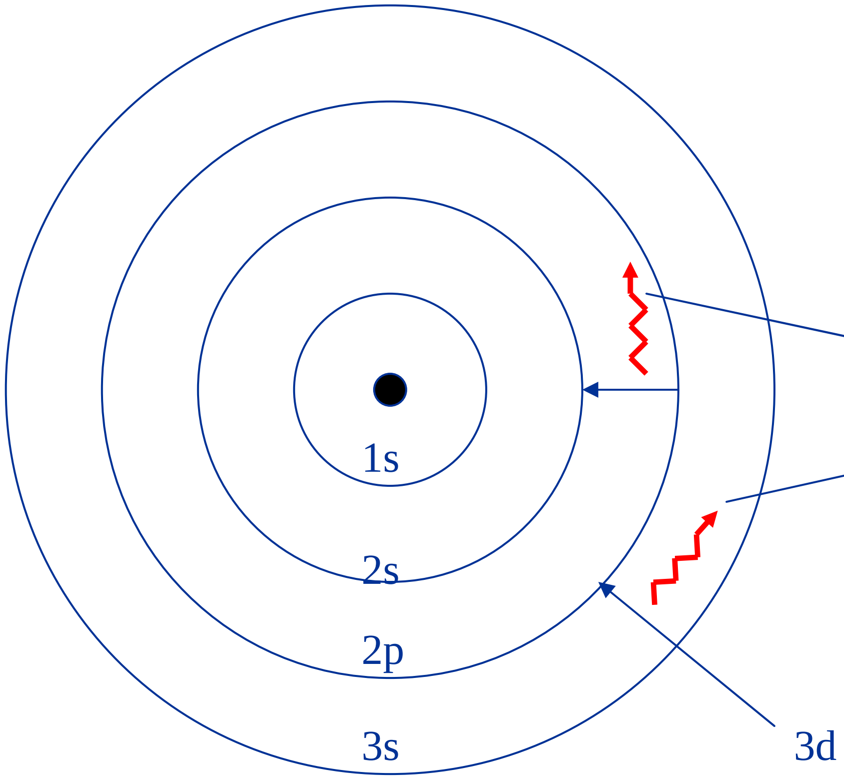
- TBC is doped with a marker material that can be detected by spectroscopy when exposed to combustion environment
- As TBC degrades (cracking, spallation, etc.), marker material is exposed to combustion environment and becomes airborne.
- TBC health-spectral response relationship is calibrated by exposing pre-damaged TBC to combustion environment.
- TBC health-spectral response calibration is used to determine the TBC health by continuously monitoring spectral response

Activities	Year 1	Year 2	Year 3
Process doped YSZ & Determine the optimum range of Li_2O content			
Process doped YSZ plasma spray powders & plasma spray TBCs			
Optimize TBC Design (location, thickness)			
Calibrate TBC health vs. spectral response relationship			
Evaluate the effect of Li_2O on TBC durability (w/ thermal cycling)			
Confirm & Fine-tune the TBC health vs. spectral response calibration			
Demonstrate *in-situ* spectroscopic monitoring (w/ burner rig)			
Prepare the final report & future recommendations			

Accomplishments

- The correlation between intensity of Li emission and degree of TBC degradation confirmed
- Optimal Li_2O dopant concentration and doped layer thickness determined
- The effect of Li_2O dopant on TBC durability determined
- A flat flame burner having much improved temperature stability compared with a welding torch has been set up

Emission Spectroscopy



Spectral Characteristics of Li

Wavelength (A)	Intensity in arc
6707.8	3000
6103.6	2000
3232.6	1000

- Light is emitted when excited electrons in atomic species return to ground state, showing a unique spectrum for each atomic species.

Intensity of Emission

$$I \propto N e^{(-\Delta E / RT)}$$

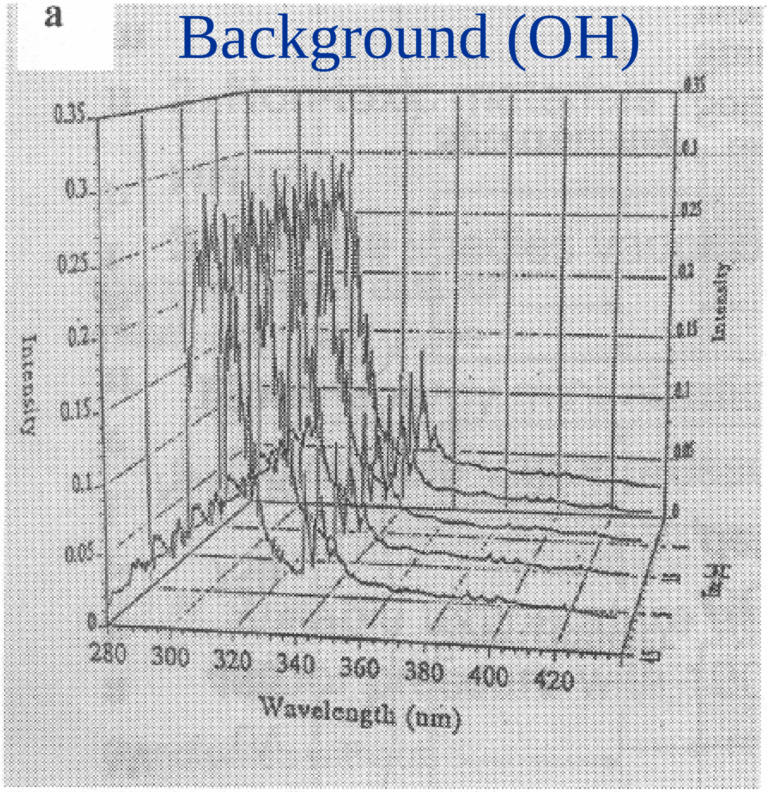
I = Emission Intensity
N = Number Density
ΔE = Transition Energy
R = Gas Constant
T = Temperature

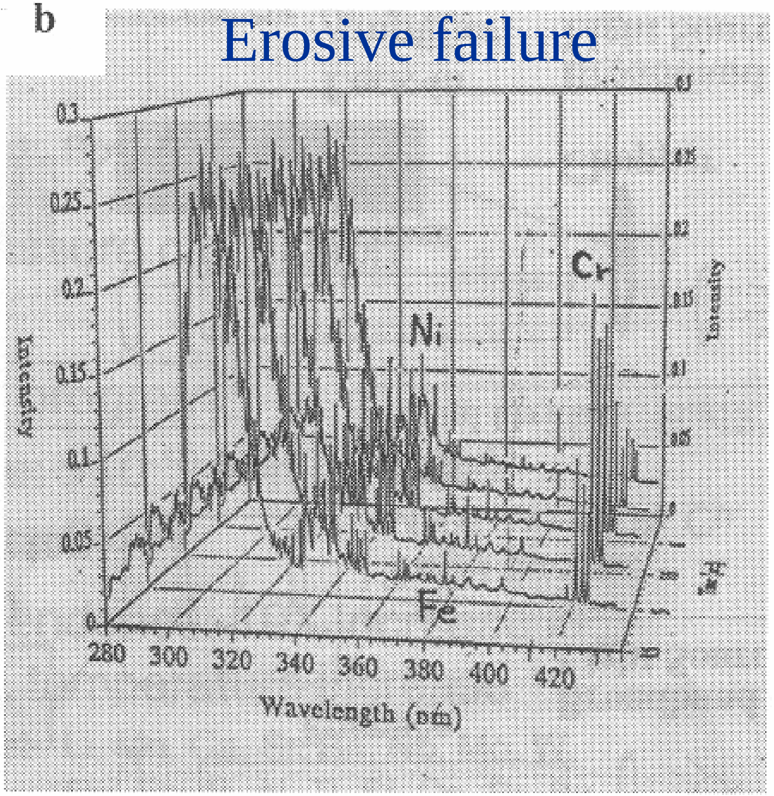
- Emission intensity increases with increasing temperature and concentration (number density) of marker species

Requirements for Marker Materials

- Must be compatible with TBC, chemically, physically and mechanically
- Must be compatible with hydrocarbon-fueled engines
- Must possess a unique spectroscopic signature, observable in the combustor or in the exhaust
- Must be different from those species that are present in the current engine environment
- Must be nontoxic

