ONTARIO POWER GENERATION

CANDU Owners Group Inc.

"Excellence Through Collaboration"

Evaluation of Eye Lens Dosimetry at CANDU Power Plants

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Current work at OPG: Need for Eye lens dosimetry at CANDU plants?

- ICRP recommendation in 2011: lowered their recommended dose limits to the lens of the eye in ICRP Publication 118
- The threshold for cataract formation was lowered to an absorbed dose of 0.5 Gy
- Hence, dose limits recommendations for NEWs was lowered from 150 to 20 mSv per year, averaged over 5 years, with no single year exceeding 50 mSv
- To address this issue, 5 year COG program started in 2015
- COG, McMaster University, OPG, Bruce Power
- One of a kind research to establish the need for physical eye dosimetry in nuclear industry (CANDU environment, in particular)

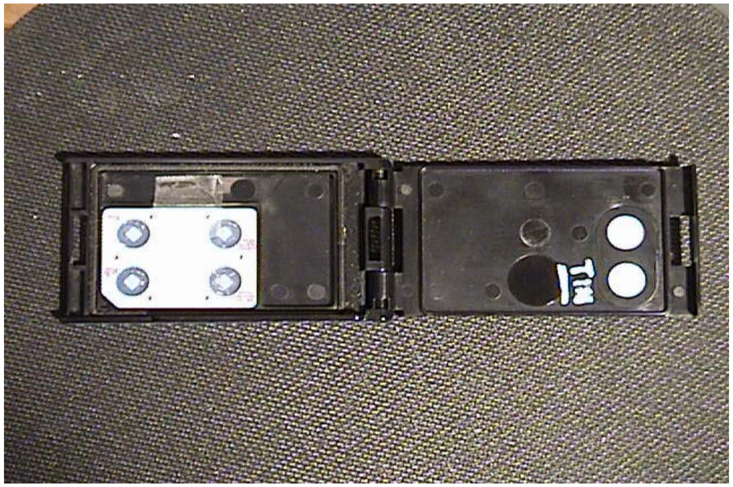
McMaster University-OPG-Bruce Power-COG Work

- Three year COG project started in FY 2015/16
- Led by McMaster University: Dr. Soo-Hyun Byun
- Multiple measurements performed at OPG (Pickering and Darlington) and Bruce Power sites
- Three MSc thesis written and defended:

1. Matthew Wong: ***Development of a Digital Beta-Gamma Spectrometry System for CANDU Open System,*** McMaster University, 2017
2. Andre Laranjeiro: ***The Characterization and Optimization of*** $LaBr_3$***(Ce) Spectroscopy System for High-Rate Spectrometry at CANDU Reactors,*** McMaster University, 2018
3. Farazdak Bohra: ***Measurement and Analysis of Beta-Ray Spectra at the Ontario Power Generation and Bruce Power CANDU Reactors,*** McMaster University, 2018

Our approach to the problem

- Quantify gamma and beta fields in terms of **energy spectra**, i.e. measure the **source term**
- Convert energy spectra into dosimetric quantities of interest
  - protection quantities: eye lens dose, effective dose, skin dose
  - operational quantities: $H_p(10)$, $H_p(0.07)$, $H_p(3)$
- Compare eye lens dose with $H_p(10)$, $H_p(0.07)$
- Compare beta and gamma components of the eye lens dose
- Conclude if additional dosimetry is required for eye lens dose, or present dosimetry is adequate



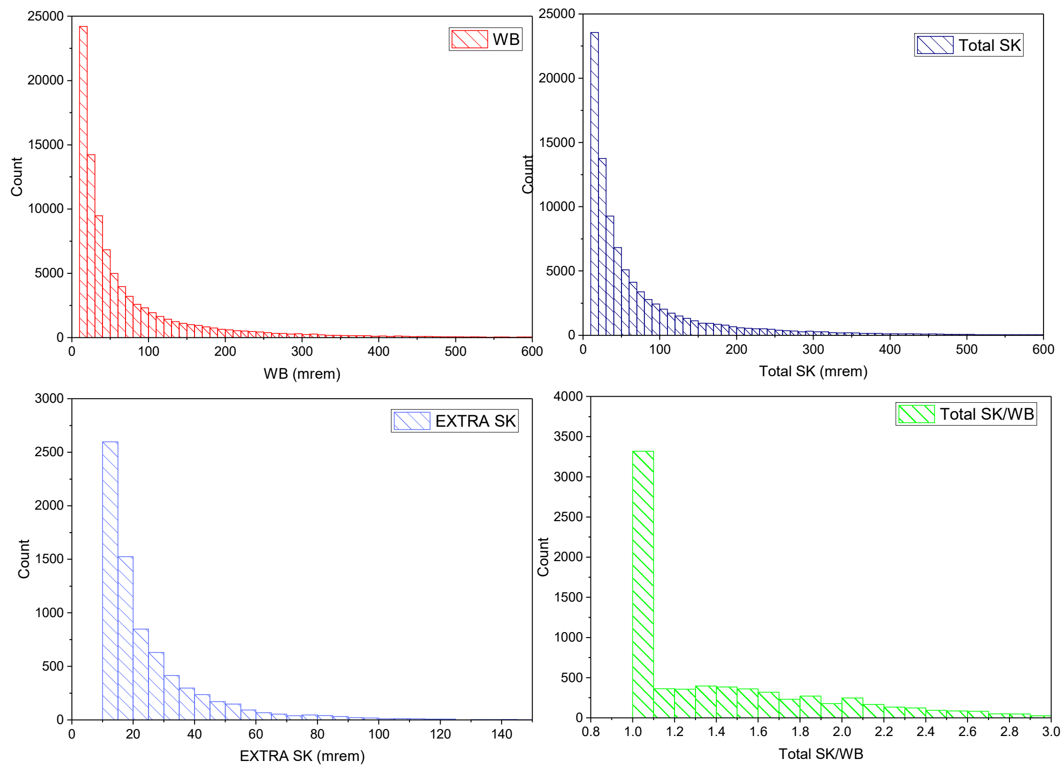
OPG 4 element dosimeter capable of measuring $H_p(10)$, $H_p(0.07)$ and beta/gamma components of $H_p(0.07)$,

Gamma and Beta spectroscopy measurements

- Detector calibrations with beta and gamma source
- Multiple measurements performed at Pickering, Darlington and Bruce Power plants
- Open boilers during the outages
- Irradiated/contaminated components: RAM head of the fueling machine, numerous swipes and smears

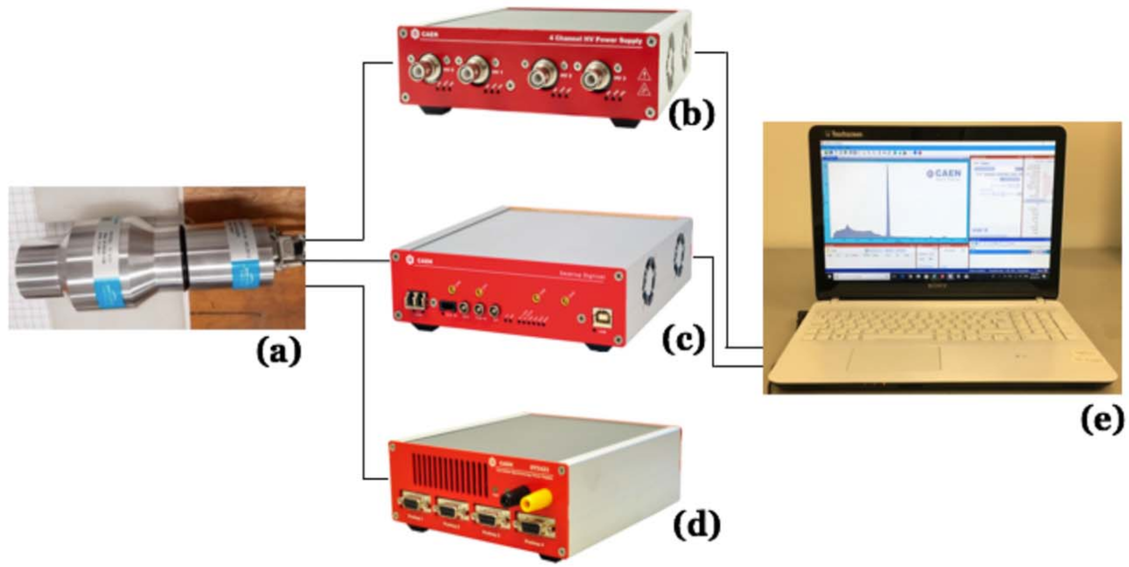
Statistics on OPG TLD results
Reportable results: 2008-mid 2018

- Total # TLD processed: 560,481
- Total # of TLD reportable (Hp(10)>9.5 mrem): 91,225 (16%)
- Total extra SK dose assigned: 7357 (8% of the total reportable, 1.3% of the total processed.



