Assessment of radiological hazard and occupational dose to the lens of the eye at the Bruce Power Nuclear Generating Station




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Bruce Power
Innovation at work

Bruce Power Overview

- Largest operating nuclear facility in the world
- The province's single largest source of power (6,400 MW at peak).
- Supply 30% of Ontario's electricity at 30% less than the average cost to generate residential power
- 4,200 employees that operate and maintain eight CANDU nuclear reactors

Bruce Power and OPG are participating in a 5 year research program to assess the need for eye dosimetry within CANDU NPPs

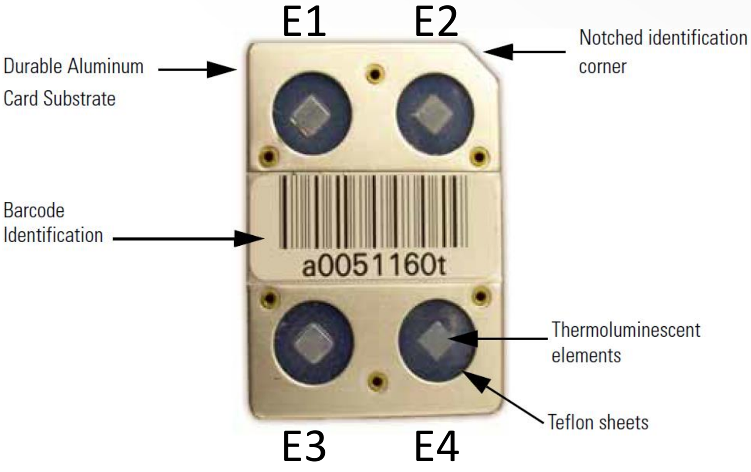
2012 – The ICRP published **ICRP Publication 118**

- Strengthening epidemiological evidence suggesting it is more appropriate to treat radiation induced cataract formation as a stochastic rather than a deterministic effect
- The threshold for cataract formation was lowered to an absorbed dose of 0.5 Gy (50 Rad)
- The recommended eye dose limit for nuclear energy workers (NEWs) was lowered to 50 mSv (5 Rem) per year and 100 mSv (10 Rem) over 5 consecutive years

2015 – The CANDU Owners Group (COG), McMaster University, Ontario Power Generation (OPG), and Bruce Power initiated a 5 year research program to assess the need for eye dosimetry programs within CANDU nuclear power plants. The research program adopts the following 5-step approach:

1. Survey historical dosimetry data and identify locations and working conditions that <u>may</u> pose a radiological hazard for the lens of the eye
2. Develop a spectroscopic detection system to characterize the gamma and beta source terms during routine plant outage work
3. Develop algorithms to process the spectroscopic data and calculate dosimetric quantities for the skin, lens of the eye, and whole body
4. Compare lens of the eye dose with whole body and skin dose
5. Conclude if eye dosimetry programs are required in CANDU NPPs

The Bruce Power and OPG personnel TLD system can measure both shallow and deep whole body dose