Emission Detected at Rocket Engine Exhaust





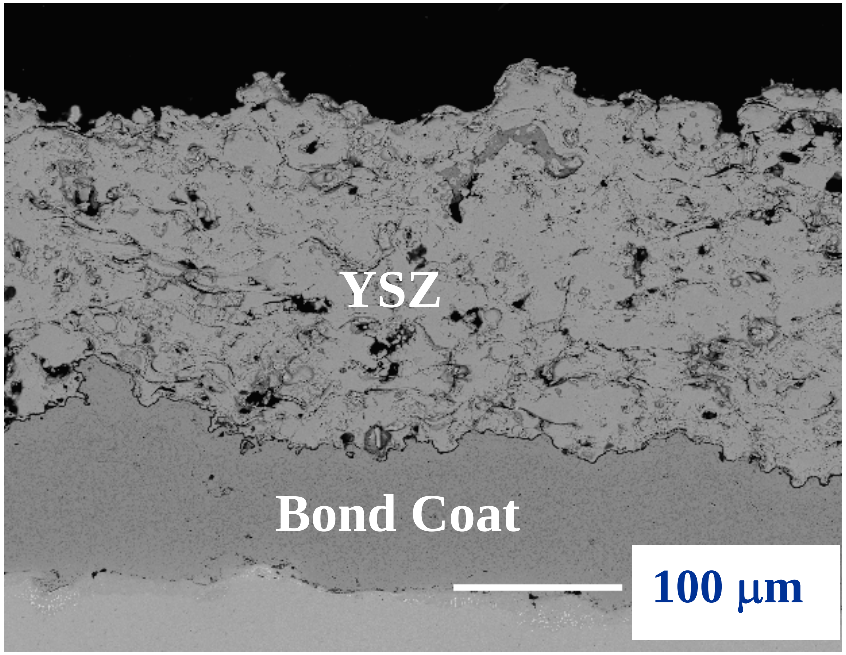
- Space shuttle main engine test runs showed substantial emissions of Cr, Ni, and Fe, all originating from stainless steel component inside the engine (W. de Groot, et al)

TBC Preparation

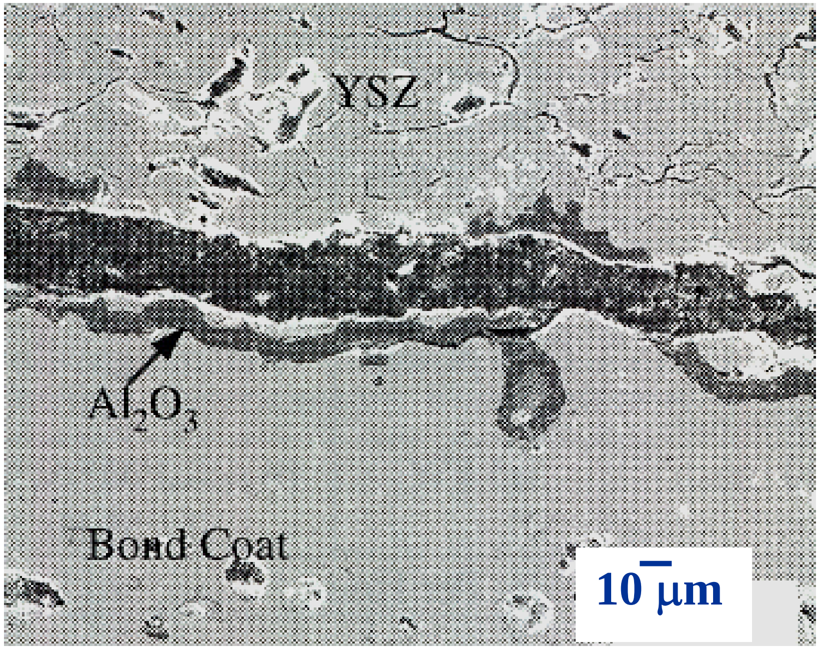
- Slurry dipping
  - CMSX4+Y substrate (1” dia coupon)
  - Binder: polyvinyl butyral (PVB)
  - Solvent: water and ethanol
- Plasma spraying
  - CMSX4+Y substrate (1” dia coupon)
  - NiCrAlY bond coat by LPPS (125 μm)
  - Doped and undoped YSZ by APS (250 μm total)

YSZ TBC Degradation Mode

As-sprayed

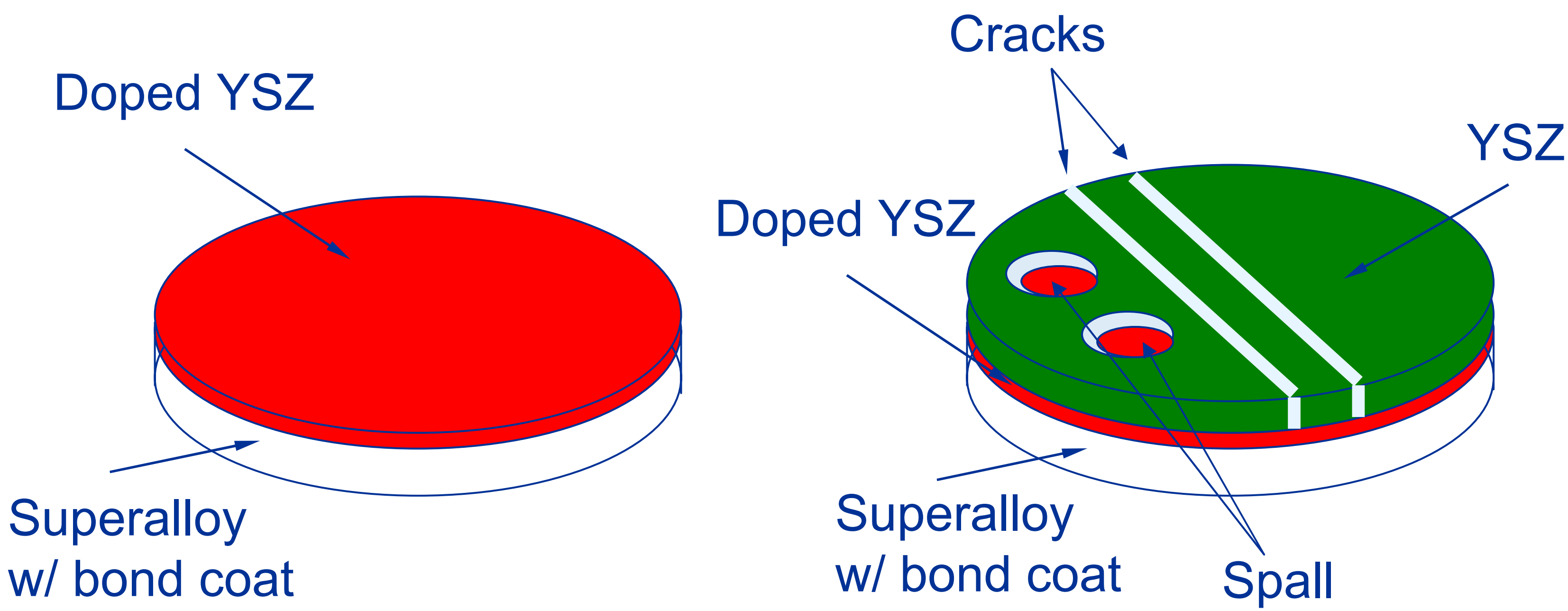


18 - 20h cycles, 1150°C in air



- TBC typically spalls in YSZ near the YSZ/TGO interface
  - Ideal location for doped YSZ

TBC Design



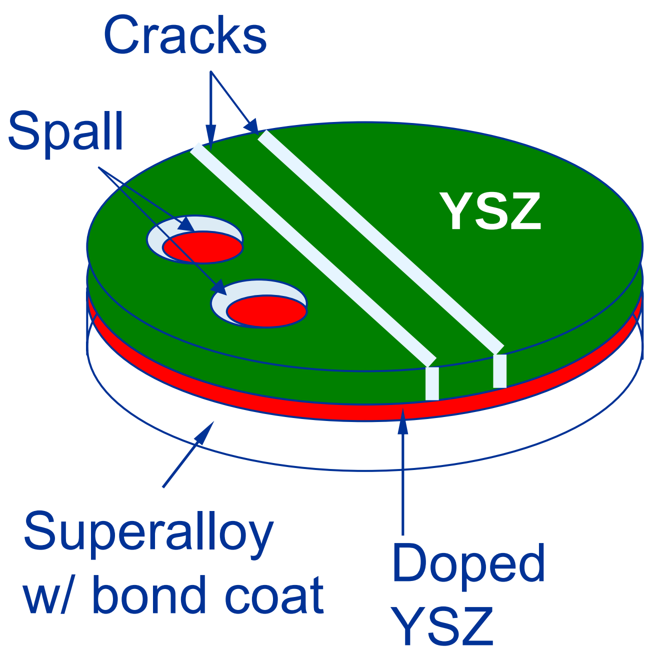
- Place doped YSZ at a location where it is most likely to be exposed to the flame when TBC spalls