	WB	Total SK	EXTRA SK	Total SK/WB
N total	91225	91225	7357	7357
Mean (mrem)	75.5	77.6	24.6	1.5
Minimum (mrem)	10	10	10	1.004
Median (mrem)	37	38	18	1.20
Maximum (mrem)	1840	1855	292	4.97

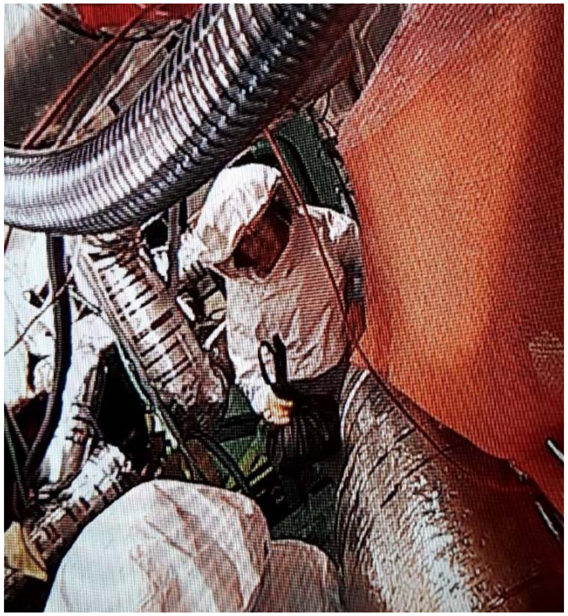
Gamma Detection System

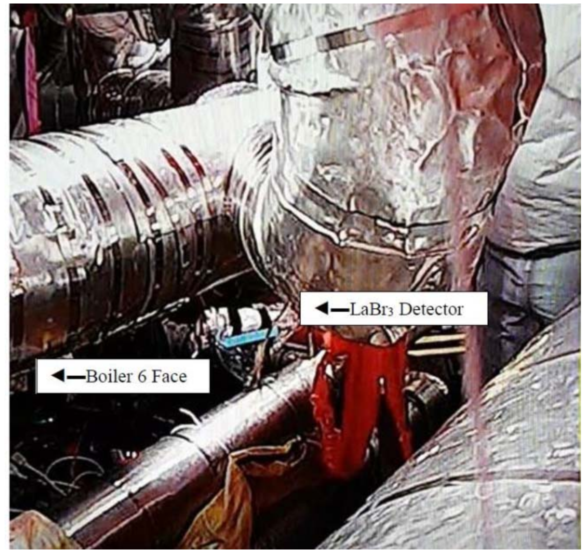


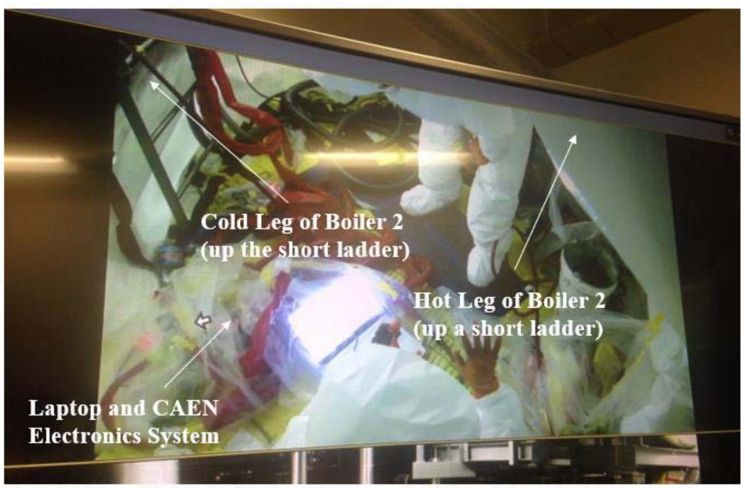
Gamma spectroscopy system consisting of (a) LaBr3(Ce) detector, (b) HV power supply, (c) Digital pulse processor, (d) Preamp power supply, and (e) Data collection laptop

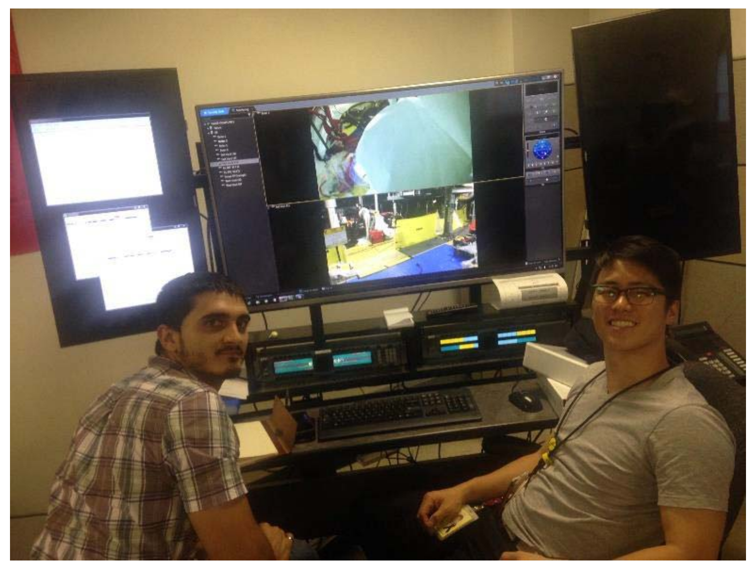
Detection systems sealed and ready for measurements in the reactor containment