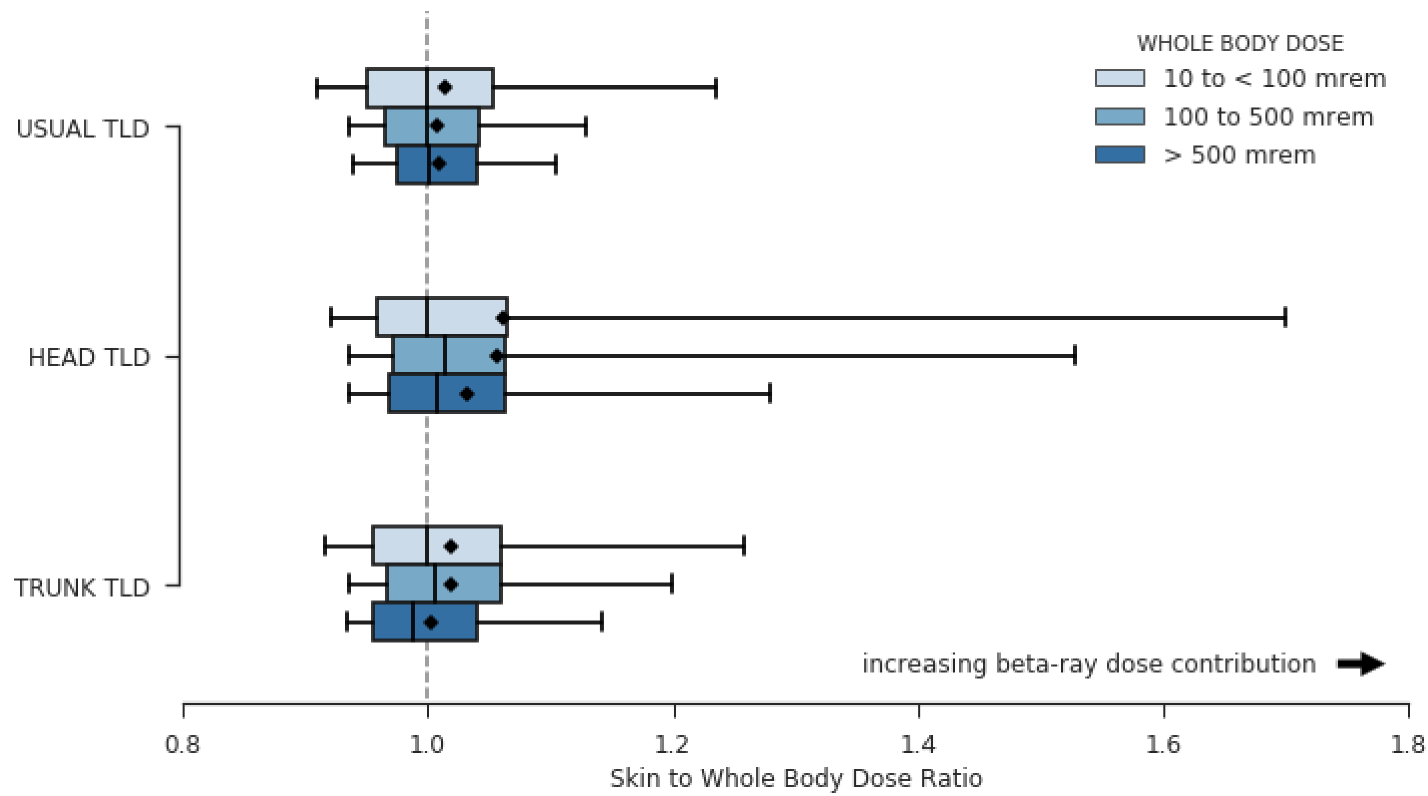


- In use since Q3, 1999
- TLD badge consists of:
  - a Harshaw four-element TLD-700 card
  - a Thermo Fisher 8828-OPG badge case
- Measures whole body, $H_p(10)$, and skin, $H_p(0.07)$, dose for both gamma and beta radiation fields*
- TLD badges readout monthly before Jan, 2017
- TLD badges readout quarterly after Jan, 2017
- ~13, 000 TLD badges processed per quarter
- <10% of TLD badges readout since Jan, 2000 contained whole body doses > 10 mrem
- Unable to directly measure dose to the lens of the eye, $H_p(3)$, without modification

References

* Chase, W. J., and C. R. Hirning. "Application of radiation physics in the design of the Harshaw 8828 beta–gamma TLD badge." Radiation Measurements 43.2-6 (2008): 525-532.

Comparison of Bruce Power skin to whole body dose ratios for usual, head, and trunk issued TLDs



Analyzed 176,051 TLD records from Jan 1st, 2000 onward which had reportable whole body dose greater than 10 mrem.

The above box and whisker plot shows the interquartile range (box) and 95% confidence interval (whiskers) of skin to whole body dose ratio from usual, head, and trunk issued TLDs.

Outliers (not shown) account for < 5% of the total number of TLD records analyzed.