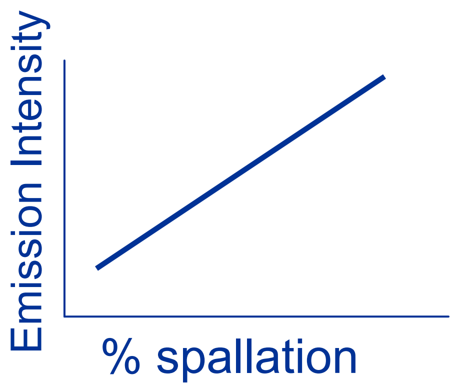
TBC Health vs. Spectral Intensity Calibration

TBC with cracks/ spallation is exposed to combustion flame

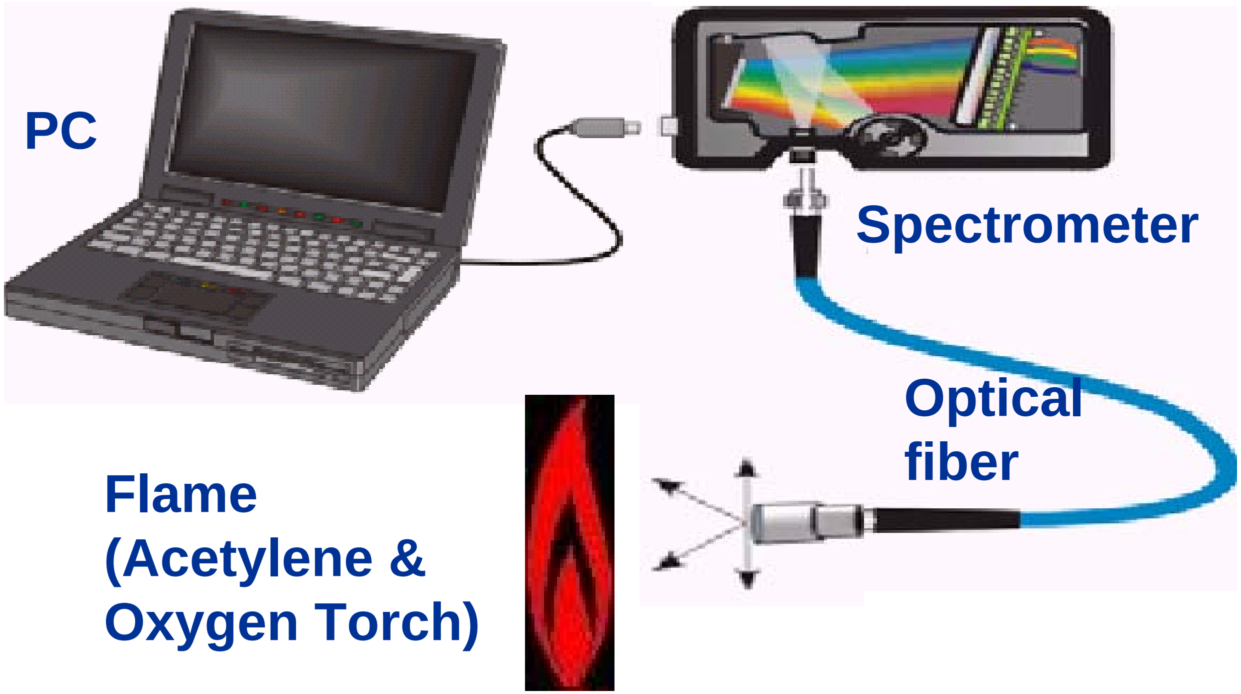
Determine TBC health-Spectral response relationship

TBC health-spectral response relationship is used in conjunction with in-situ emission spectroscopy To monitor TBC degradation