Operations at Pickering and Darlington supervised by teledosimetry crew

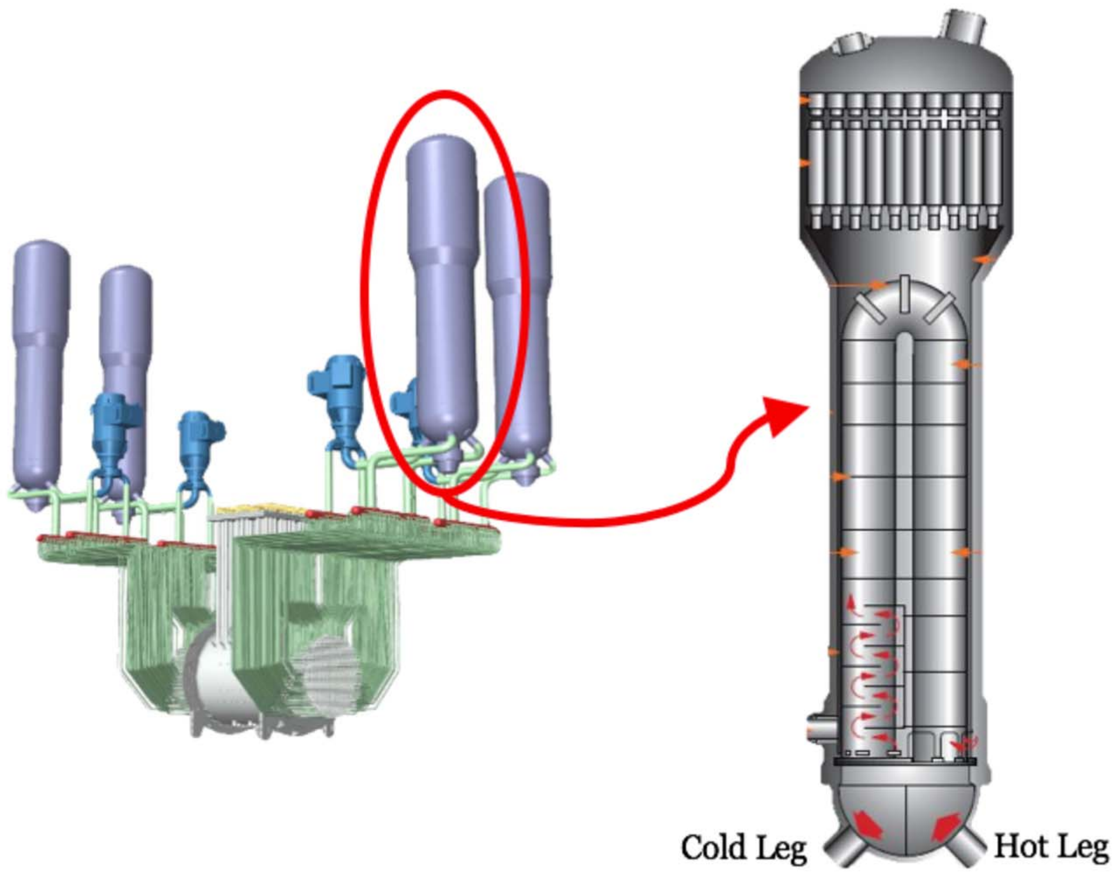






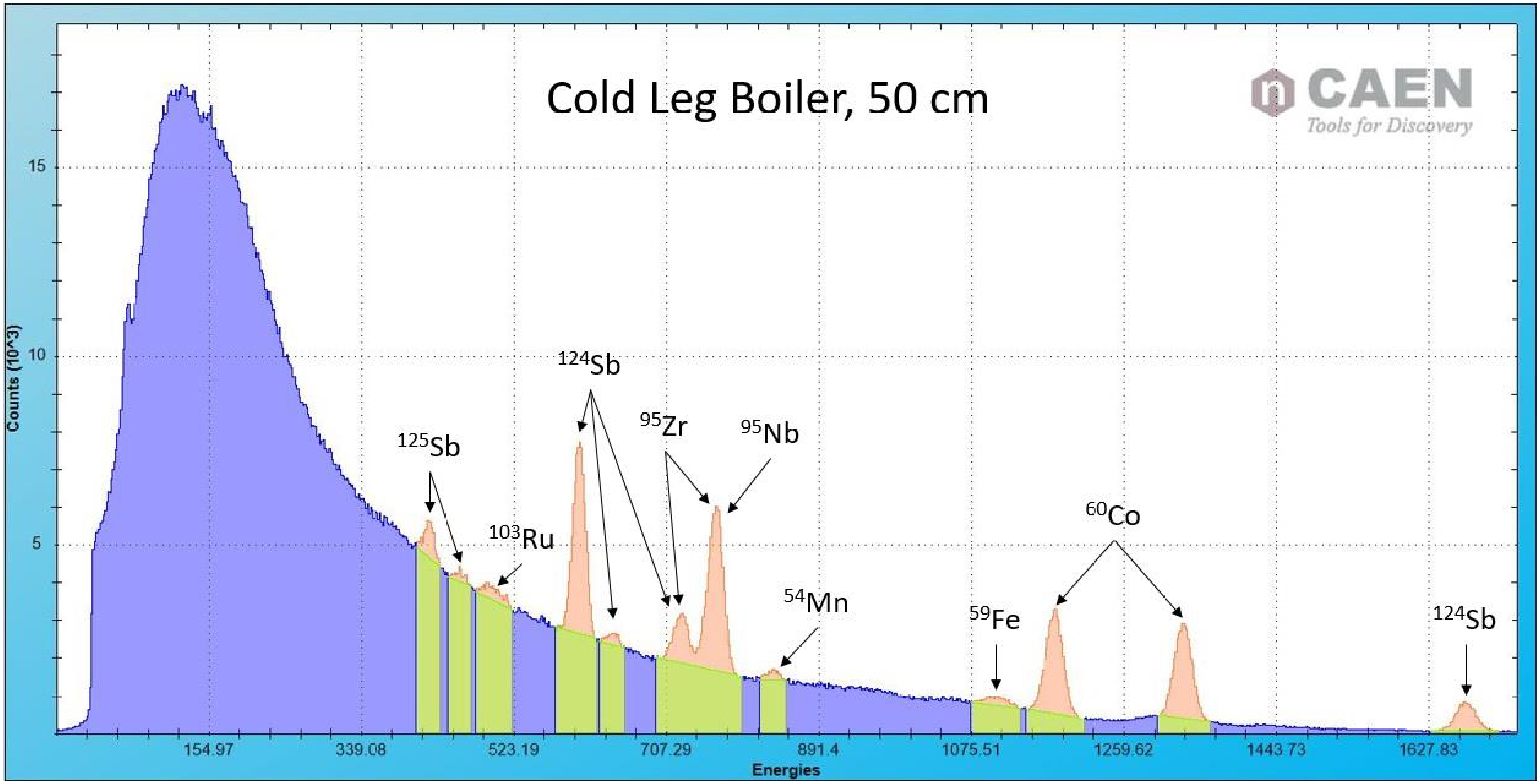


Schematics of Darlington Station Boiler Position

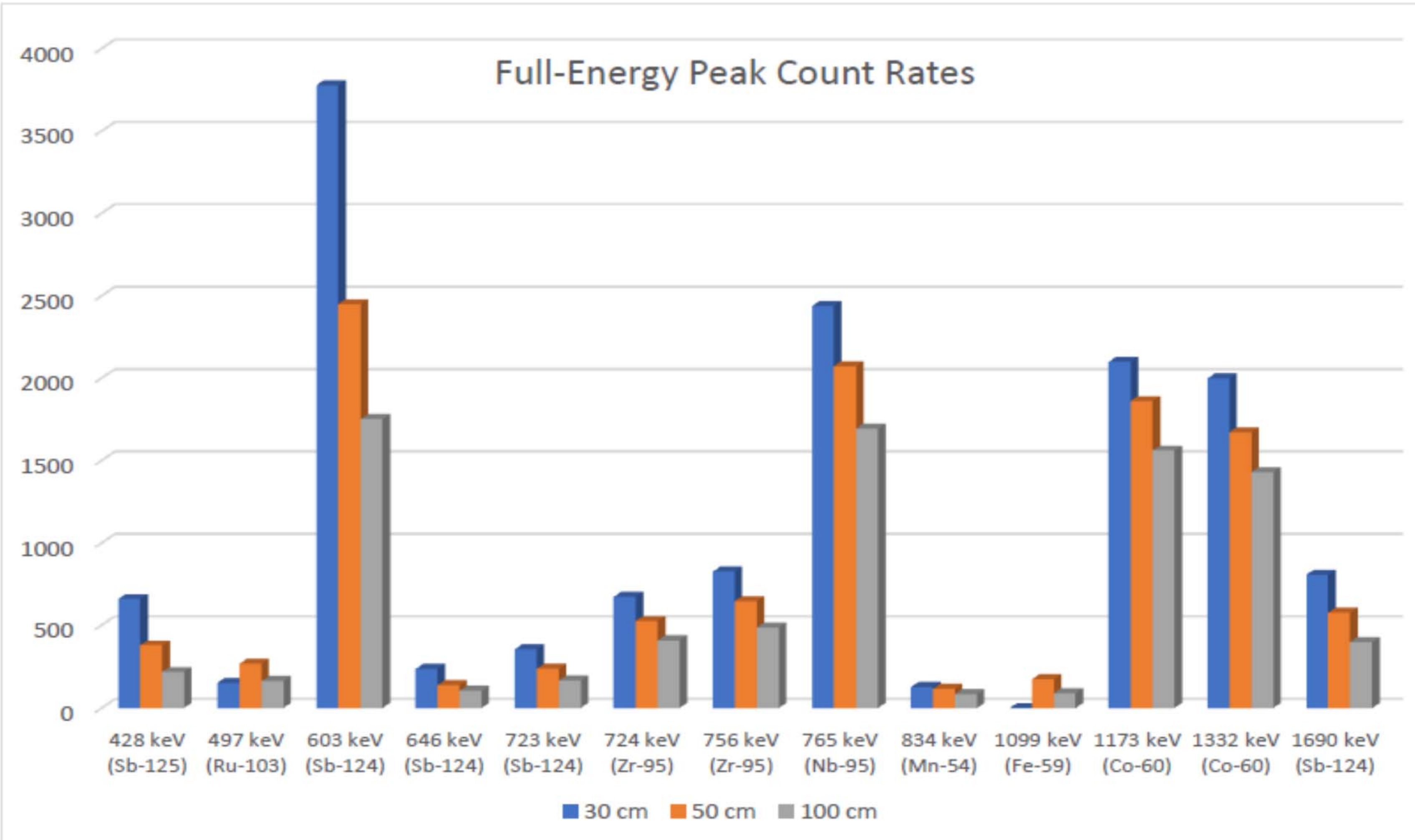


CANDU reactor (left) consisting of calandria, feeder pipes, headers, etc., with a zoomed in boiler (right), showing the hot and cold leg, where PHT water from core goes in and out, respectively.