Summary of Bruce Power skin to whole body dose ratios

- The 176,051 TLD records analyzed correspond to <10% of <u>all</u> TLD badges issued since Jan 1st, 2000
- The remaining records (~1.8 million) have non-reportable doses < 10 mrem
- TLDs issued for usual work have an average (95% CI) skin-to-whole body dose ratio of 1.01 (0.90 - 1.21)
- TLDs issued for the head have an average (95% CI) skin-to-whole body dose ratio of 1.05 (0.93 - 1.58)
- TLDs issued for the trunk have an average (95% CI) skin-to-whole body dose ratio of 1.02 (0.93 - 1.21)
- Confirms that in CANDU NPPs, most of the dose is received from exposure to a photon dominated source term
- The 95% CI from head issued TLDs is wider which suggests that some work is being performed in mixed photon and beta radiation fields. Examples:
  - boiler inspections and maintenance,
  - reactor face inspection and maintenance
  - fueling machine inspection and maintenance

In 2015, Bruce Power joined a collaborative research program to assess lens of the eye dose from working in CANDU plants

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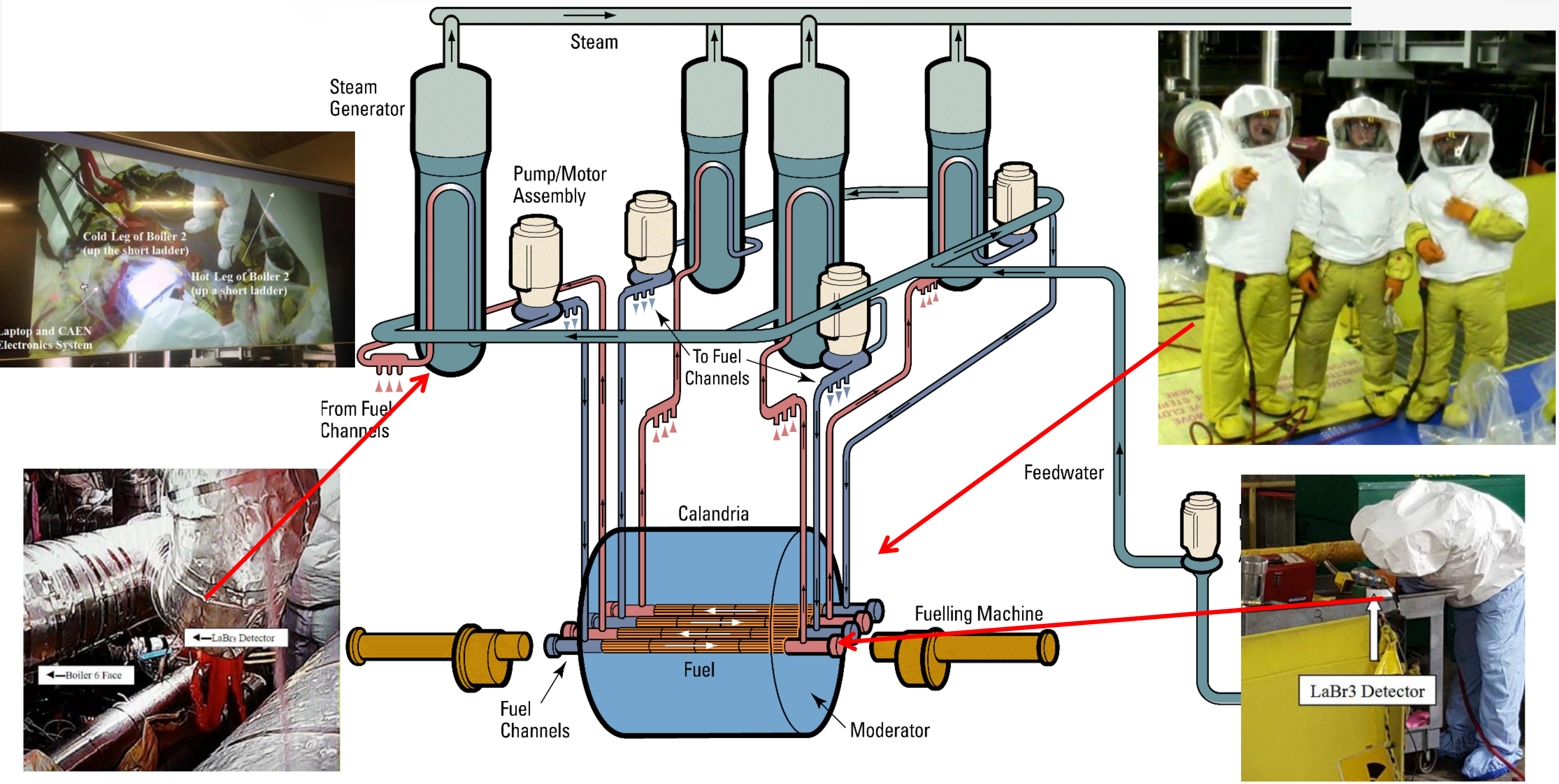
The program focuses on characterizing the β and γ-ray source term around CANDU systems known for high solid particulate deposits