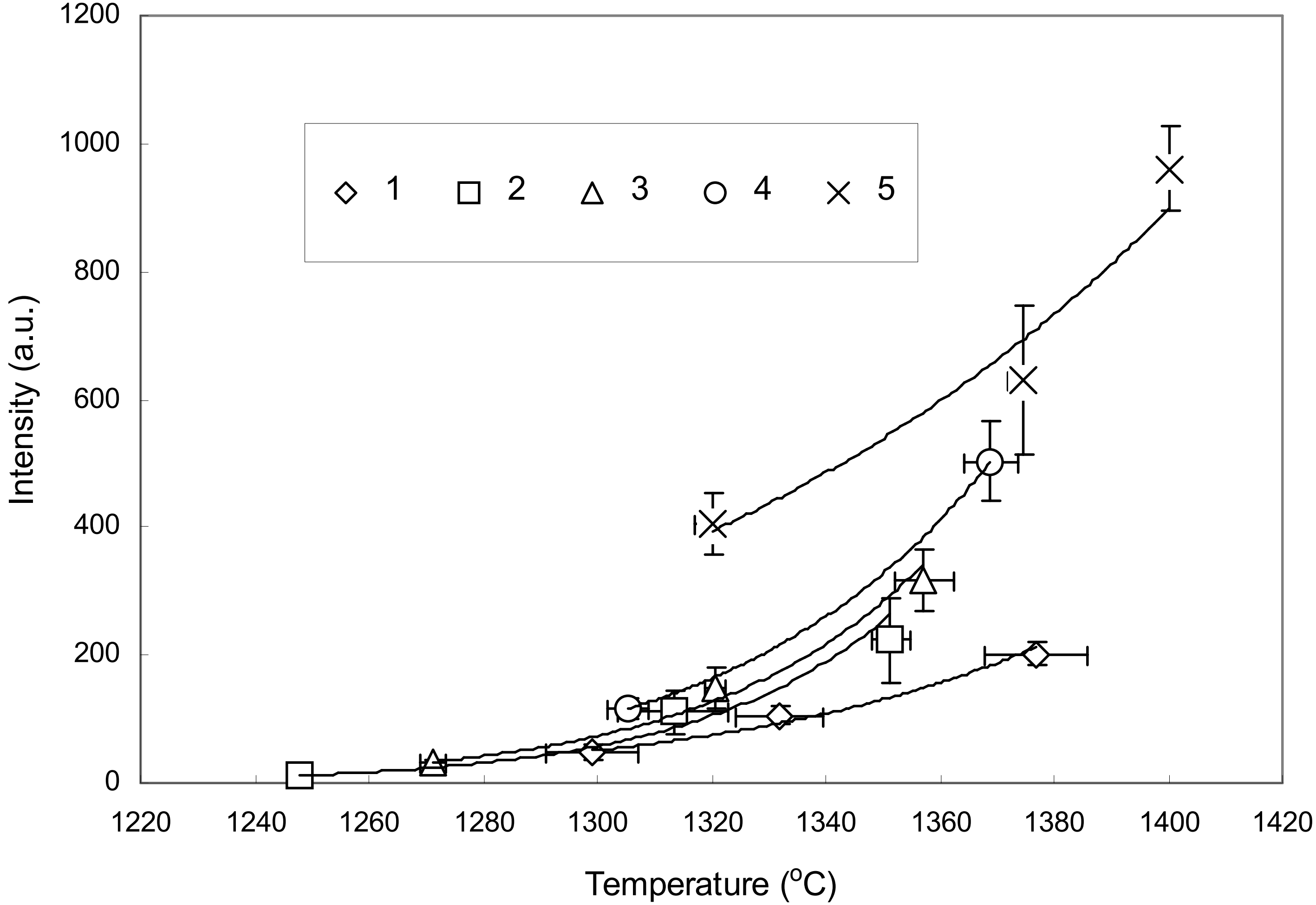


Emission Spectroscopy Setup

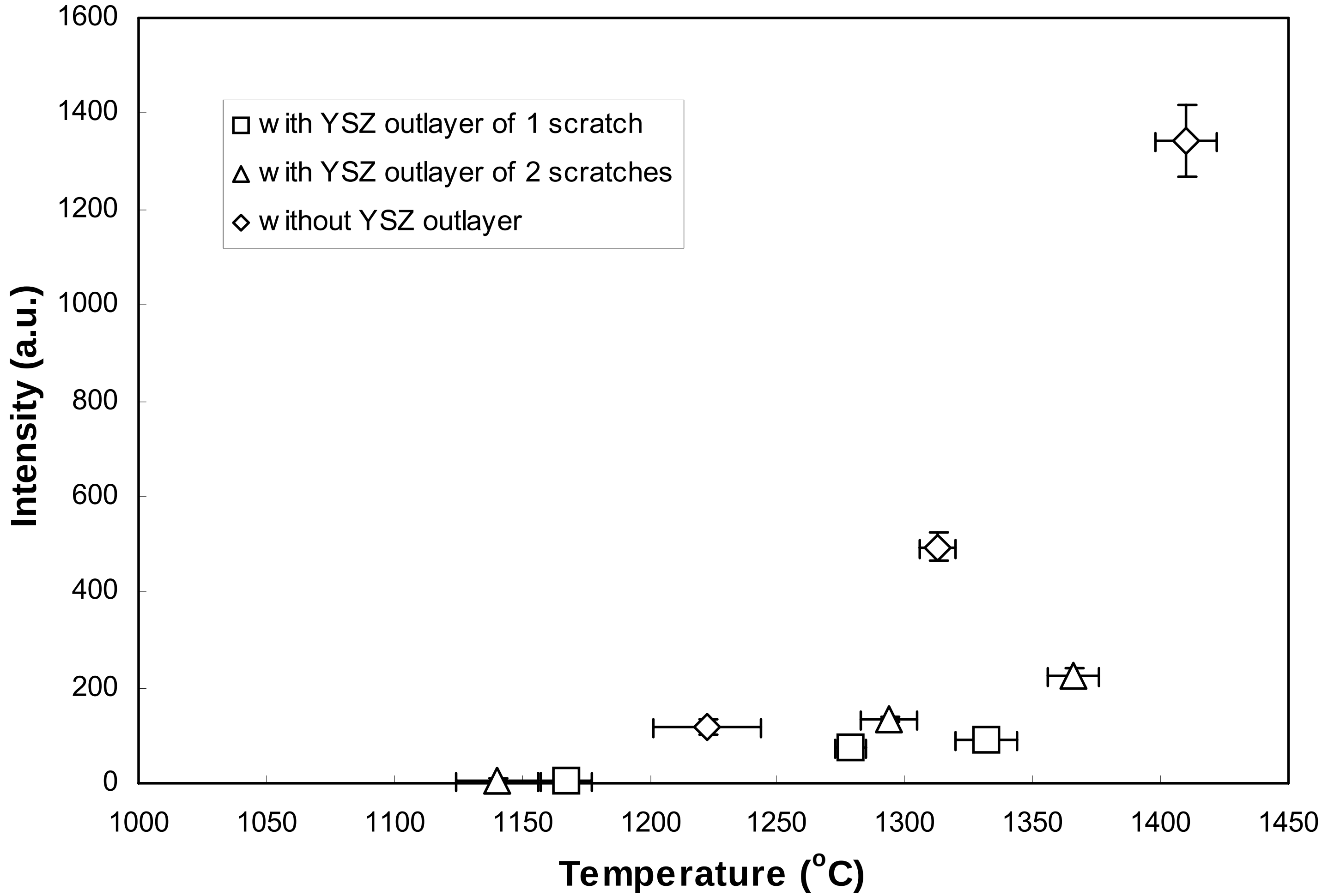


• The emitted light from lithium atoms in flame travels into an input fiber, which carries the light information to the spectrometer. The spectrometer then transmits the information to the PC for data acquisition of measured spectra

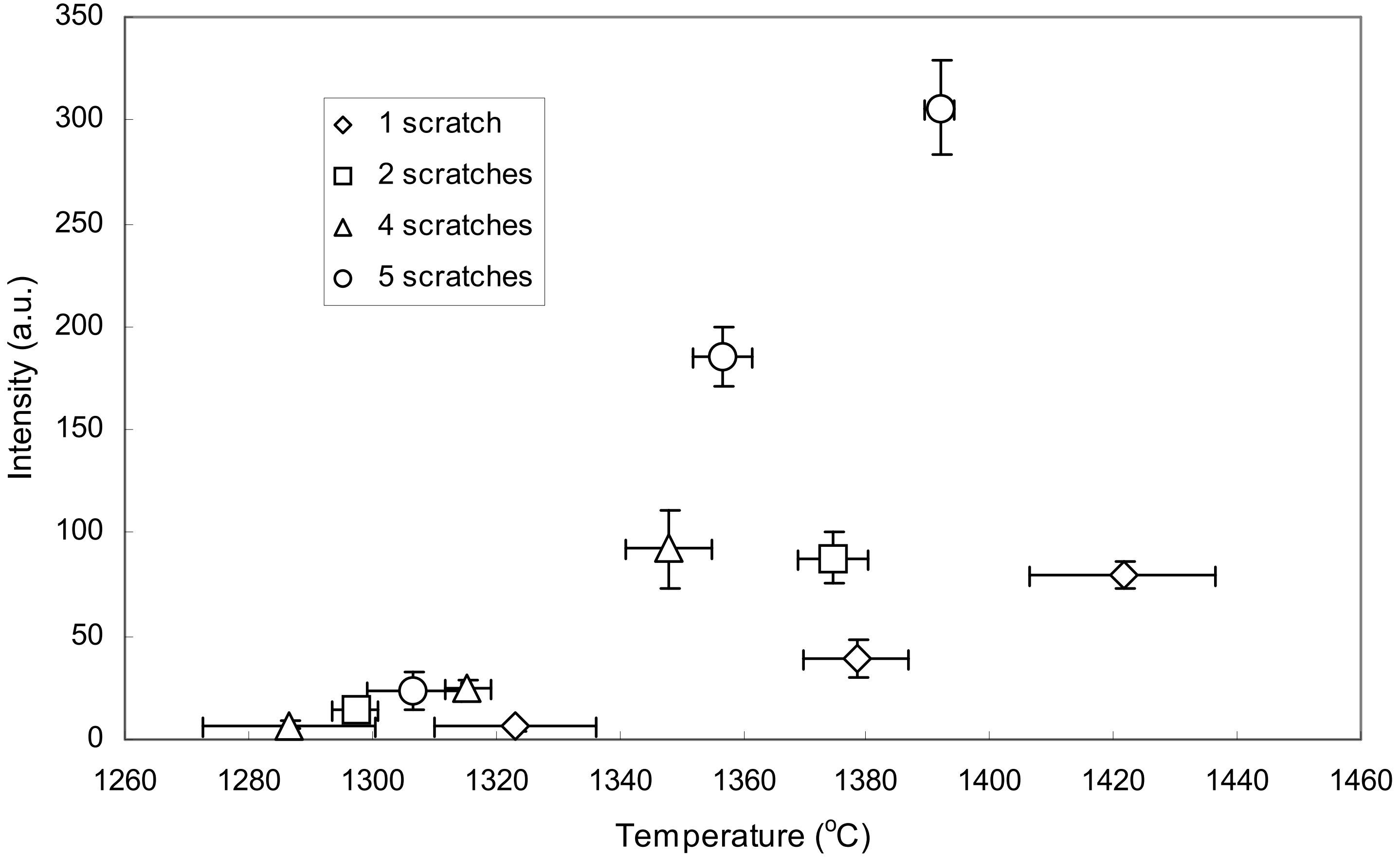
Intensity vs. Simulated spallation (Slurry - 1 w/o Li_2O-Doped YSZ/YSZ TBC)