Source: A. Laranjeiro's MSc thesis and canteach.candu.org

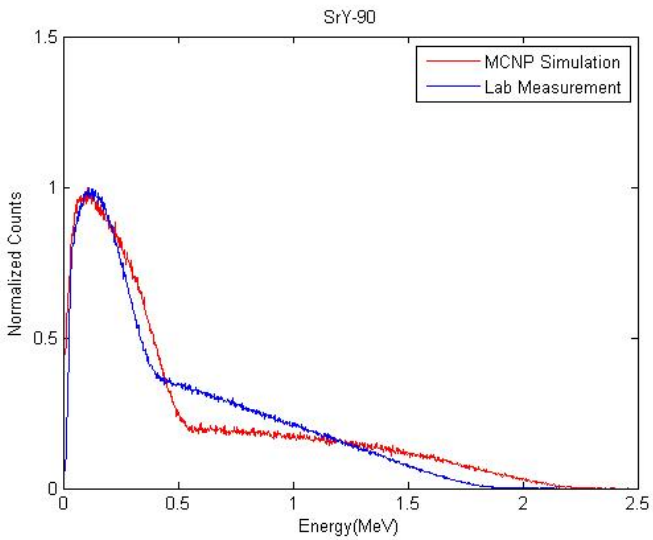
Pickering boiler cold leg measurement with $LaBr_3(Ce)$ scintillator

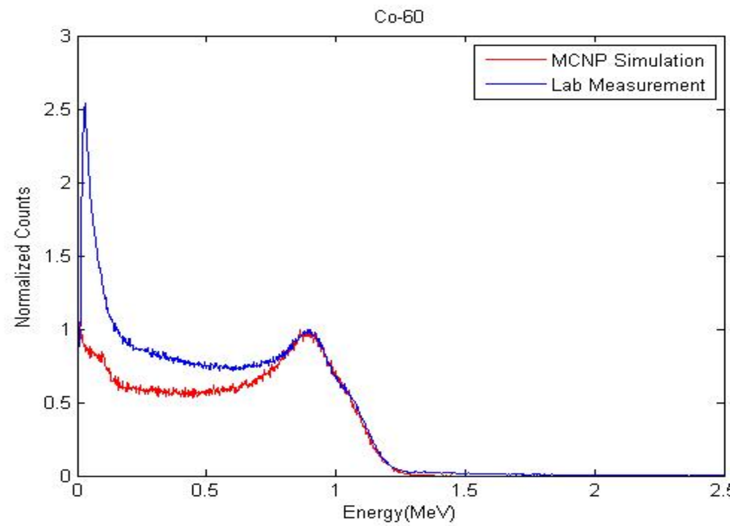


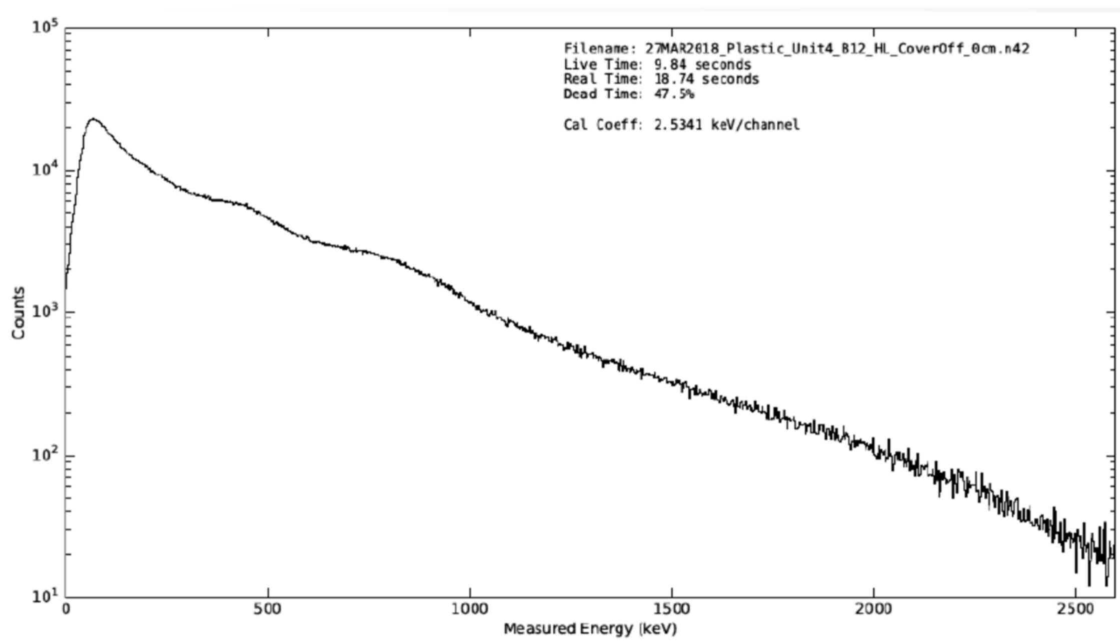
Full energy peak count rates for boiler measurements at Pickering



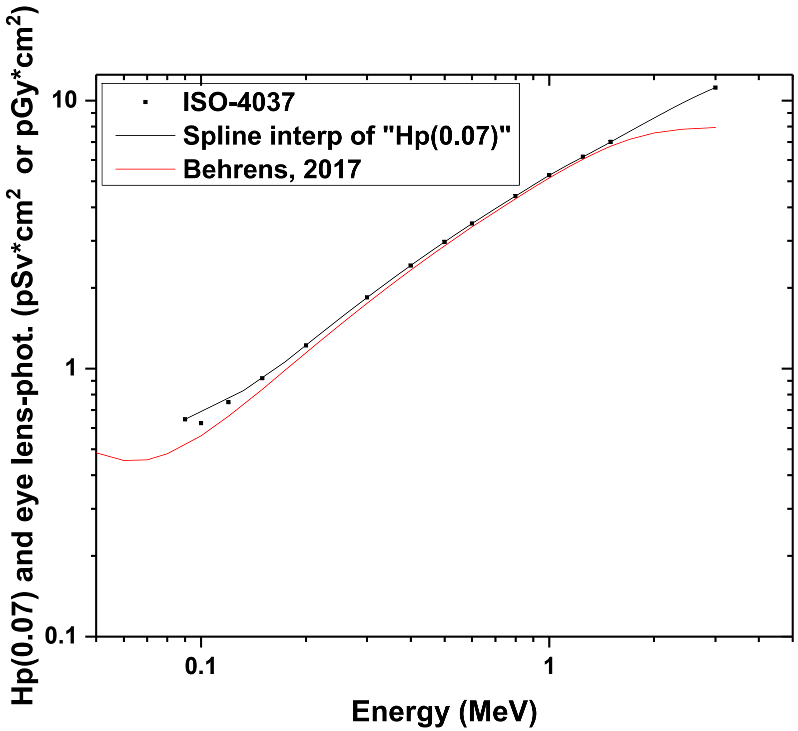
Plastic scintillator spectra: beta, gamma from source and beta/gamma in CANDU environment