McMaster University developed a β and γ-ray sensitive detector system to collect in-situ measurements near open systems

GOOD — POOR

GAMMA-RAY RESPONSE

Saint-Gobain
$LaBr_3$(Ce)

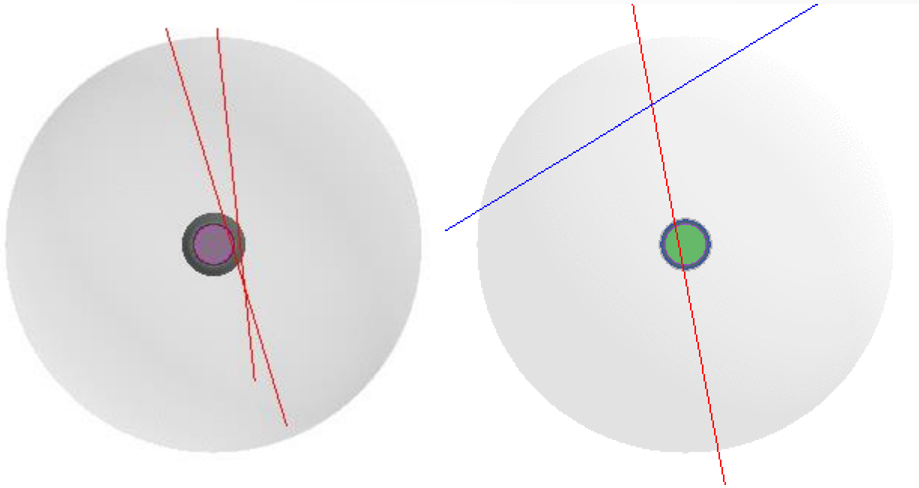
Eljen EJ-204
Plastic Scintillator Detector

Ortec CR-020-450-500
Silicon Detector

BETA-RAY RESPONSE

POOR — GOOD

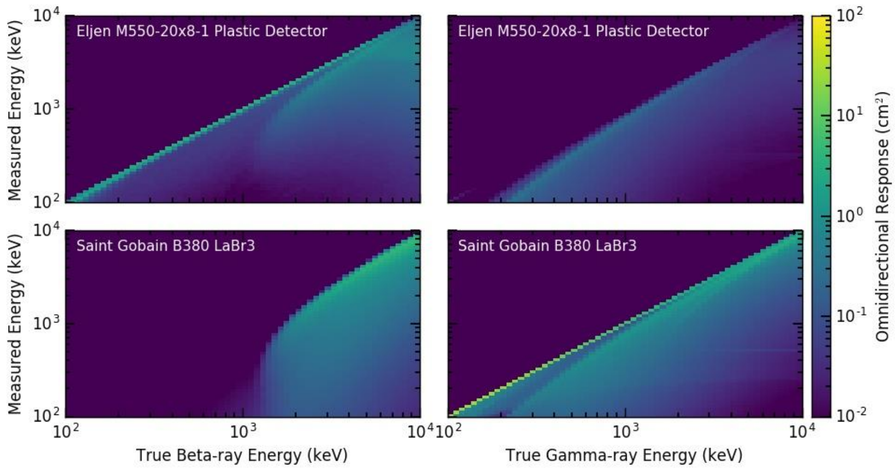
The detectors are characterized using Monte Carlo simulations and benchmarked against real experimental measurements

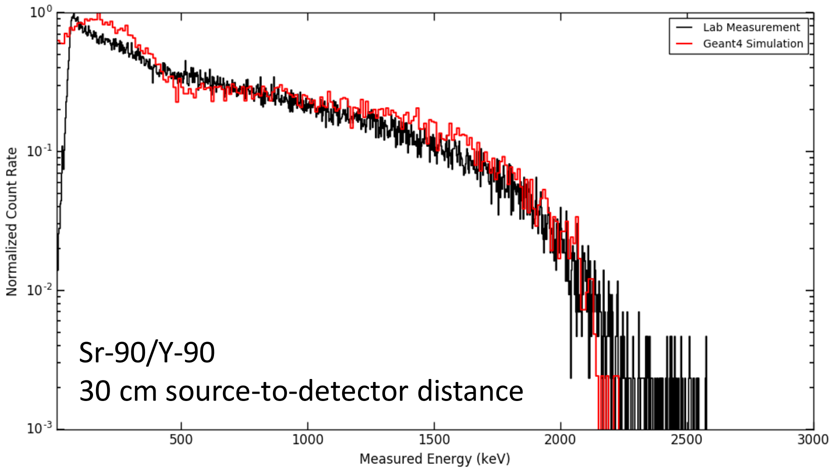


Objective of the Monte Carlo simulation

To determine the instrument response matrix for each detector and use them to estimate the source spectrum from spectra measured with our instruments in the field.