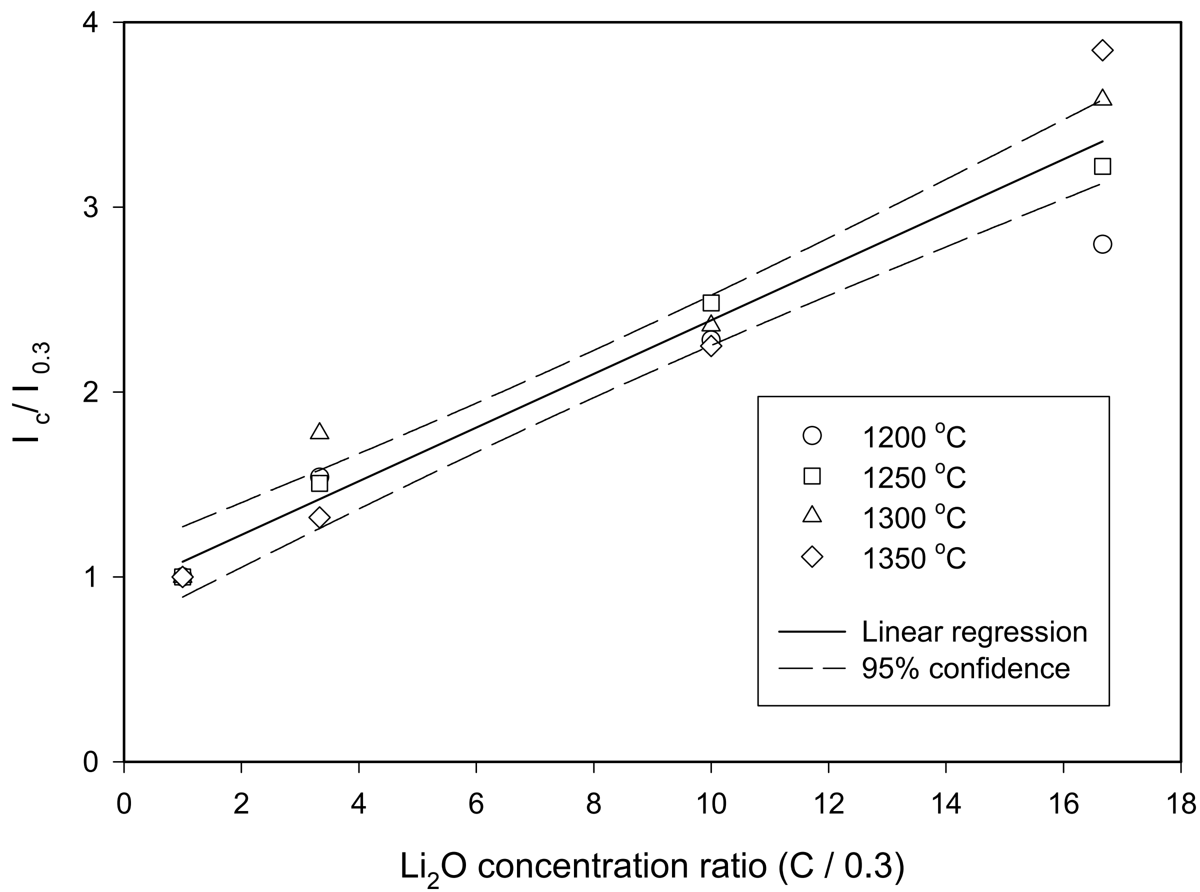
Intensity vs. Simulated cracks (Slurry - 1 w/o Li_2O-Doped YSZ/YSZ TBC)



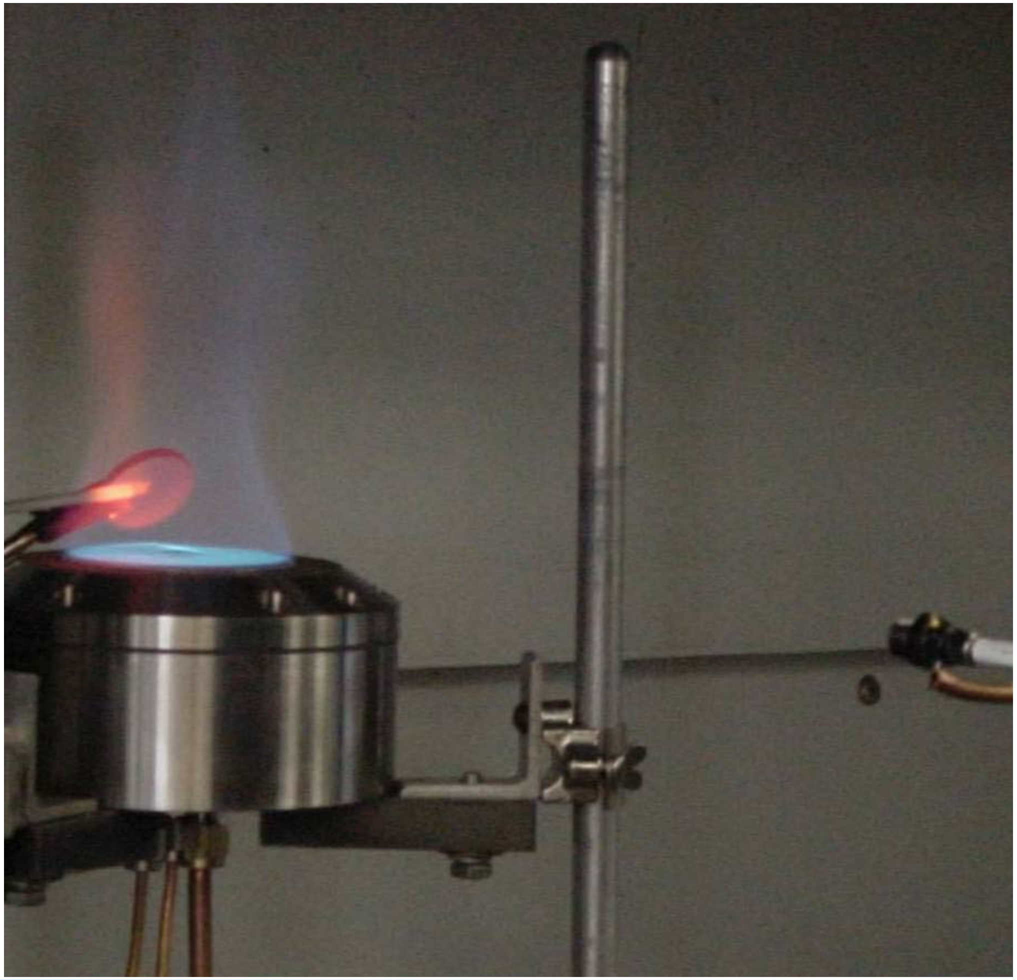
Intensity vs. Simulated cracks (Plasma - 1 w/o Li_2O-Doped YSZ/YSZ TBC)



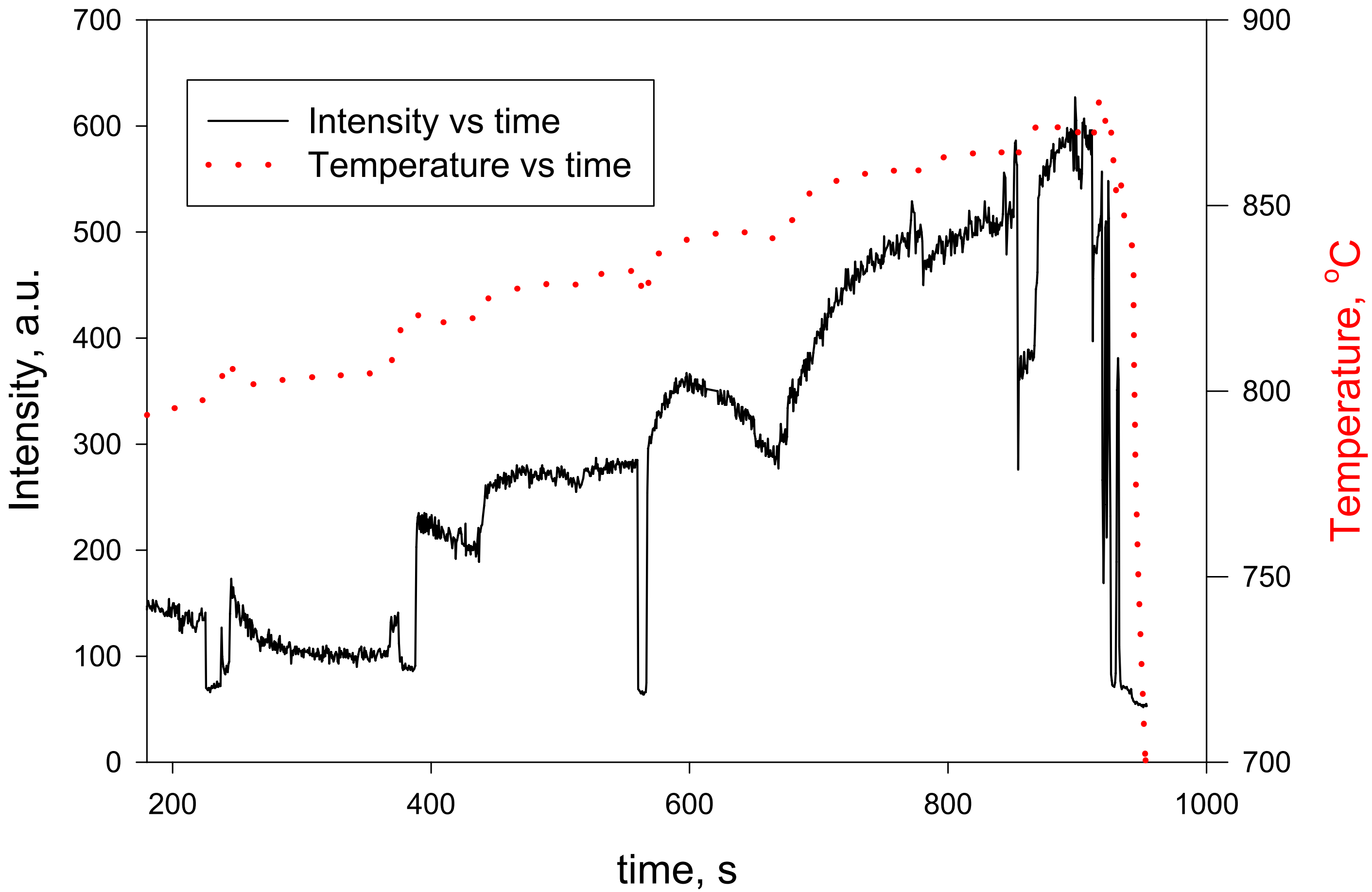
Intensity vs. Li_2O Concentration
(Slurry - 1 w/o Li_2O-Doped YSZ/YSZ TBC w/ one scratch)