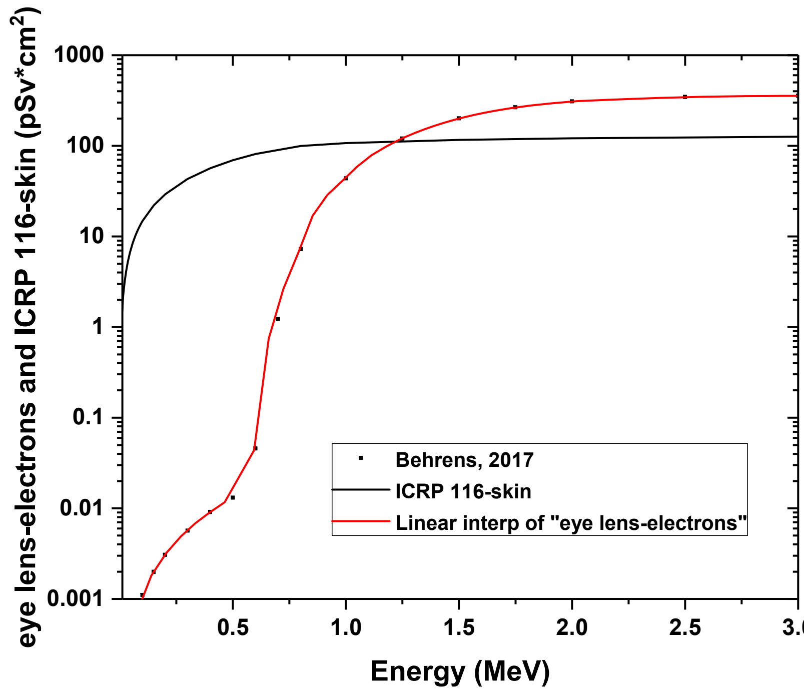






DCCs for photons and electrons used: Hp(10) and Hp(0.07) from ISO-4037, eye lens dose conversion coefficients from ICRP116 and latest Behrens conversion coefficients (*Behrens, RPD (2017), Vol 174, No.3, pp 348-370*)

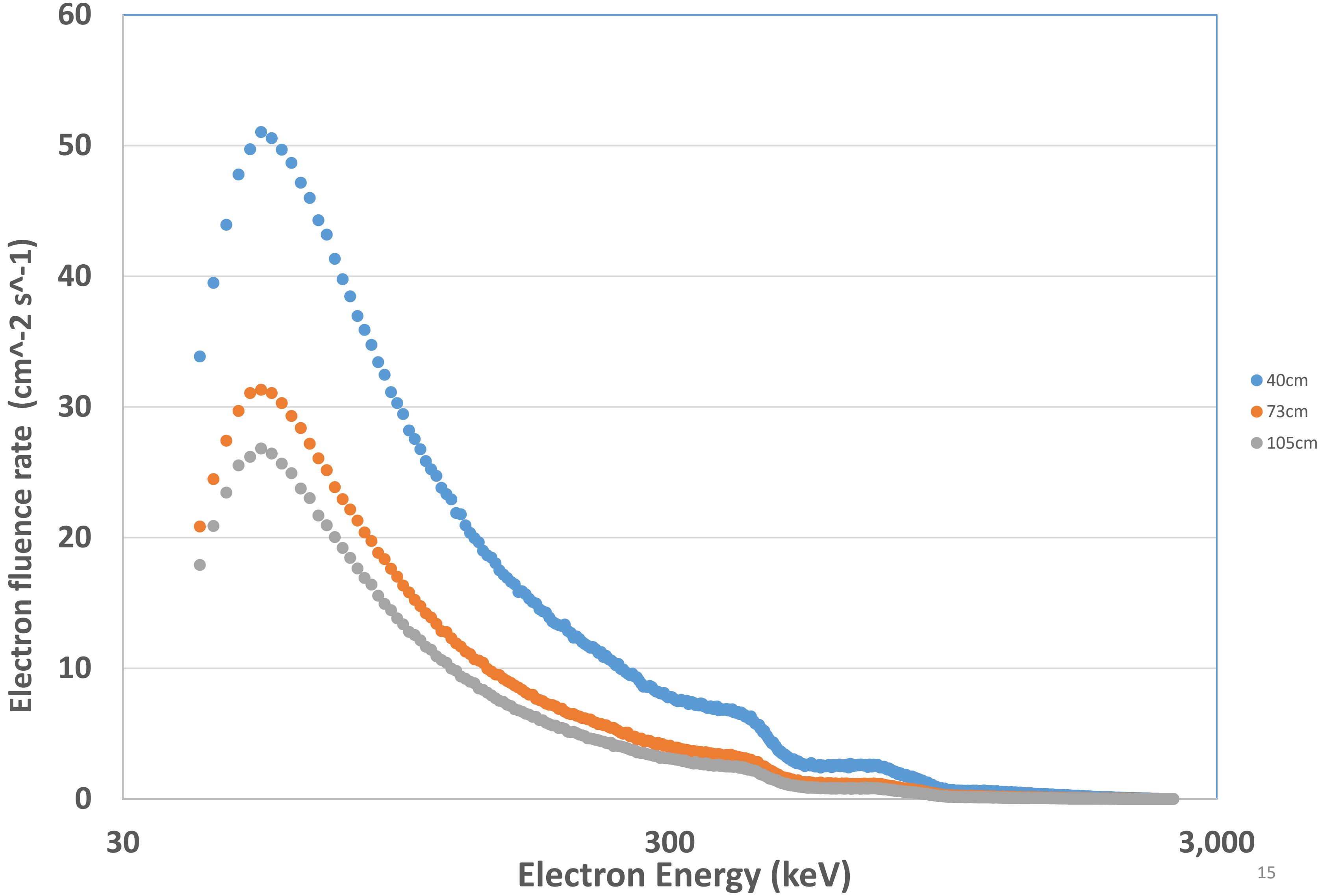




According to Behrens and Dietze (Phys. Med. Biol. 55 (2010) and 56 (2011):

- For photons < 30 keV; Hp(0.07) overestimates eye lens dose between 1.1 and 5 times
- For photons > 30 keV; Hp(0.07)/eye lens dose ~ 1.1
- For electrons < 600 KeV and photons; Hp(0.07) overestimates eye lens dose between 1 and 550 times
- For electrons > 600 keV and photons; Hp(0.07) overestimates eye lens dose between 1 and 60 times

Measurements at Pickering (plastic scintillator): Pure Beta Spectra at three distances from open boiler



Results of measurements: *Pickering Unit 4, Boiler 12, Hot leg*

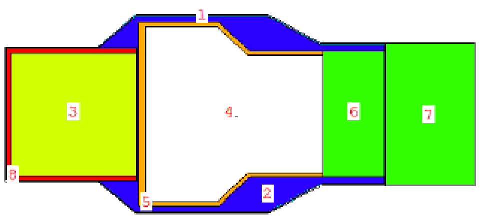
	Eye lens dose rate (mrad/h)		Skin (SK) dose rate (mrem/h)		Whole body (WB) dose rate (mrem/h)	
	$\dot{D}_{lens,\beta}$	$\dot{D}_{lens,\gamma}$	$\dot{H}_p(0.07)_\beta$	$\dot{H}_p(0.07)_\gamma$	$\dot{H}_p(10)_\beta$	$\dot{H}_p(10)_\gamma$
Pos 1	9.4	6.7	43.0	6.8	1.6	6.8
Pos 2	2.9	6.3	20.2	6.5	0.7	6.5
Pos 3	0.4	4.2	1.0	4.3	0.1	4.3

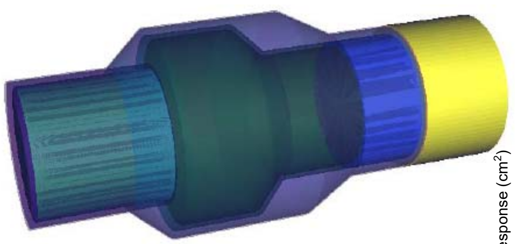
Conclusion:

