Heat-flux Sensor Calibrations at NIST
Physical Measurements Laboratory

Charles Gibson, Howard Yoon

NIST

NIST Heat Flux Gauge Calibration Facilities

- 25 mm Variable Temperature Blackbody - Primary facility
  Aperture: 25 mm dia., Temp.: 2533 K, Radiant flux: 50 kW/m^2
- Electrical Substitution Radiometer (upper limit of 50 kW/m^2)
- 23 cm Spherical Blackbody Mikron M300 - Cooled enclosure for sensors. Aperture: 25 mm dia., Temp.: 1373 K, Radiant flux: 100 kW/m^2
- High power argon and krypton lasers (up to 8 W single-line)
- 51 mm Variable Temperature Blackbody - In development
  Aperture: 51 mm dia., Temp.: 2773 K, Radiant flux: 67 kW/m^2

High Heat Flux Calibration

NIST - Methodology

VTBB method or Detector based calibration (ISO Method 3)

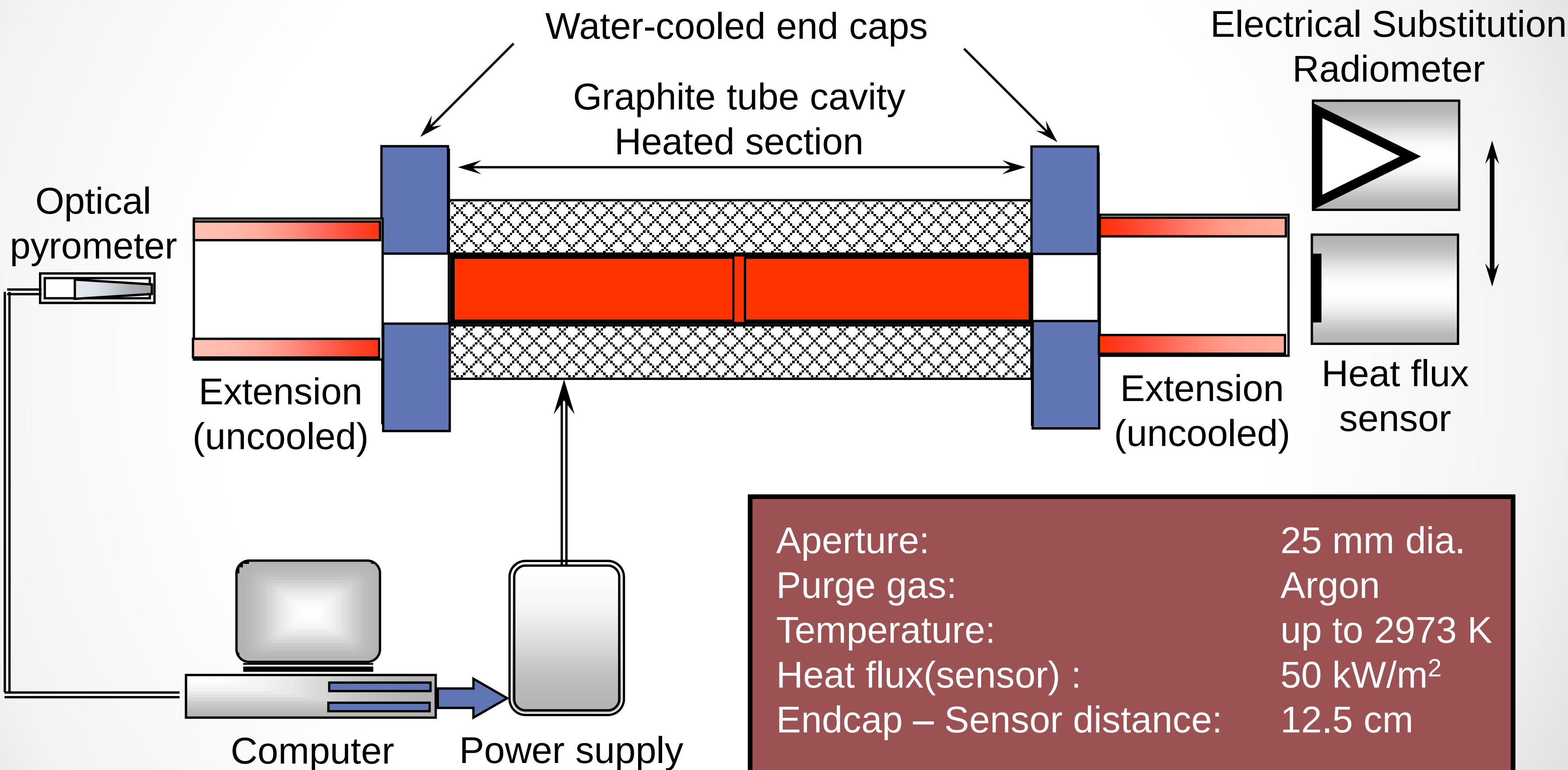
≈50 kW/m^2	Flux-scale (ESR*) transfer using open-mode Graphite tube blackbody

*Electrical Substitution Radiometer

Source based calibration (ISO Method 2) (*in progress*)