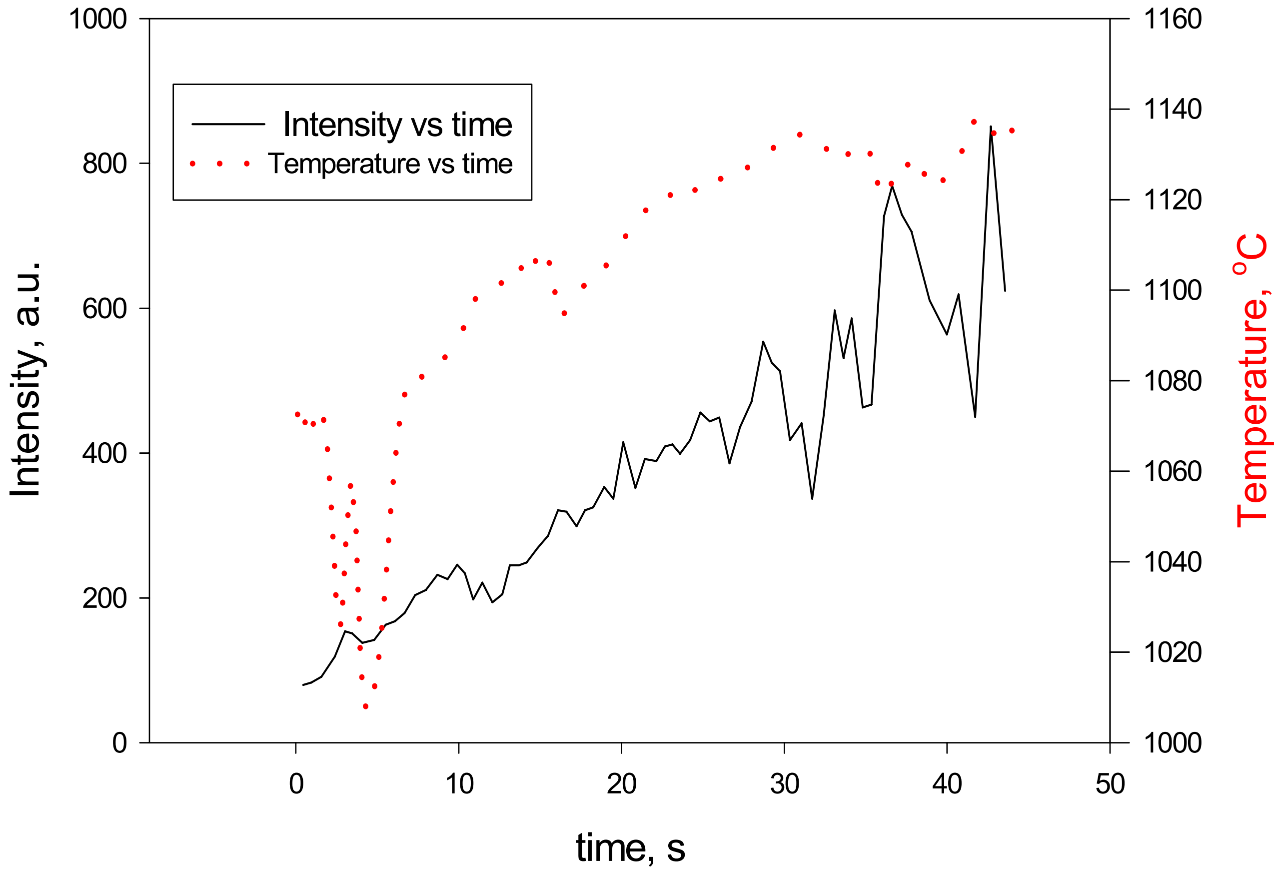
Flat Flame Burner



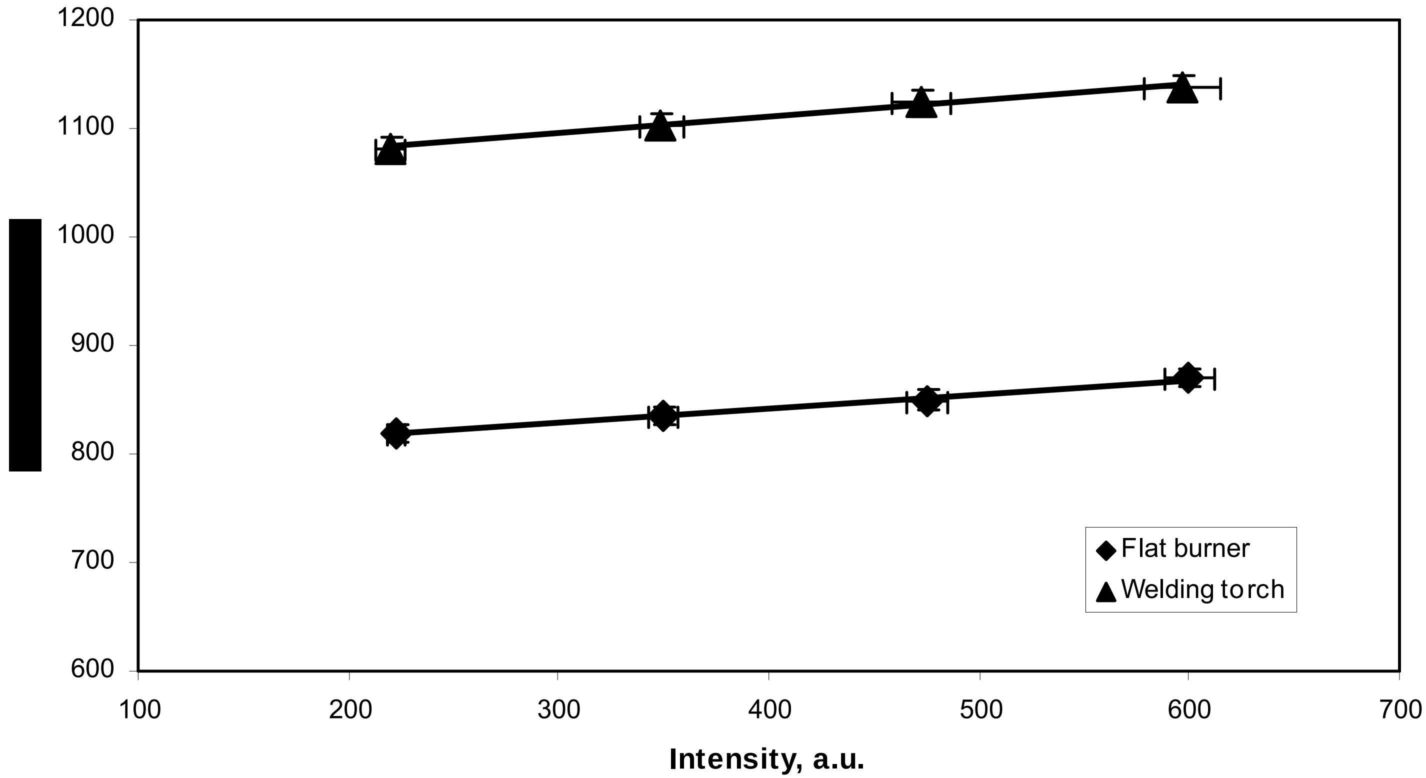
In-situ measured temperature and Intensity (Flat Flame) (Slurry - 1 w/o Li_2O-Doped YSZ pellet)



In-situ measured temperature and Intensity (Torch) (Slurry - 1 w/o Li_2O-Doped YSZ pellet)