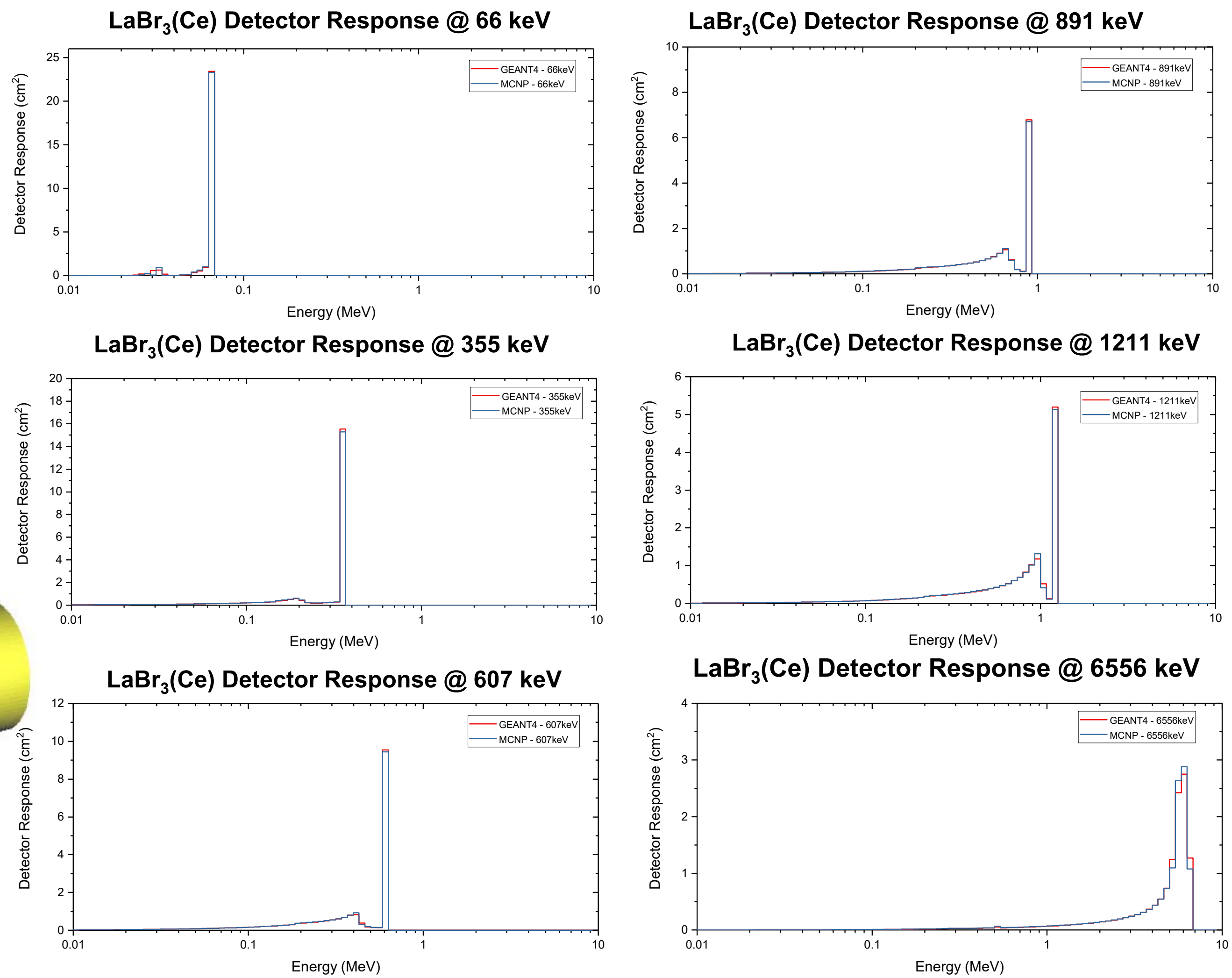
Field measurements showed that in CANDU mixed fields:

- gamma portions of Hp(10) and Hp(0.07) are conservative estimates of gamma portion of eye lens dose,
- while beta portion of Hp(0.07) is a very conservative estimate of beta portion of eye lens dose.
- This is in agreement with *Behrens and Dietze*, Phys. Med. Biol., 55(2010) 4047-4062 and Phys. Med. Biol., 55(2011) 511

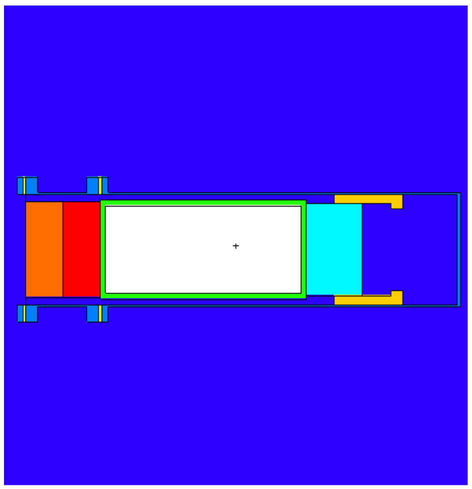
Monte Carlo work: Calculation of $LaBr_3(Ce)$ photon response functions using GEANT4 and MCNP

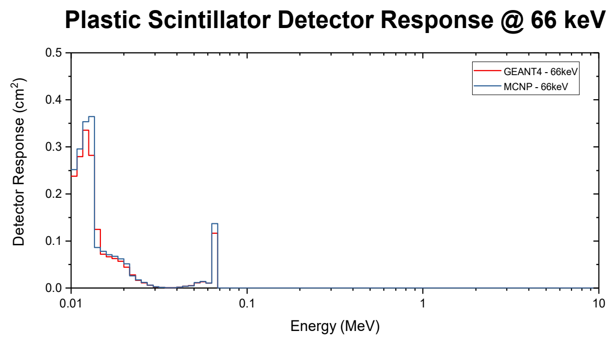


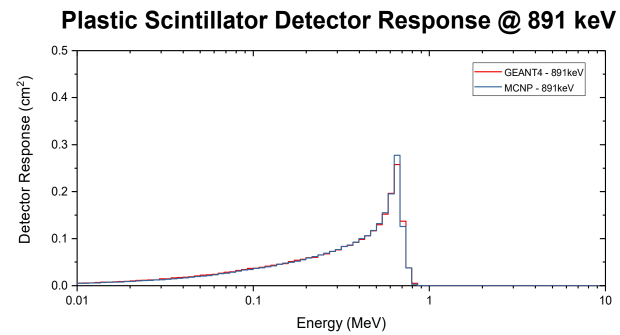


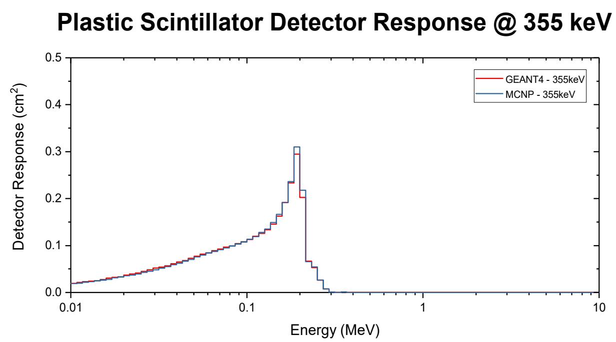


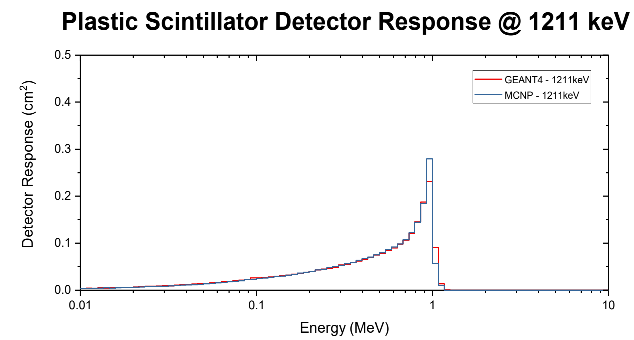
Monte Carlo work: Calculation of plastic scintillator photon response functions using GEANT4 and MCNP