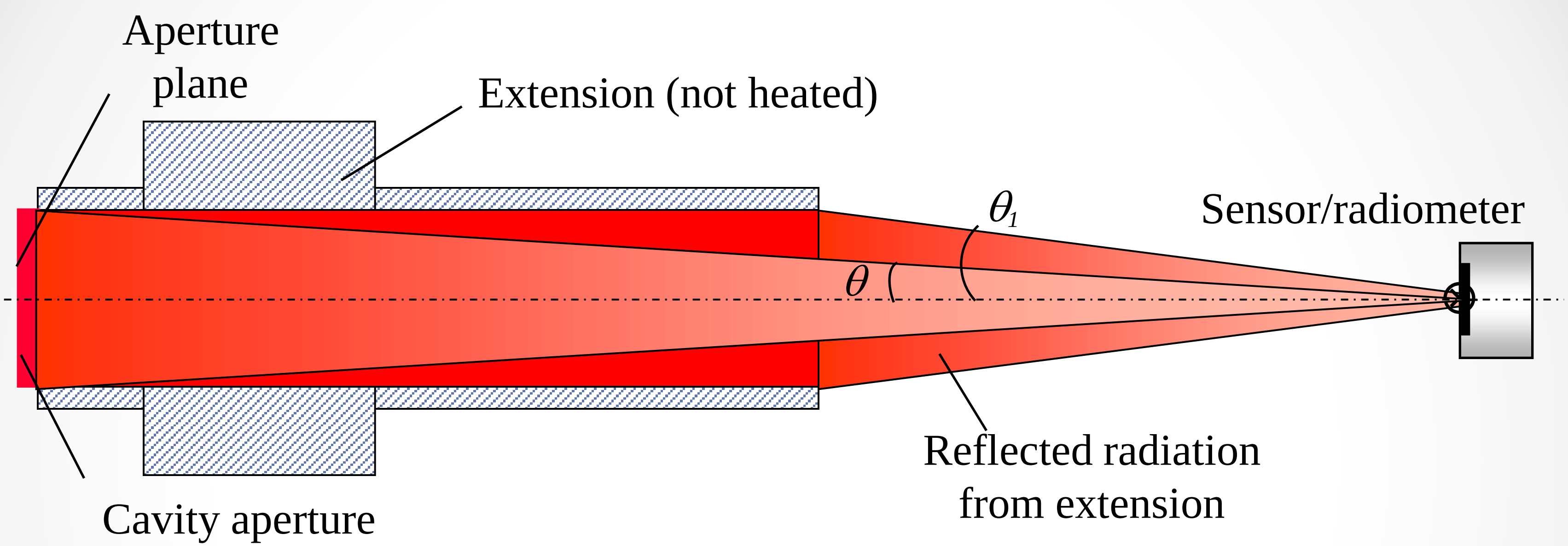
50 – 100 kW/m^2	Temperature-scale calibration Closed-mode Spherical blackbody

VTBB experimental setup



Aperture:	25 mm dia.
Purge gas:	Argon
Temperature:	up to 2973 K
Heat flux(sensor) :	50 kW/m^2
Endcap – Sensor distance:	12.5 cm

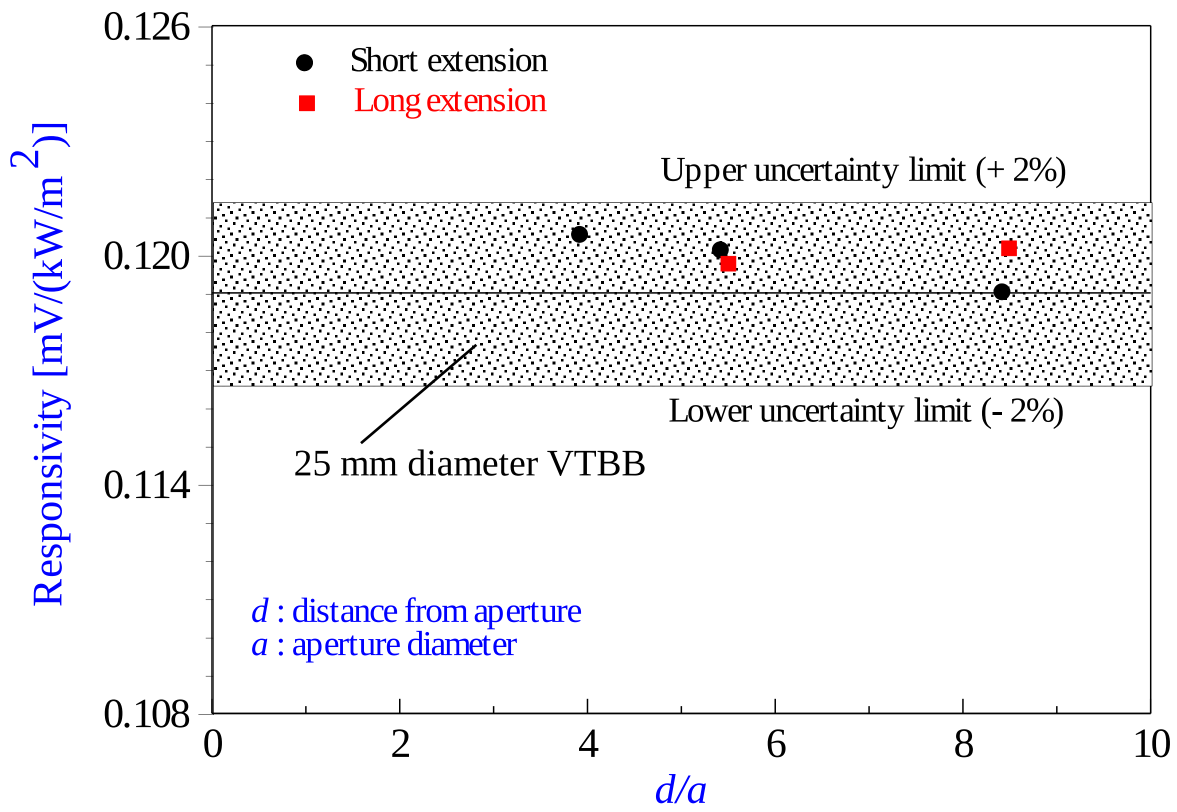
Flux Scale & Reflected Radiation



- Radiative flux at sensor is sum of :
  - cavity aperture radiation, and
  - reflected radiation from the extension inner-surface
- Reflected radiation (15 % - 20 %) difficult to calculate.
- Effective view angle greater than θ