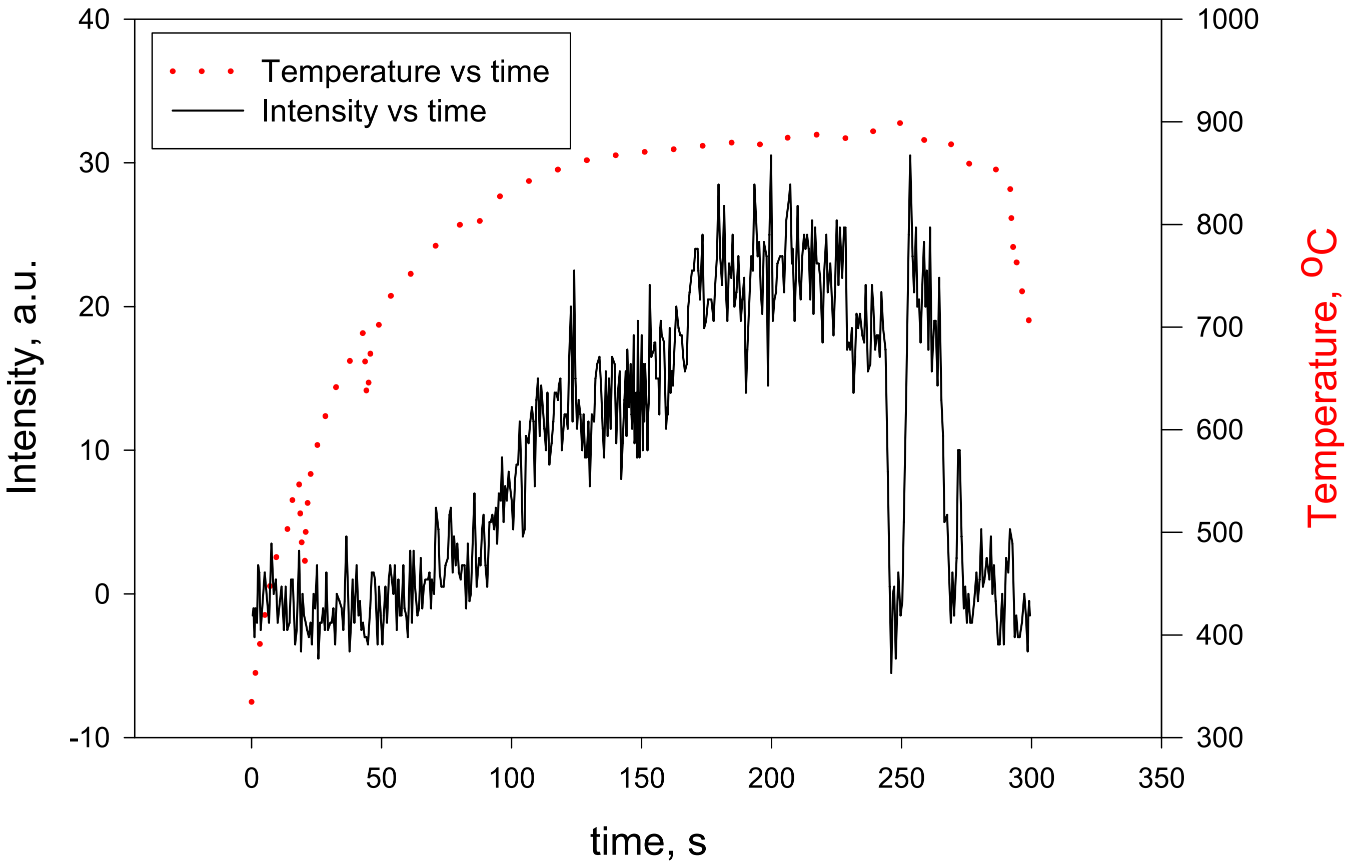


Flat flame burner *vs.* Welding torch
(Slurry - 1 w/o Li_2O-Doped YSZ pellet)

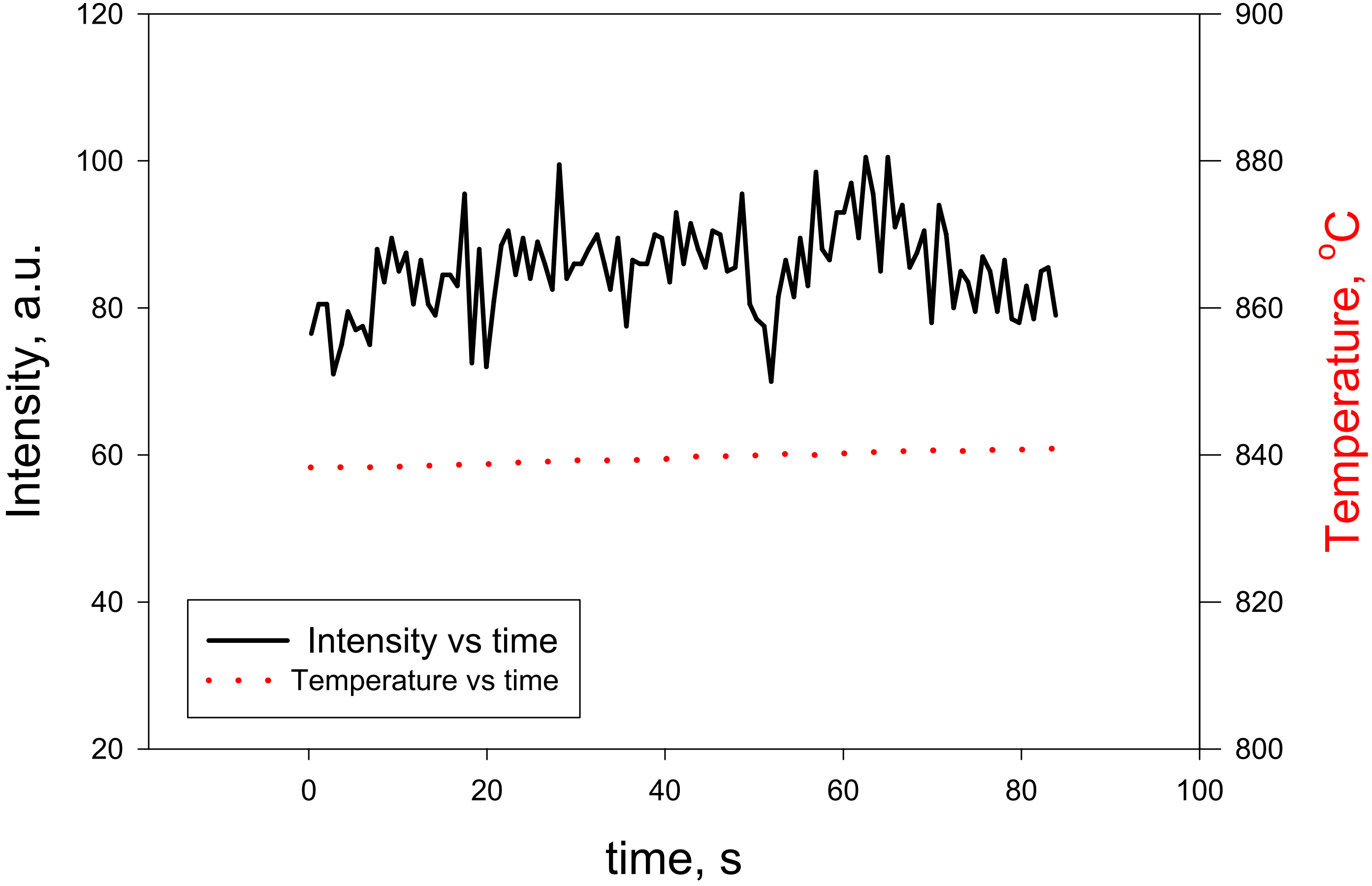


Nr.	**CH_4 (slpm)**	**Air (slpm)**	**Phi**	**Tad (^oC)**	**T (^oC)**
1	1.31	<12.15	1.02		Unstable
2	1.31	12.86	0.96		915
3	1.31	13.58	0.91		926
4	1.31	15.02	0.83		917
5	1.31	19.72	0.63		984
6	1.31	20.18	0.61		973
7	1.31	>20.98	0.59		No flame
Ref	***1.31***	***12.4***	***1***	***1953***	***1517 (CARS)***
8	1.733	<17.93	0.92		Unstable
9	1.733	18.67	0.88		992
10	1.733	19.42	0.85		1000
11	1.733	20.98	0.79		1008
Ref	***1.733***	***16.5***	***1***	***1953***	***1613 (CARS)***
12	2.55	23.92	1.01		Unstable
13	2.55	25.03	0.96		1048
14	2.55	25.34	0.95		1054
15	2.55	25.79	0.94		1070
Ref	***2.55***	***24.14***	***1***	***1953***	***1736 (CARS)***

Intensity vs. Temperature (Flat Flame)
(Plasma - 1 w/o Li_2O-Doped YSZ/YSZ TBC w/ one scratch)



Intensity vs. Temperature (Flat Flame)
(Plasma - 1 w/o Li_2O-Doped YSZ/YSZ TBC completely spalled)