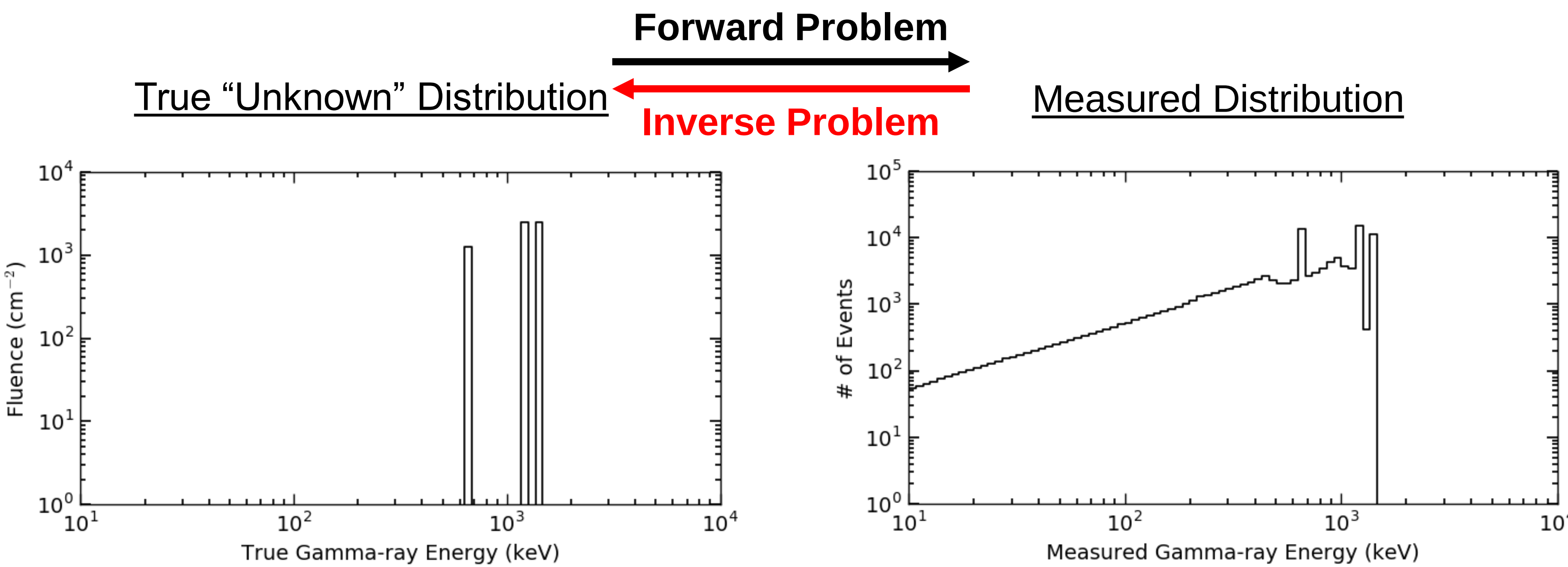
- Built using the Geant4 10.4 Monte Carlo toolkit
- Simple, but realistic, detector models
- Omnidirectional incident particle fluence spectra
- Simulates all photon and electron interactions in the 1 keV – 10 MeV energy range





To estimate dose to the lens of the eye we unfold the β and γ-ray source term from our measurements

Q: Given a measured spectrum $\mathrm{M} = \{M_1, M_2, \dots, M_N : M_N \in \mathbb{Z}^+\}$, and the detector response matrix $R = P(M, \Phi)$, what is the most probable particle fluence spectrum $\Phi = \{\Phi_1, \Phi_2, \dots, \Phi_N : \Phi_N \in \mathbb{R}^+\}$ that could have produced the measured spectrum?



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To unfold the β and γ-ray source term from our measurements, we developed a novel multi-detector spectral unfolding algorithm

Mathematically, the spectrum measured by each detector is related to the source spectrum via the following generative model:

$$D_{LaBr3} = \sum_{t=1}^{N_t} \Phi_\beta \cdot P(D_{LaBr3}|\Phi_\beta) + \sum_{t=1}^{N_t} \Phi_\gamma \cdot P(D_{LaBr3}|\Phi_\gamma) + Background$$

$$D_{Plastic} = \sum_{t=1}^{N_t} \Phi_\beta \cdot P(D_{Plastic}|\Phi_\beta) + \sum_{t=1}^{N_t} \Phi_\gamma \cdot P(D_{Plastic}|\Phi_\gamma) + Background$$

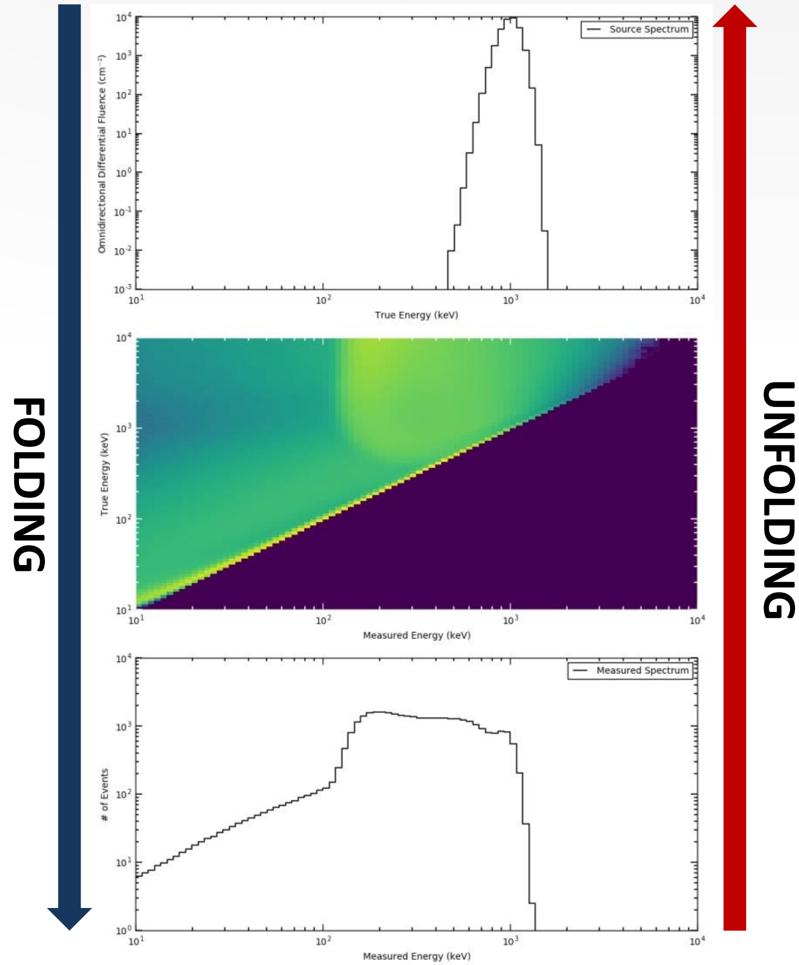
$$D_{Si} = \sum_{t=1}^{N_t} \Phi_\beta \cdot P(D_{Si}|\Phi_\beta) + \sum_{t=1}^{N_t} \Phi_\gamma \cdot P(D_{Si}|\Phi_\gamma) + Background$$