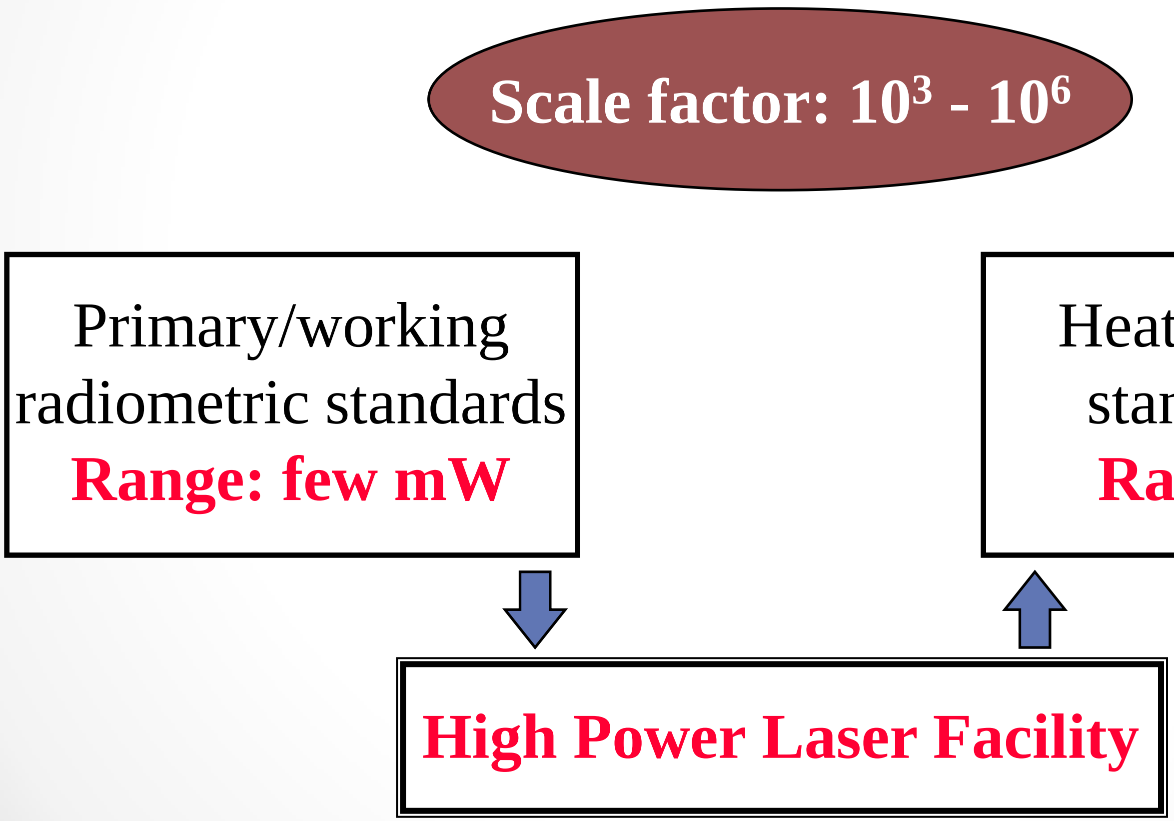
Flux Scale Calibration Comparison

In 25 mm and 51 mm Blackbodies

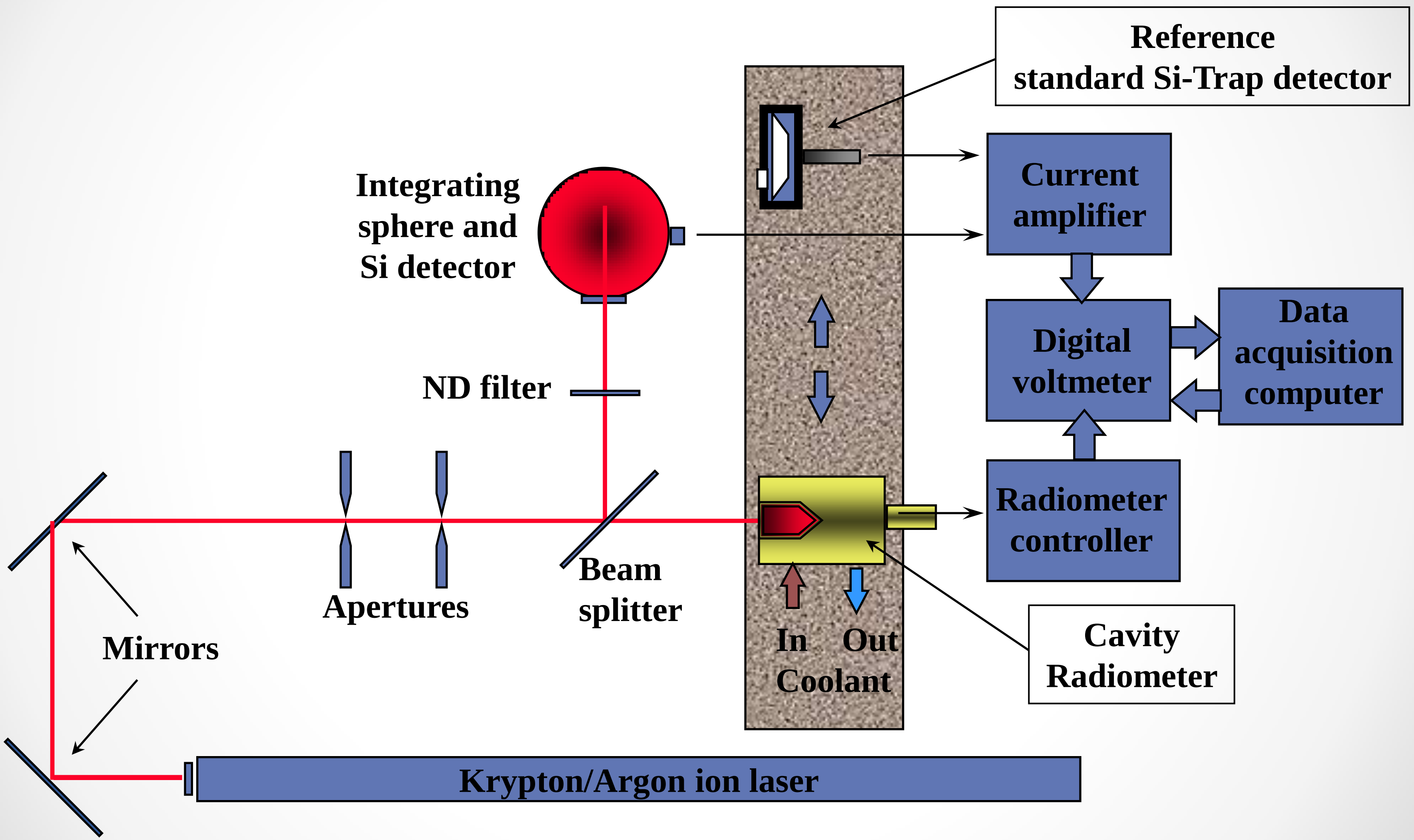


Measured responsivity in the 51 mm