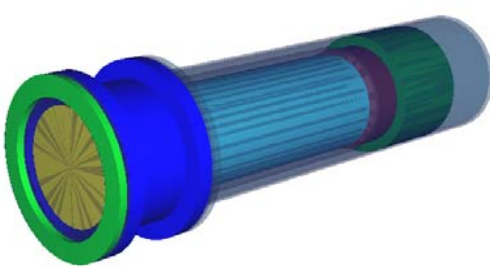


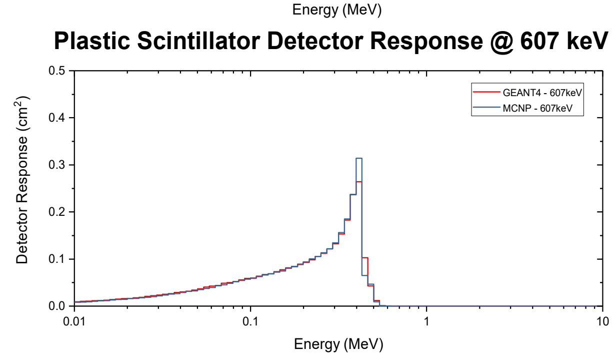


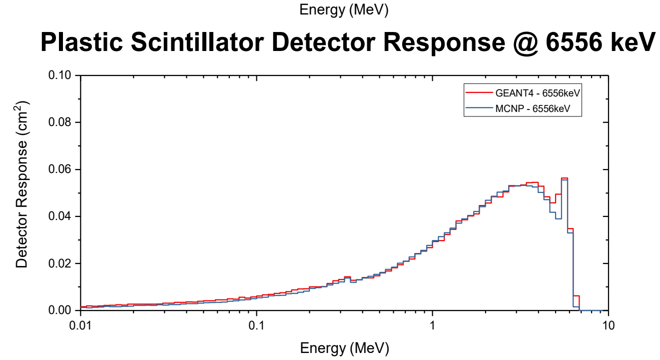




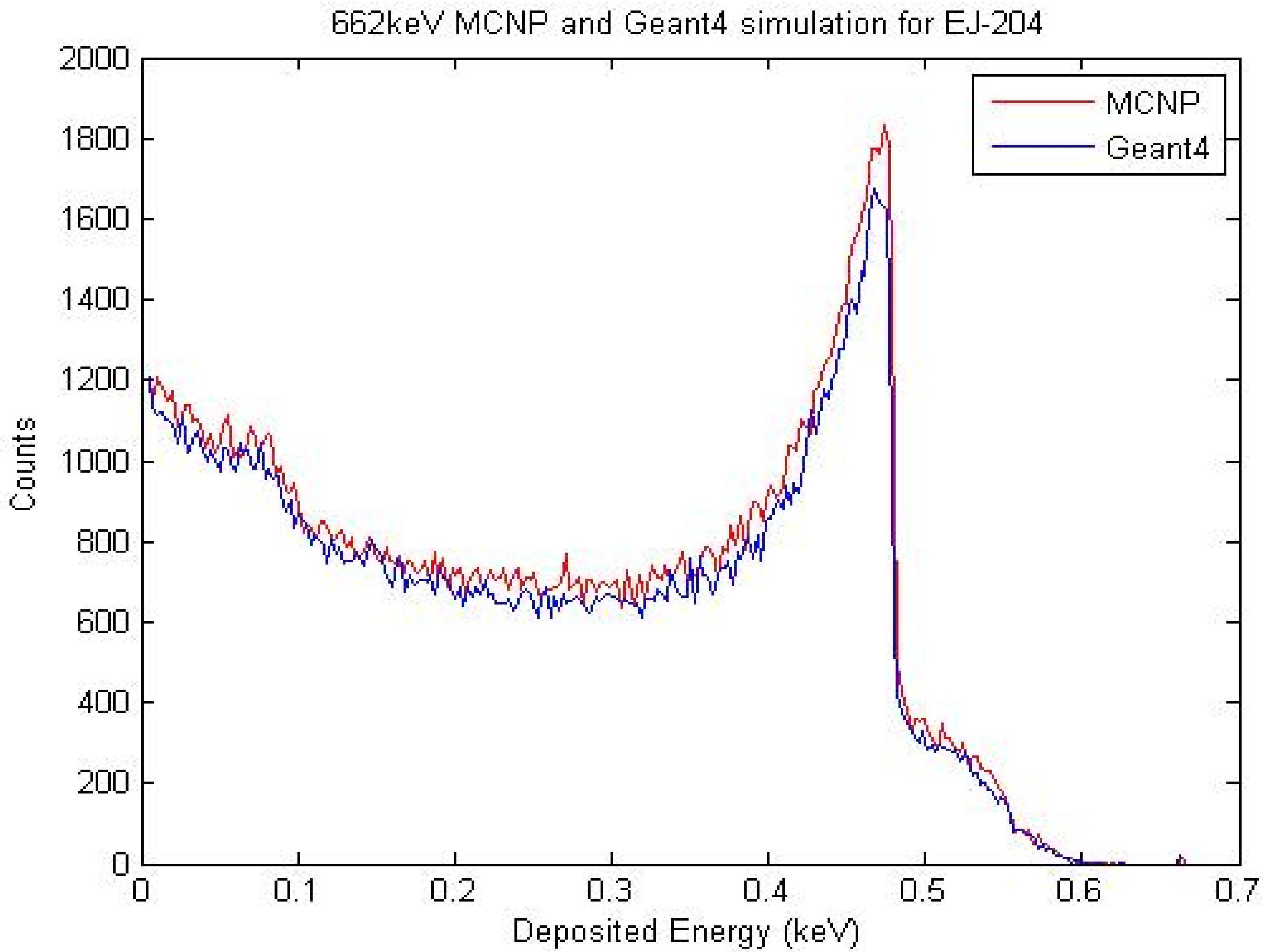








GEANT4 and MCNP Simulation of plastic scintillator response for 662 keV gamma rays



Monte Carlo work: calculations of eye lens dose conversion coefficients using MCNP

Behrens, Rad. Prot. Dosim., 174-3 (2017), 348-370

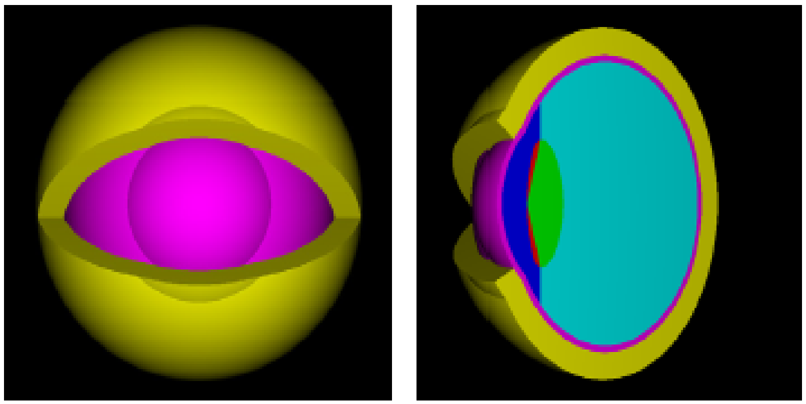


Figure 2. Three-dimensional views of the eye geometry used in the simulations. The different colours indicate different materials (see table 1). The graphs were produced using egspp (Kawrakow 2005).

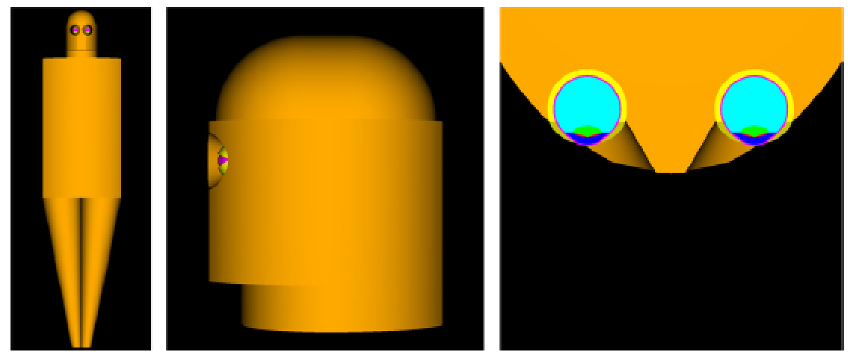


Table 1. Density and composition of substances used in the calculations.