Assuming the measured data follow Poisson statistics, the likelihood can be specified as follows:

$$L\left(D_{LaBr3}|\Phi_\gamma\right) \propto Poisson(D_{LaBr3})$$
$$L\left(D_{Plastic}|\Phi_\beta\right) \propto Poisson(D_{Plastic})$$
$$L(D_{Si}|\Phi_\beta) \propto Poisson(D_{Si})$$

Using Baye's theorem, the posterior distributions for the β and γ-ray source term can be specified as follows and sampled via MCMC:

$$P\left(\Phi_\gamma|D_{LaBr3}\right) \propto L(D_{LaBr3}|\Phi_\gamma) \cdot \pi(\Phi_\gamma)$$
$$P\left(\Phi_\beta|D_{Plastic}\right) \propto L\left(D_{Plastic}|\Phi_\beta\right) \cdot \pi\left(\Phi_\beta\right)$$
$$P\left(\Phi_\beta|D_{Si}\right) \propto L(D_{Si}|\Phi_\beta) \cdot \pi(\Phi_\beta)$$



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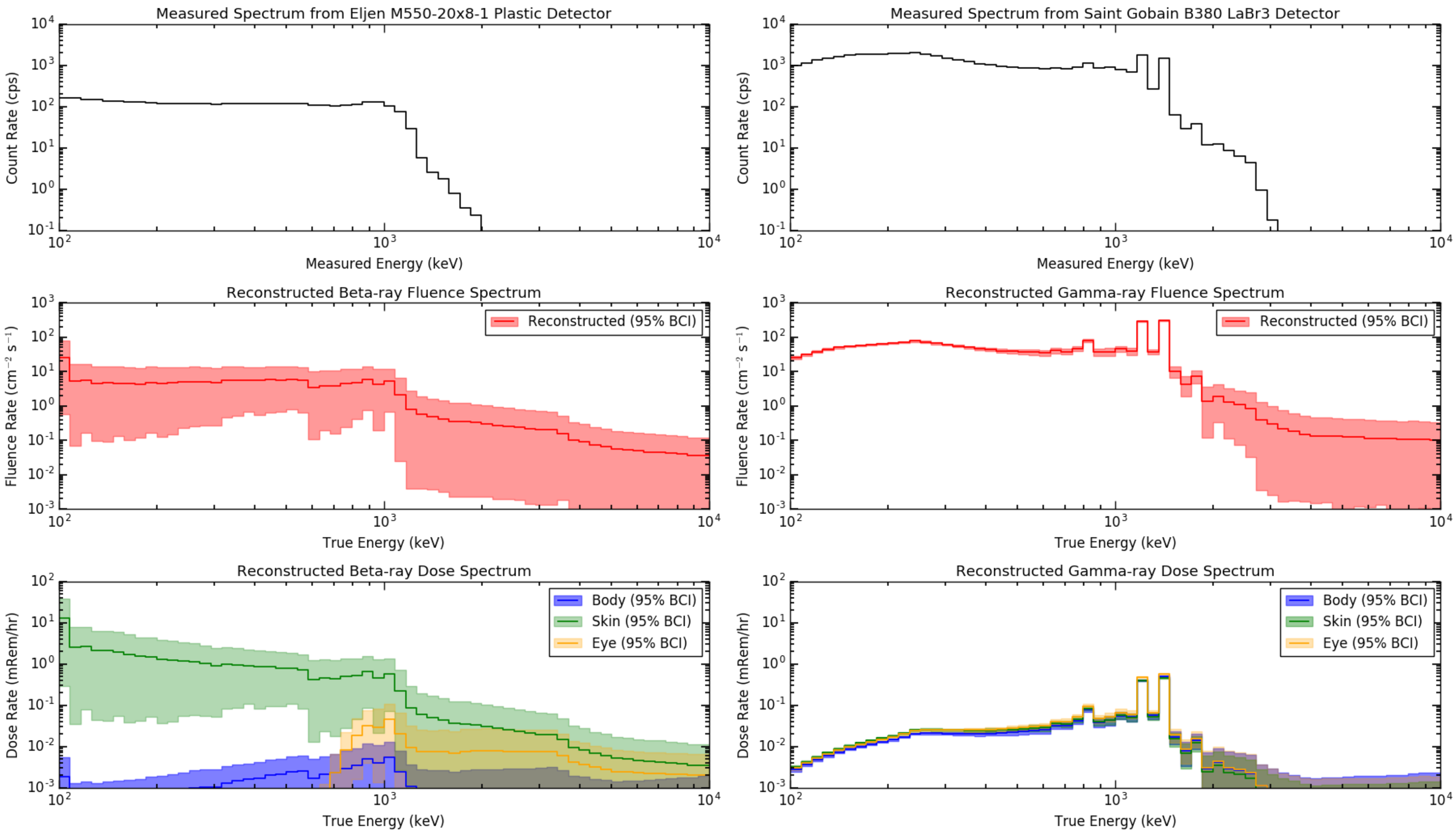
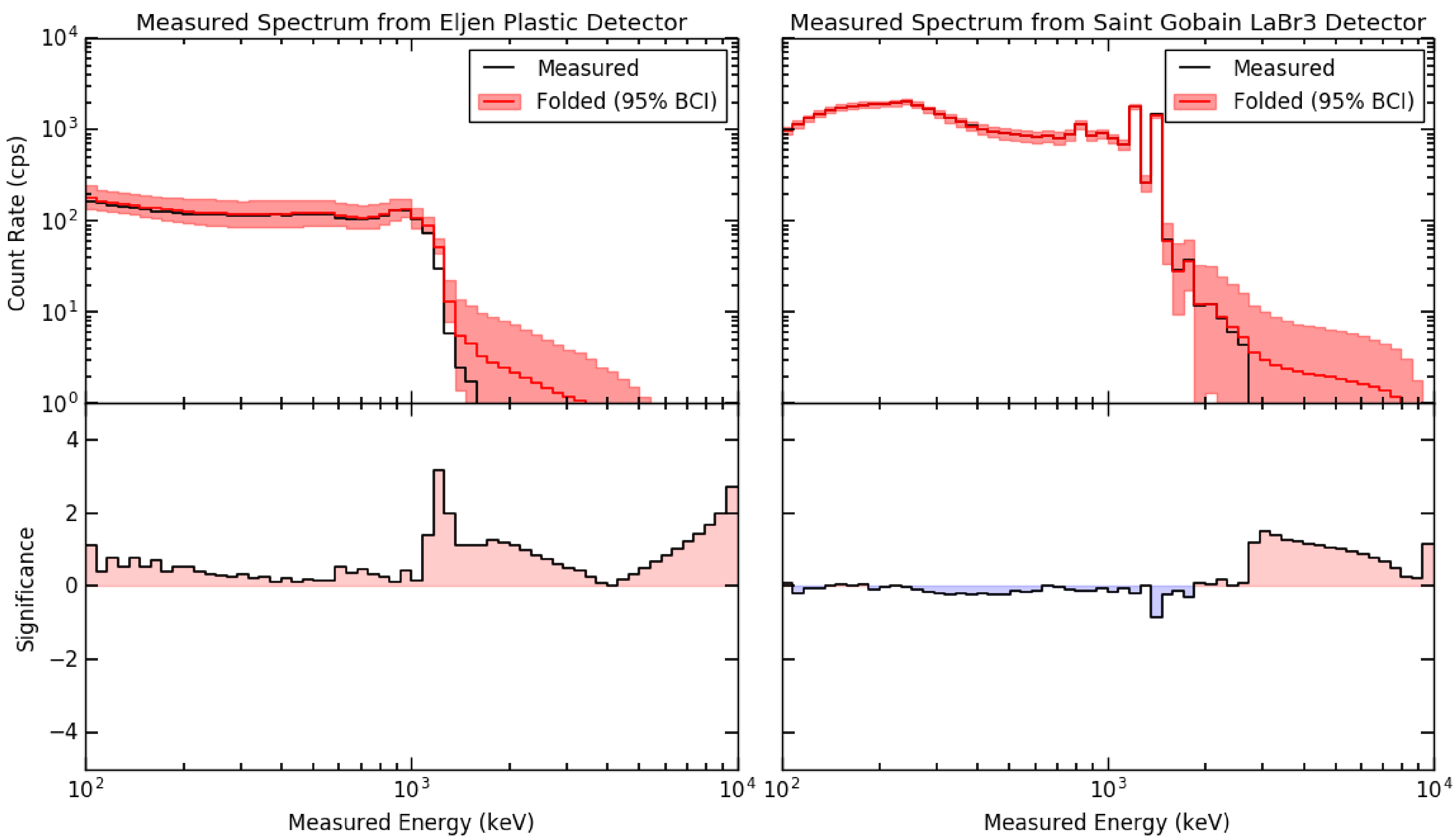
Sample unfolding of β and γ-ray fluence rate spectra measured near a fueling machine in Bruce B during the Sep, 2017 outage



Unfolding verification of β and γ-ray fluence rate spectra measured near a fueling machine in Bruce B during the Sep, 2017 outage