and 25 mm VTBB facilities agree
[Component of reflected radiation decreases with increasing *d*/*a*]

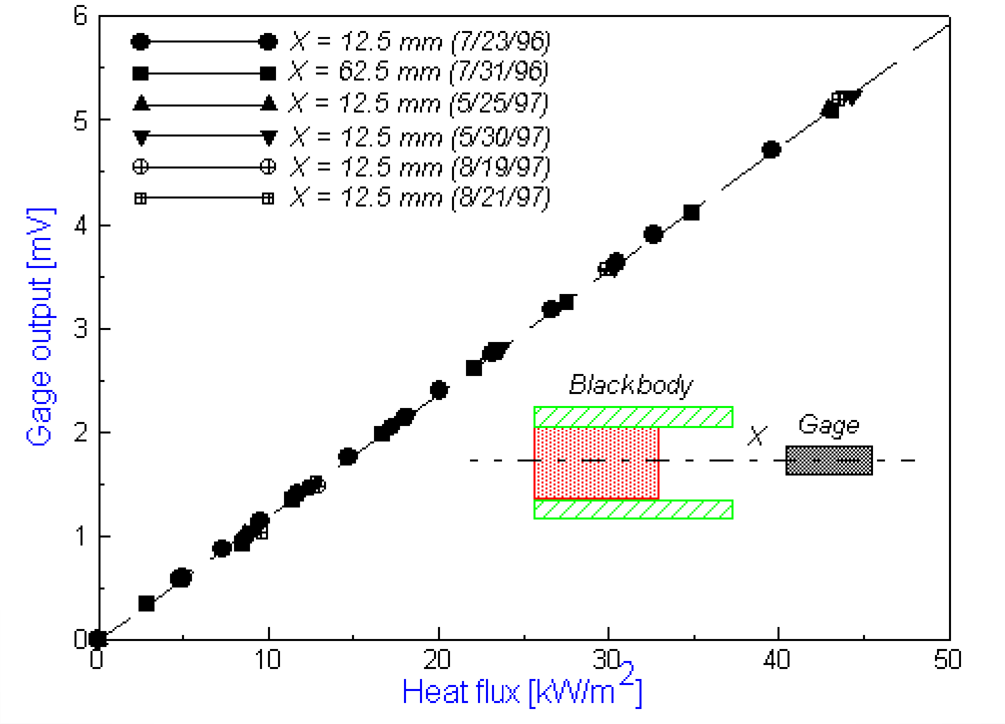
Scaling Calibration from Primary Standard