Thermal Cycling Life

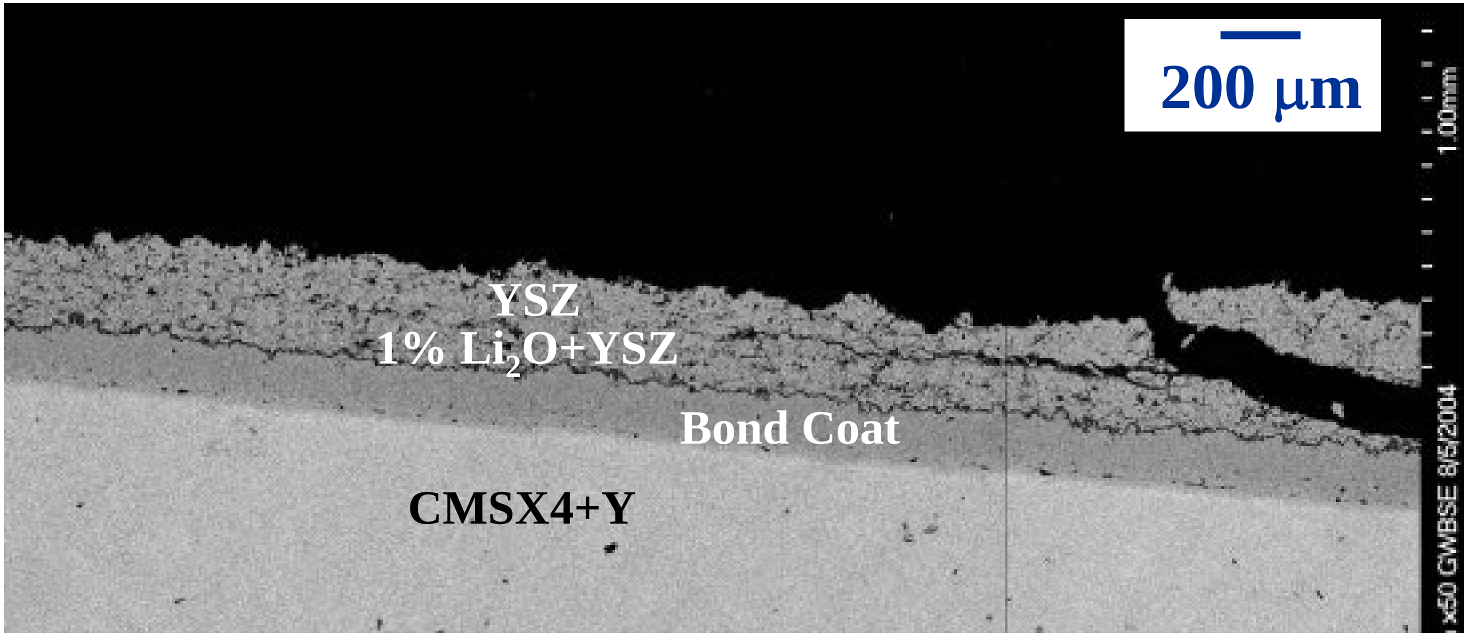
4h anneal at 1100^{o}C (Ar-5% H_2) / 20h cycles at 1100^{o}C (Air)

	1 wt% Li_2O	3 wt% Li_2O	5 wt% Li_2O
5*/5**	1	0 (anneal)	0 (anneal)

* Thickness of inner doped YSZ layer (mils)
** Thickness of outer undoped YSZ layer (mils)

Effects of Dopant on TBC Durability

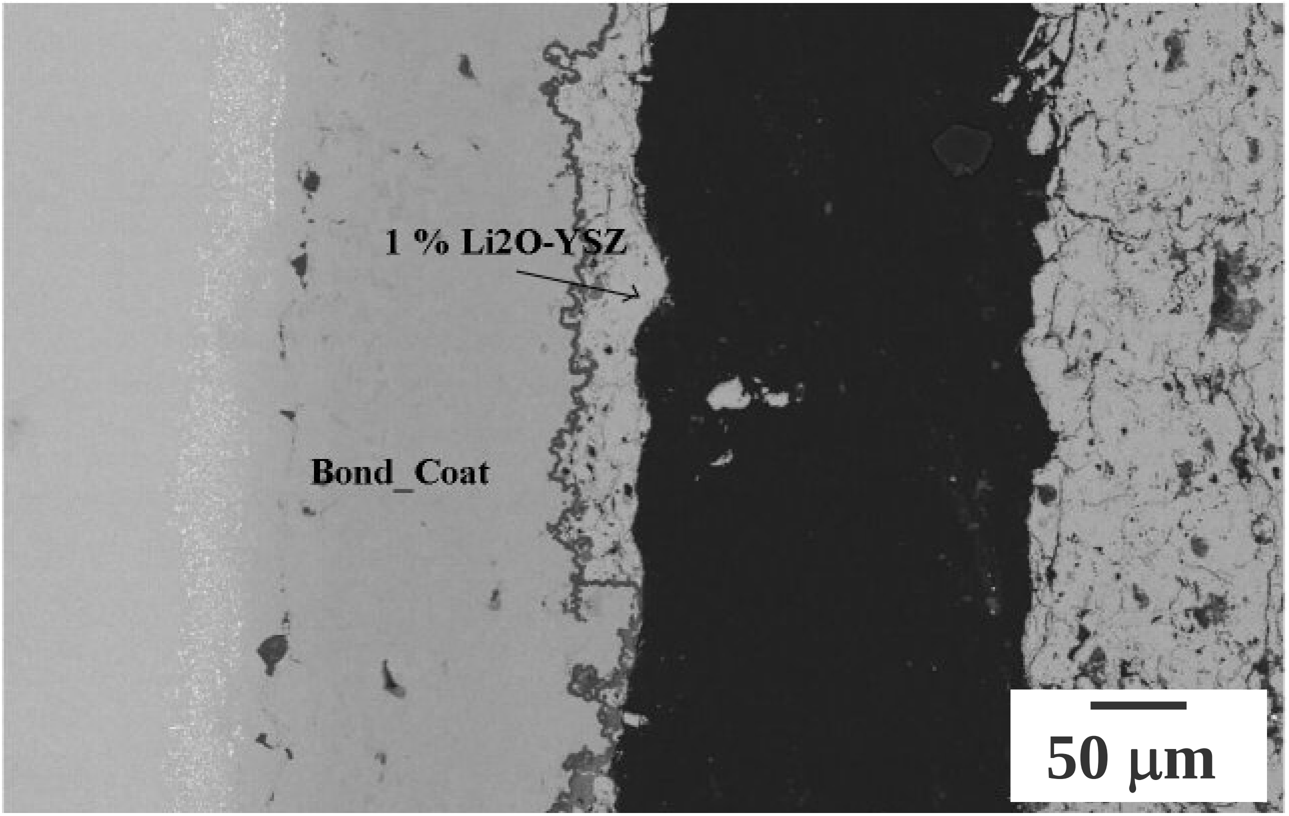
1 wt% Li_2O+YSZ (125 μm) / YSZ (125 μm)



1 – 20h cycle at 1100°C

Effects of Dopant on TBC Durability

1 wt% Li_2O+YSZ (125 μm) / YSZ (125 μm)



1 – 20h cycle at 1100°C

Thermal Cycling Life (1150°C - 20h cycles)

Configuration	1 wt% Li_2O	3 wt% Li_2O
1/9	16, 22	> 20
2/8	18, 20	19
3/7	13, 20	3
Standard YSZ	22	

Thermal Cycling Life
(1115ºC - 20h cycles)

Configuration	1 wt% Li_2O	2 wt% Li_2O	3 wt% Li_2O
1/9	25, 35	30	32, 103
Standard YSZ	25, 49, 75		

Thermal Cycling Life
(1100ºC - 1h cycles)

Configuration	1 wt% Li_2O	2 wt% Li_2O	3 wt% Li_2O
1/9	790, 840	900	790, 910
2/8	900	-	20
Standard YSZ	483, 750		

Conclusions

- The intensity of Li emission correlates well with temperature, Li_2O dopant concentration, and degree of TBC degradation
- A flat flame burner provides much improved temperature stability compared with a welding torch
- Optimal Li_2O dopant concentration is 1 ~ 3 wt%
  - Li_2O-doped inner YSZ layer does not cause a debit in TBC thermal cycling life if the thickness is kept within ~1mil
- Emission spectroscopy is a promising tool for in-situ TBC health monitoring

Future Work

- **In-situ measurement of emission in a burner rig to demonstrate the feasibility of applying the emission spectroscopy in gas turbines**

Questions?