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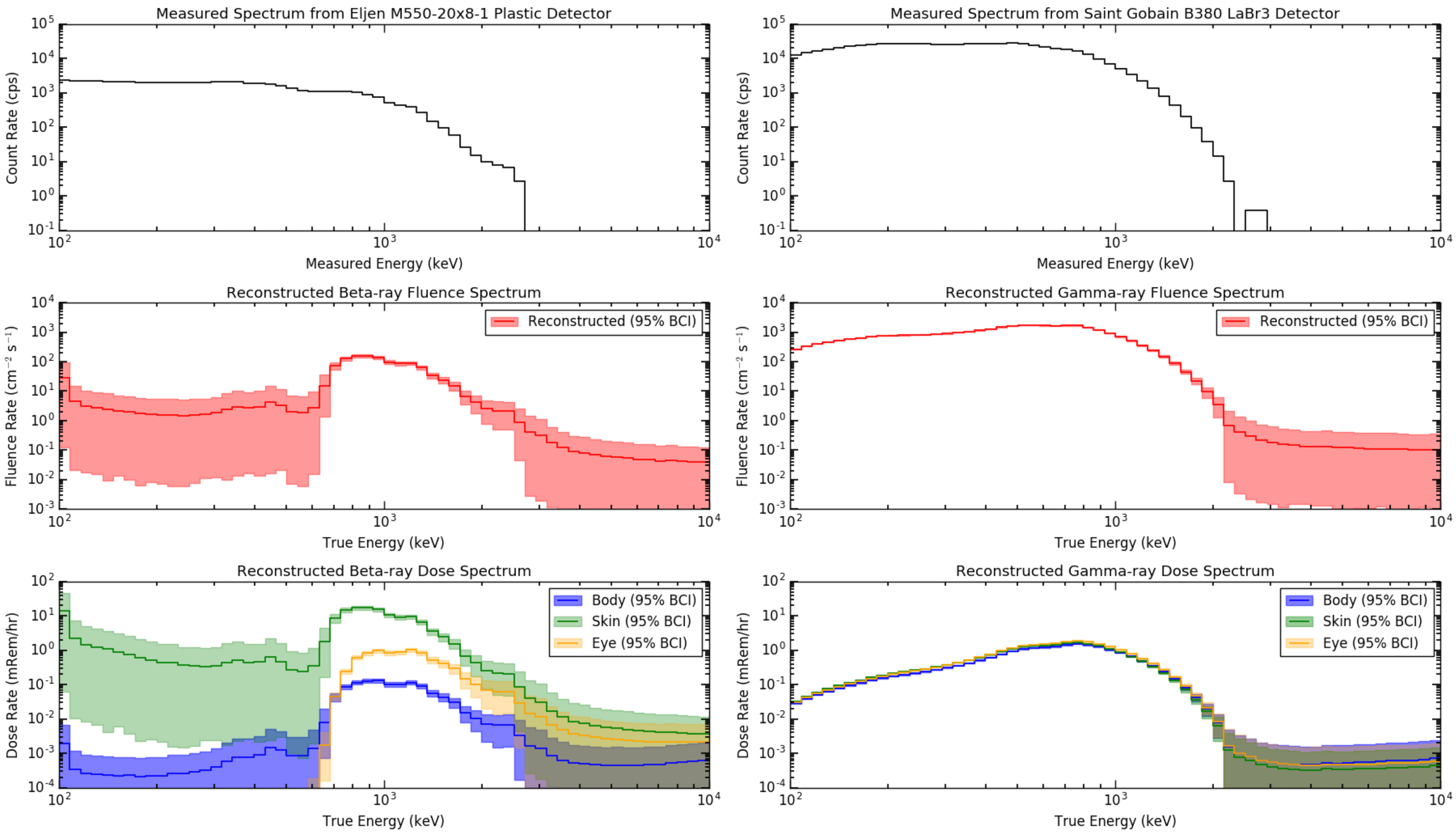
Summary of estimated skin, eye, and whole body dose rates near opened fueling machine in Bruce B during the Sep, 2017 outage

Station	Unit	Location	Distance (cm)	Skin Dose Rate (mRad/hr)*	Eye Dose Rate (mRad/hr)*	Body Dose Rate (mRem/hr)*	Skin-to-Body Ratio**	Eye-to-Body Ratio**
Bruce B	0	Fueling Machine (Snout)	30	50.2 (6.6 – 150)	7.9 (7.1 – 9.0)	6.6 (6.1 – 7.2)	7.6 (1.1 – 21)	1.25 (1.2 – 1.3)
Bruce B	0	Fueling Machine (Snout)	50	42.1 (4.0 – 128)	4.6 (4.0 – 5.6)	3.8 (3.4 – 4.3)	11.1 (1.2 – 30)	1.25 (1.2 – 1.3)
Bruce B	0	Fueling Machine (Snout)	100	48.9 (3.6 – 138)	2.4 (1.9 – 3.2)	1.8 (1.6 – 2.2)	26.6 (2.3 – 63)	1.3 (1.2 – 1.5)
Bruce B	0	Fueling Machine (Tail Stock)	30	45.9 (3.9 – 129)	2.7 (2.1 – 3.7)	2.1 (1.8 – 2.5)	21.8 (2.2 – 51)	1.3 (1.2 – 1.5)
Bruce B	0	Fueling Machine (Tail Stock)	50	43.6 (3.8 – 120)	2.1 (1.6 – 3.0)	1.6 (1.3 – 1.9)	27.6 (2.9 – 62)	1.3 (1.2 – 1.5)
Bruce B	0	Fueling Machine (Tail Stock)	100	29.5 (1.4 – 88)	1.3 (0.9 – 2.1)	1.0 (0.8 – 1.2)	30.8 (1.9 – 71)	1.4 (1.2 – 1.7)