Cavity-Radiometer Calibration

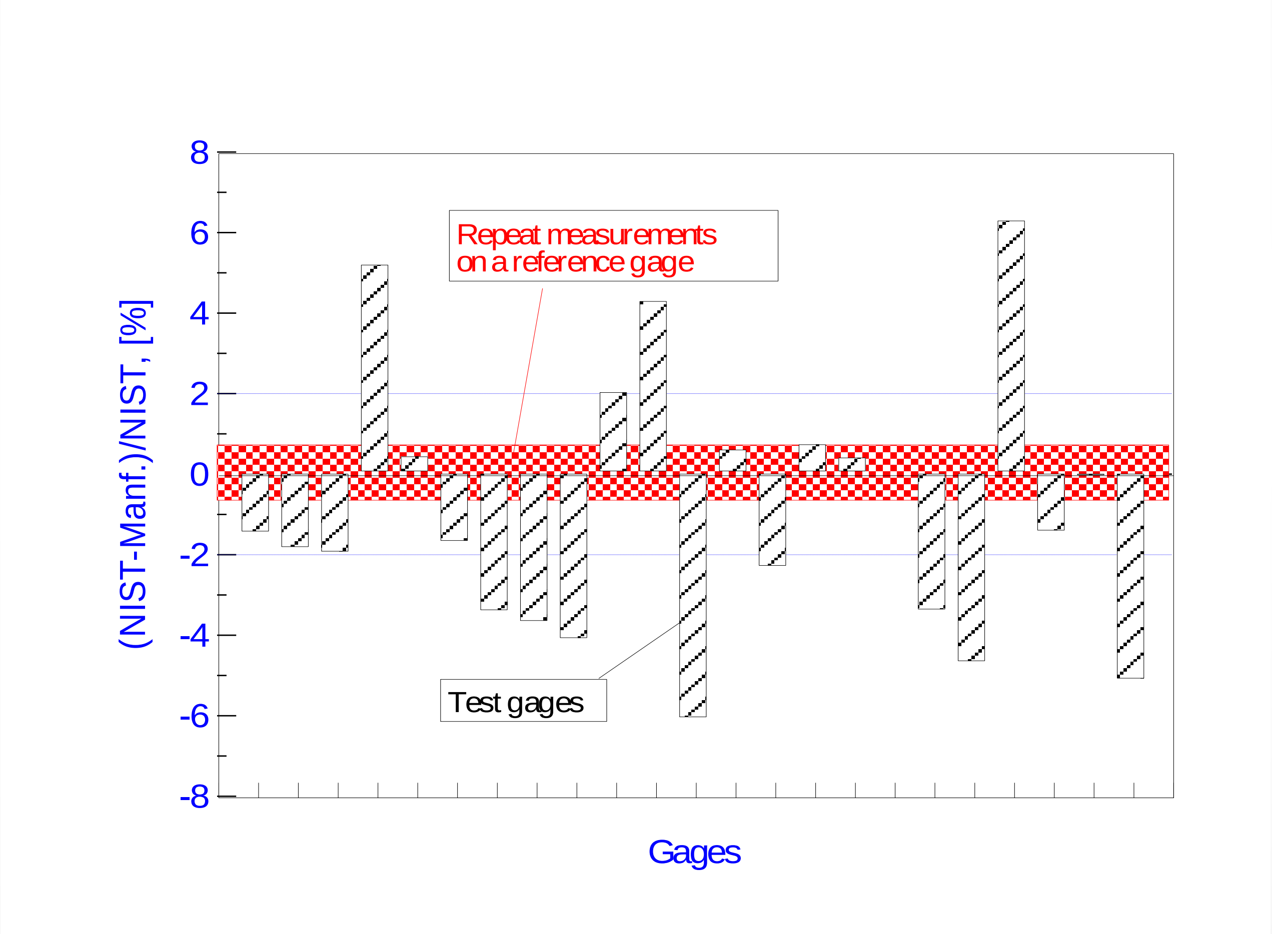


Repeat calibrations on a reference Schmidt-Boelter sensor using the VTBB



NIST National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Comparison of manufacturers' and NIST calibration of different sensors