	Lid (skin)[a]	Lens[b]	Aqueous humour[c]	Vitreous humour[c]	Cornea[d]
Colour used in figure 2	Yellow	Red/green sensitive/insensitive	Dark blue	Light blue	Magenta
Density in $g\ cm^{-3}$	1.09	1.06	1.003	1.0089	1.076
Scaling factor relative to water[e]	0.982	0.979	1.000	1.000	0.985
Element	Mass fraction (%)				
H	10.0	9.6	11.2	11.2	10.16
C	20.4	19.5			12.62
N	4.2	5.7			3.69
O	64.5	64.6	88.8	88.8	73.14
Na	0.2	0.1			0.065
P	0.1	0.1			0.065
S	0.2	0.3			0.195
Cl	0.3	0.1			0.065
K	0.1				

We created equivalent MCNP models and the results are in excellent agreement with Behrens’ data

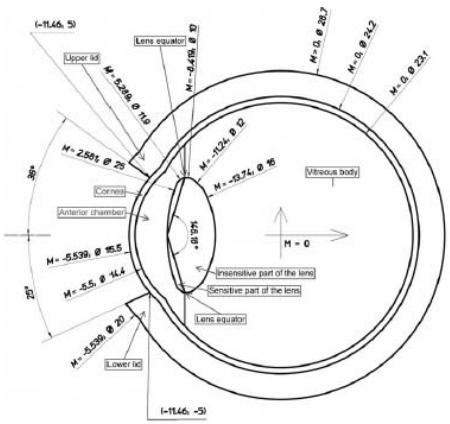
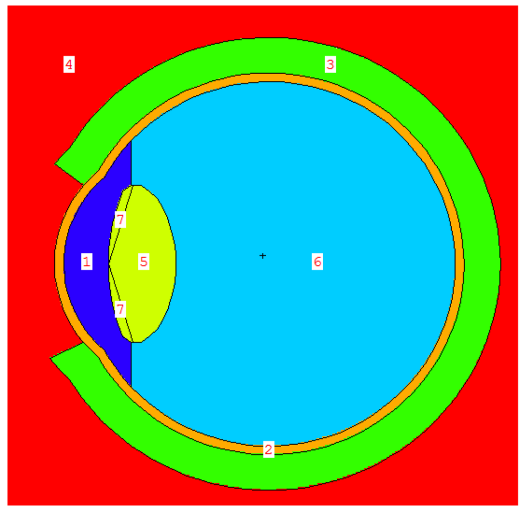
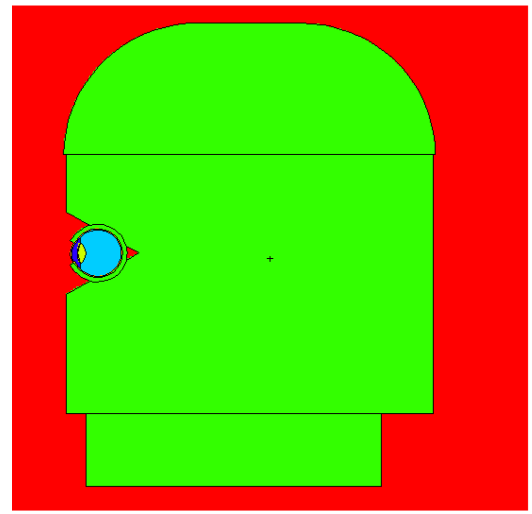
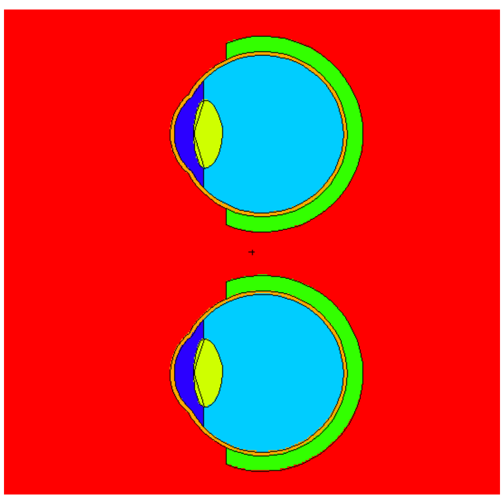
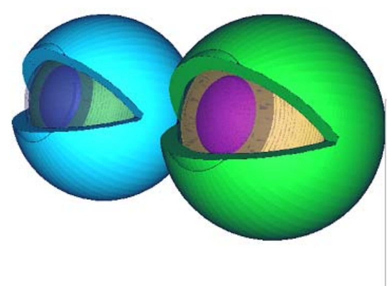


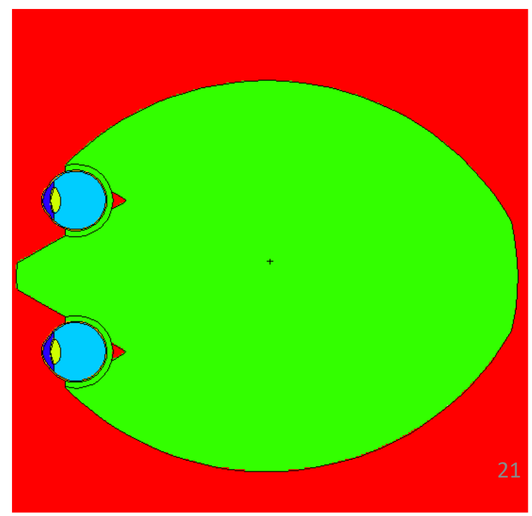
Figure 1. Eye geometry used in the simulations. All dimensions are given in mm. *M* denotes the *x*-position of the centres of the spheres (*M* = 0 denotes the centre of the eye ball) and Ø denotes the corresponding diameters.











Conclusions

- Detectors well characterized using laboratory measurements and Monte Carlo (GEANT4 and MCNP codes)
- Beta and gamma measurements performed in mixed fields at both OPG and Bruce Power
- For plastic scintillator detector, two techniques for separating gamma signal from beta signal were developed: direct subtraction and unfolding
- Literature Dose Conversion Coefficients (DCCs) validated with MCNP, by creating realistic eye and head geometries
- Three MSc theses written on this work
- $LaBr_3$(Ce) and plastic scintillator response functions successfully calculated using GEAN4 and MCNP
- Field measurements showed that in CANDU mixed fields: gamma portions of Hp(10) and Hp(0.07) are conservative estimates of gamma portion of eye lens dose, while beta portion of Hp(0.07) is a very conservative estimate of beta portion of eye lens dose (in agreement with present literature)
- OPG Head TLD dosimeter is adequate protection for eye lens dose in CANDU power plants

Team members

- Dr. Soo Hyun Byun, Professor, McMaster University (team leader)
- Dr. Jovica Atanackovic, OPG, Senior Scientist, Dosimetry
- Dr. Andrei Hanu, Bruce Power, Senior Scientist, Dosimetry
- Andre Laranjeiro, MSc, OPG (former McMaster)
- Farazdak Bohra, MSc, OPG (former McMaster)
- Matthew Wong, MSc, OPG (former McMaster)

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- **John Chase**, *External Dosimetry Specialist*
- **Dr. Kristina Taylor**, *Manager, Dosimetry*
- **Joe Zic**, *Radiation Protection Manager, Pickering (present Senior HP, McMaster U.)*
- **Karen McDougall**, *Radiation Protection Manager, Pickering*
- **Ben Chui**, ALARA *Section Manager, Darlington*
- **Ephraim Schwartz**, *Manager, Health Physics*
- **Liette Lemieux**, *Director, Radiation Safety*
- **Peter Ernst**, *Program Manager, CANDU Owners Group, Inc.*
- RP staff from both Pickering and Darlington stations

Thank you for you attention!