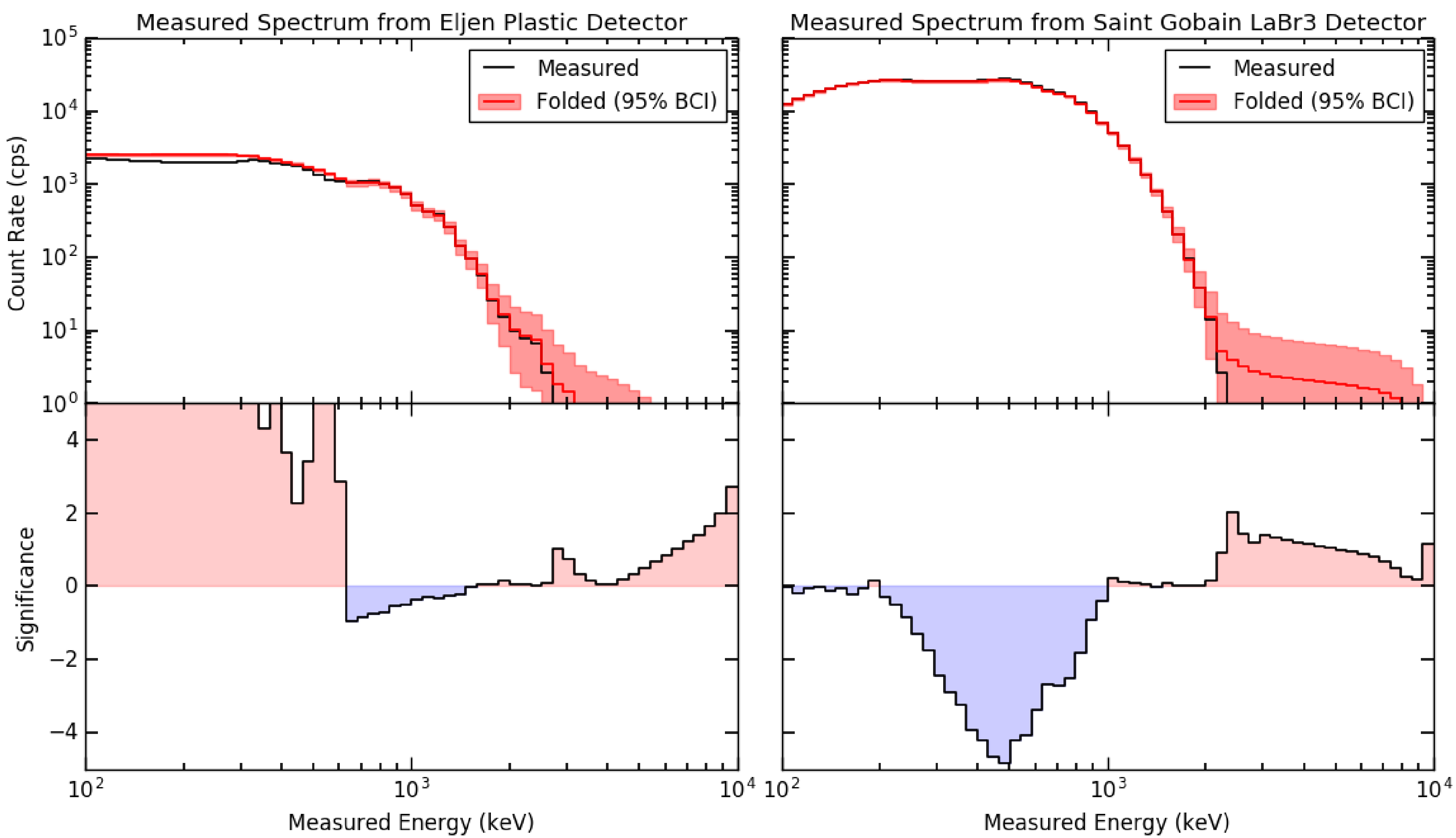
* Dose rates have been estimated by convolving and summing the unfolded β and γ-ray fluence rate spectra with ICRP 116 fluence-to-dose conversion coefficients for fully isotropic irradiations.

** Shielding due to personal protective equipment (eg. plastic suit, coveralls, safety glasses, etc.) was <u>not</u> taken into consideration. Thus, this represents the highest and therefore worst case dose ratios.

Sample unfolding of β and γ-ray fluence rate spectra measured near Boiler 6 in Unit 1 of Bruce A during the outage in Jan, 2018



Unfolding verification of β and γ-ray fluence rate spectra measured near Boiler 6 in Unit 1 of Bruce A during the outage in Jan, 2018



Summary of estimated skin, eye, and whole body dose rates near Boiler 6 in Unit 1 of Bruce A during the Jan, 2018 outage

Station	Unit	Location	Distance (cm)	Skin Dose Rate (mRad/hr)*	Eye Dose Rate (mRad/hr)*	Body Dose Rate (mRem/hr)*	Skin-to-Body Ratio**	Eye-to-Body Ratio**
Bruce A	1	Boiler 6 Cold Leg	20	171 (121 – 264)	32 (30 – 35)	21 (20 – 22)	8 (6 – 12)	1.54 (1.49 – 1.59)
Bruce A	1	Boiler 6 Cold Leg	50	65 (15 – 182)	18 (17 – 19)	15 (14 – 16)	4 (1 – 12)	1.20 (1.19 – 1.22)
Bruce A	1	Boiler 6 Cold Leg	72	32 (13 – 78)	15 (14 – 16)	13 (12 – 14)	2.5 (1.1 – 5.8)	1.20 (1.19 – 1.22)
Bruce A	1	Boiler 6 Cold Leg	170	23 (4 – 71)	4.3 (4 – 5)	3.5 (3 – 4)	6 (1.2 – 18)	1.23 (1.20 – 1.30)
Bruce A	1	Boiler 6 Hot Leg	150	821 (597 – 1065)	5.6 (4.9 – 6.6)	4.6 (4.2 – 5.1)	180 (144 – 208)	1.22 (1.18 – 1.30)

* Dose rates have been estimated by convolving and summing the unfolded β and γ-ray fluence rate spectra with ICRP 116 fluence-to-dose conversion coefficients for fully isotropic irradiations.

** Shielding due to personal protective equipment (eg. plastic suit, coveralls, safety glasses, etc.) was <u>not</u> taken into consideration. Thus, this represents the highest and therefore worst case dose ratios.

Summary of occupational dose and radiological hazard to the lens of the eye at the Bruce Power Nuclear Generating Station

- TLDs issued for usual wear have reported an average (95% CI) skin-to-whole body dose ratio of 1.02 (0.91 - 1.24); consistent with work being performed in predominantly isotropic photon radiation fields.
- TLDs issued for head wear have reported an average (95% CI) skin-to-whole body dose ratio of 1.05 (0.93 - 1.58); consistent with some work being performed in mixed photon and beta radiation fields.
- In 2015, a 5 year collaborative research program was initiated to characterize the radiation source term in or near various CANDU systems and assess the need for eye dosimetry programs.
- Bruce Power has participated in 3 field measurement campaigns focused on areas of plant (eg. steam generators and fueling machines) where mixed photon and beta radiation fields are known to exist.
- Field measurements have shown the average (95% CI) unshielded eye-to-whole body and skin-to-whole dose ratios are 1.29 (1.22 – 1.40) and 29.6 (15.0 – 50.3), respectively.
- These measurements confirm that work being performed at the Bruce Power Nuclear Generating Station does not present a radiological hazard to the lens of the eye
- Confirms that dosimeters calibrated in terms of personal skin dose, $H_p(0.07)$, will conservatively monitor, but overestimate, eye lens dose.

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