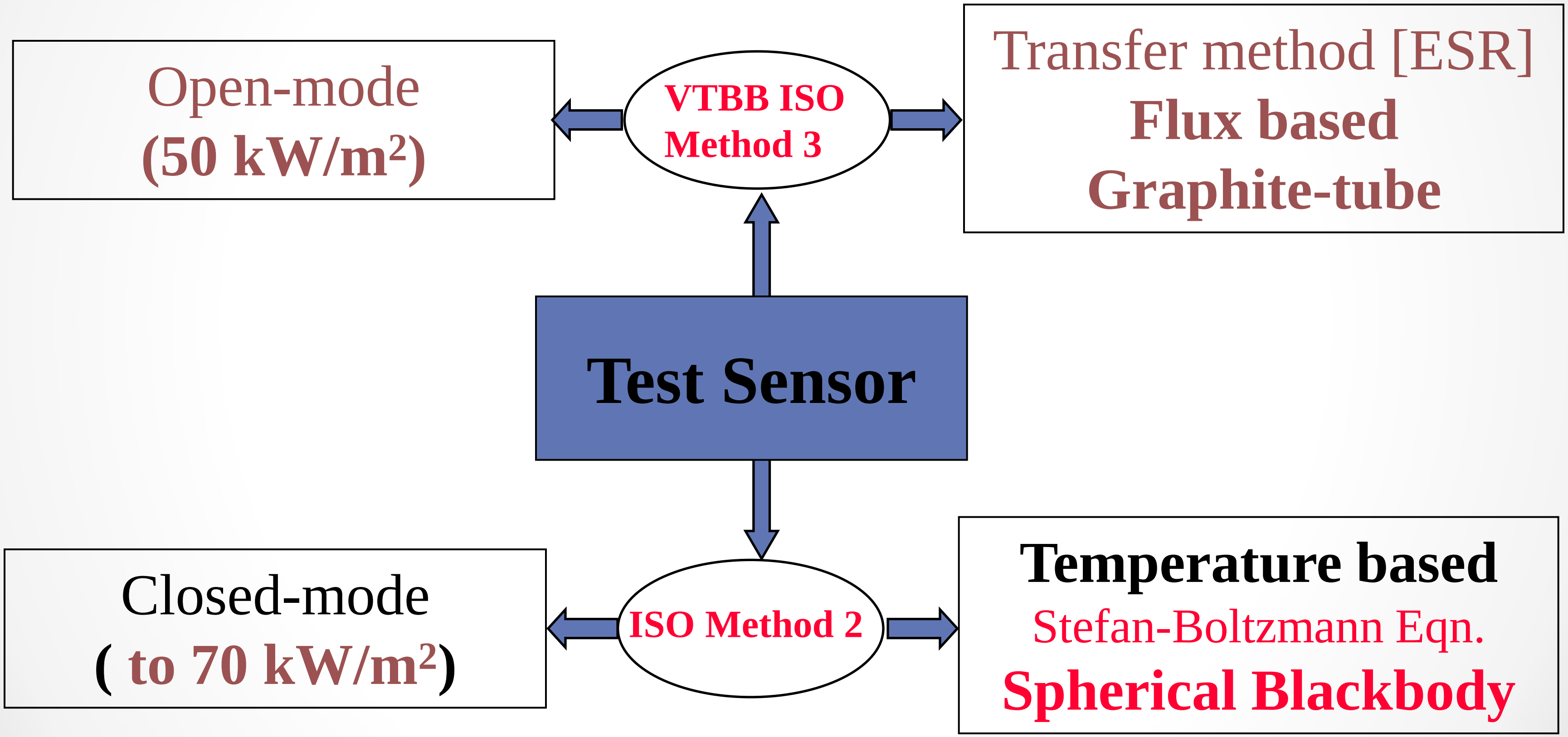


Flux Scale Technique (ISO Method 3) - Merits

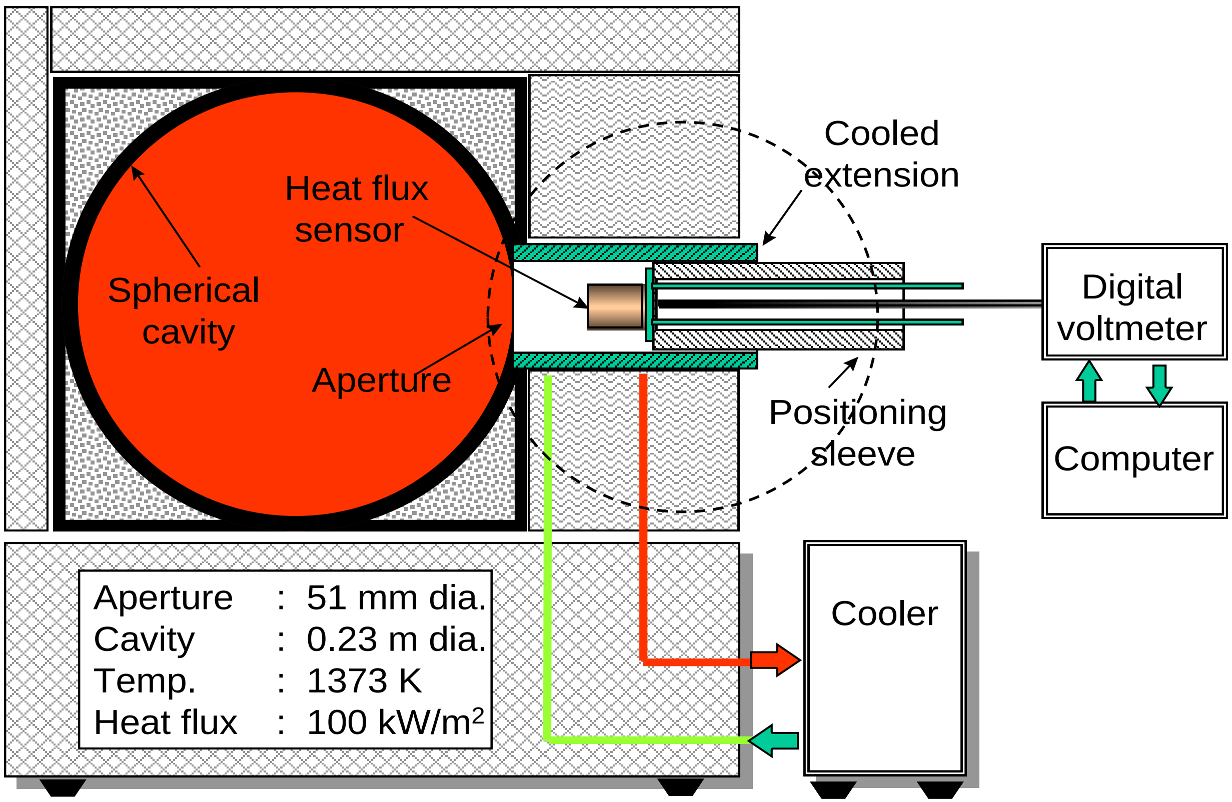
- **Transfer standard radiometer absorbs all the incident flux at the measurement location.**
- **Reflected radiation and other extraneous effects are same on both radiometer and sensor.**
- **Provides flux traceability to national standards.**

Temperature/Flux Scale Comparison

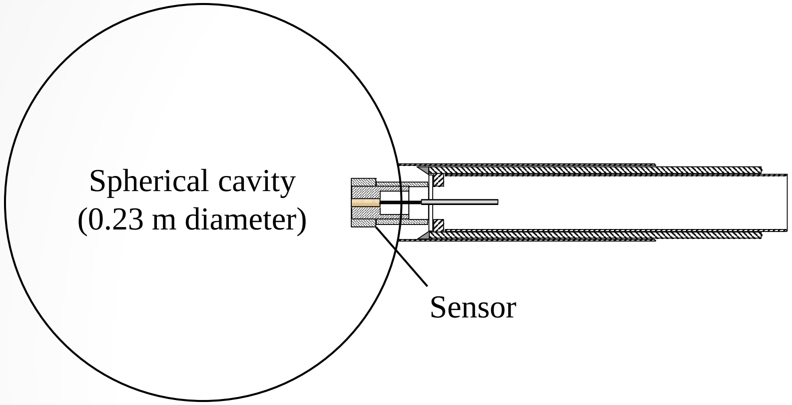
(50 kW/m² to 70 kW/m²)



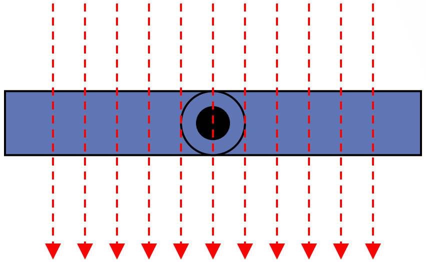
Spherical blackbody - cooled enclosure



Convection effects - Modeling



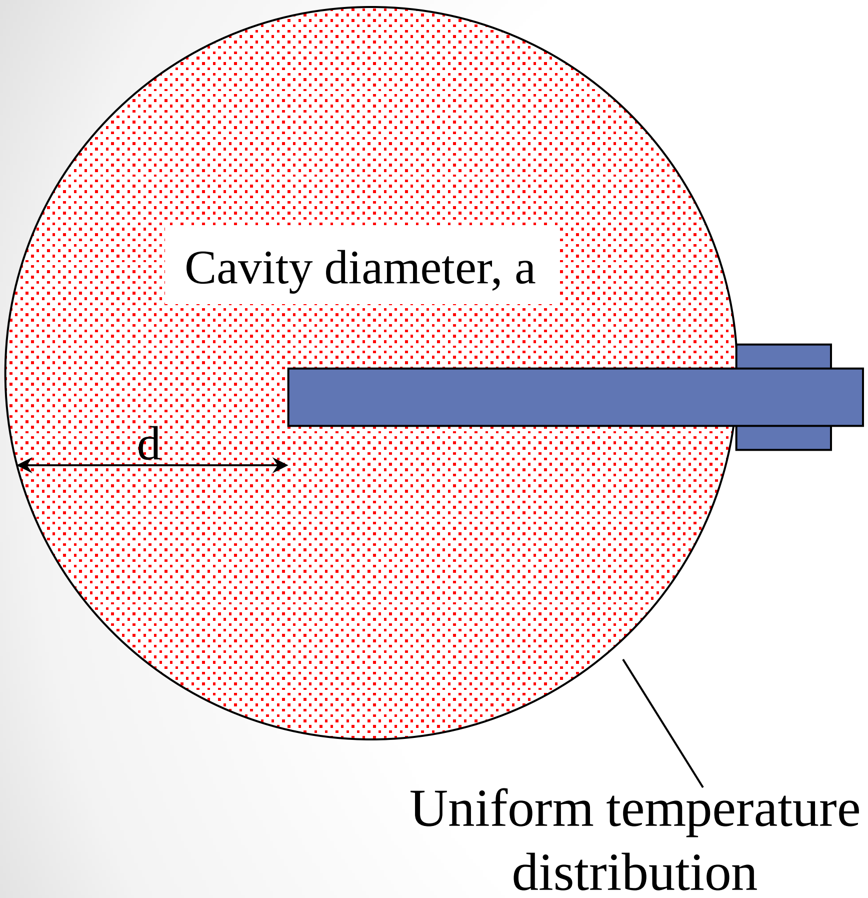
2-D approximation

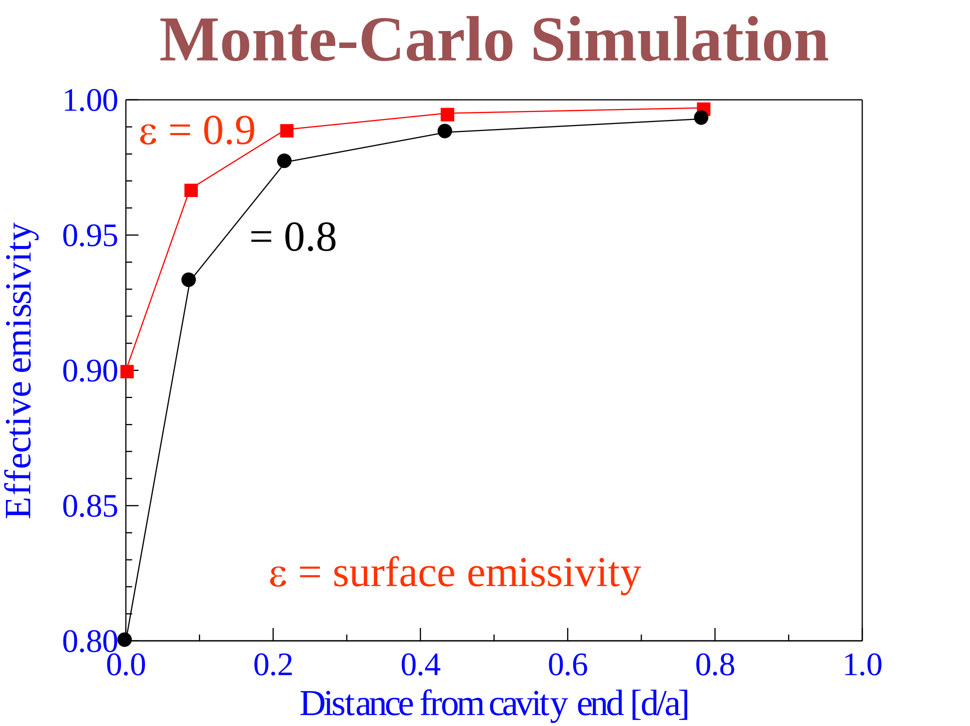


- Cavity surface area large compared to sensor/holder size
- Sensor/holder at ambient temperature (300 K)
- Environment temperature = blackbody temperature (Max)
- Nearly free convection conditions prevail

Rayleigh number: 6×10^4 – 24×10^4, laminar boundary layer

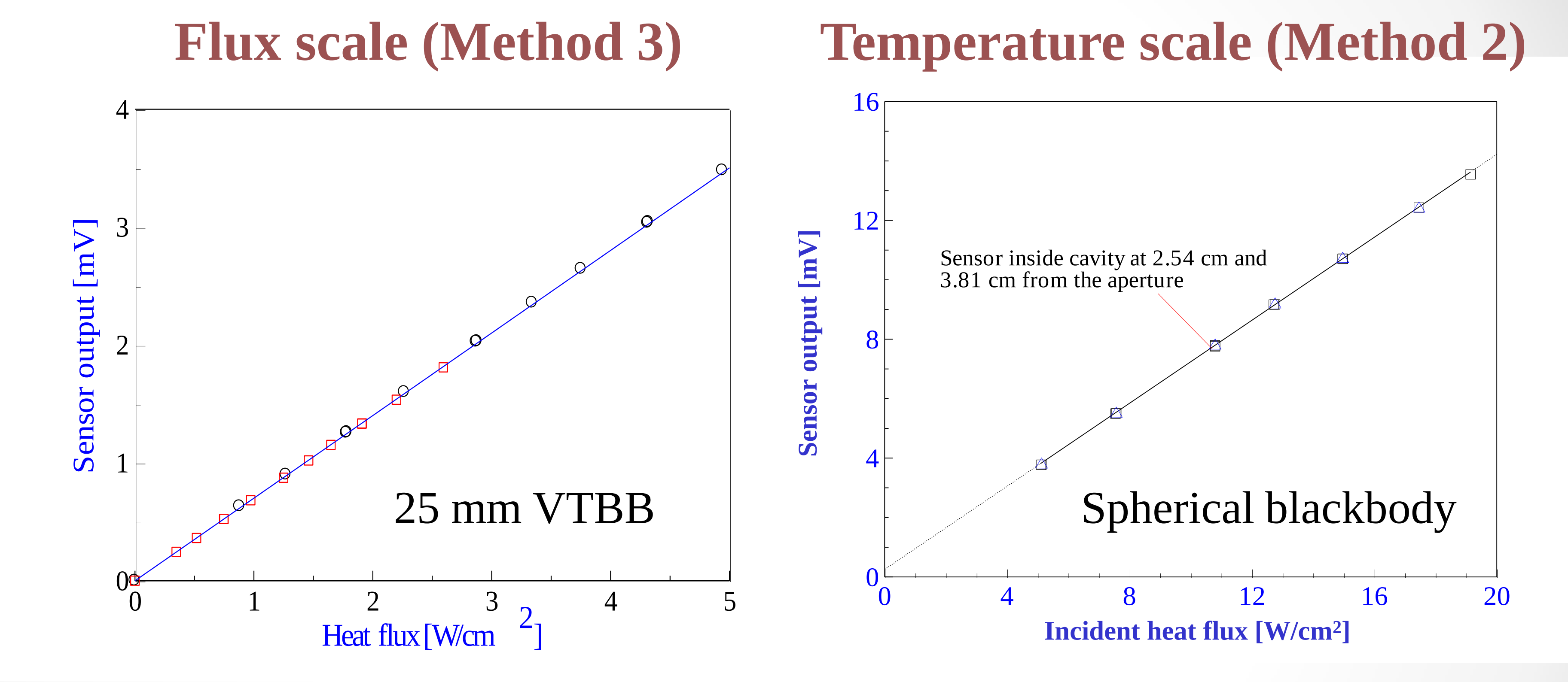
Effective Emissivity





Effective emissivity (hemispherical) at sensor <1.0

Method 3/Method 2 Comparison at NIST



Measured responsivity [0.700 mV/(kW/m²)]
Two methods agree within measurement uncertainty limits

Convection & emissivity effects in spherical blackbody data

Flux (Method 3)/Temperature (Method 2) Scale Comparison

Position	Distance (cm)	View angle	Responsivity
2	-2.54 cm	180 deg.	0.704 mV/(W/cm^2)
2	-2.54 cm		0.698 mV/(W/cm^2)
3	-3.82 cm		0.701 mV/W/(cm^2)
Mean responsivity (Measured)			**0.700 mV/(W/cm^2)**
Corrections			
Effective emissivity		0.5%	
Natural convection		-1.9%	
Corrected Value (Temperature Scale)			**0.689 mV/(W/cm^2)**
Expanded uncertainty (k =2)			**3%**
Flux scale calibration (VTBB)			**0.700 mV/(W/cm^2)**

Temperature and flux based calibrations agree within uncertainty limits

NIST PML Heatflux Gauge Calibration (Method 3) Uncertainties

Uncertainty	Type	Relative uncertainty %
Reference radiometer	B	0,6
Black-body temperature	B	0,1
Black-body emissivity	B	0,0
Black-body aperture uniformity	B	0,0
Sensor/radiometer alignment (distance)	B	0,4
Sensor/radiometer alignment (angular)	B	0,1
Radiometer aperture averaging effect	B	0,1
Radiometer output reading	A	0,2
Sensor output reading	A	0,2
Repeat tests on a similar gauge	A	0,7
Combined expanded relative uncertainty	k = 2	2,1

Heatflux Gauge Comparisons in 2000 and in 2008 as percent differences from SP

		Forum RR (2000-2004) (kW/m^2) at 10 mV			
ISO Method		Schmidt-Boelter		Gardon	
1	LNE	90.32	-0.66%	121.45	0.89%
2	SP	90.92	0.00%	120.38	0.00%
3	NIST	86.4	-4.97%	117.3	-2.56%

		ISO (2008-2010) (kW/m^2) at 10 mV					
ISO Method		Gardon (meter 1)		Schmidt-Boelter (meter 2)		Schmidt-Boelter (meter 3)	
1	LNE	80.9	1.76%	61.9	4.38%	18.7	5.65%
2	SP	79.5	0.00%	59.3	0.00%	17.7	0.00%
3	NIST	75.5	-5.03%	57.3	-3.37%	17.0	-3.95%

Conclusions

- **Flux-scale calibrations (ISO Method 3) suitable when reflected component is large, and/or source characteristics are difficult to establish**
- **Temperature & flux scales equivalence demonstrated within measurement uncertainty (Lambertian sensor)**
- **Intercomparisons show that persistent differences between the three ISO methods exist outside the combined uncertainties**