Analysis of thermal neutron attenuation of shielding materials using neutron facility at HANARO

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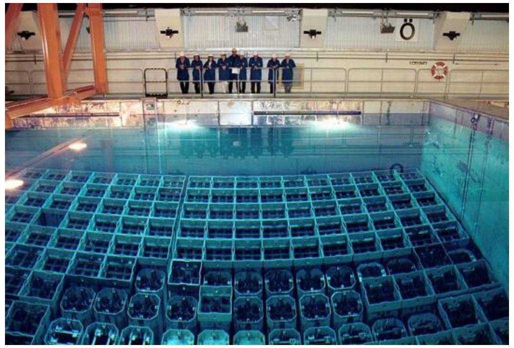
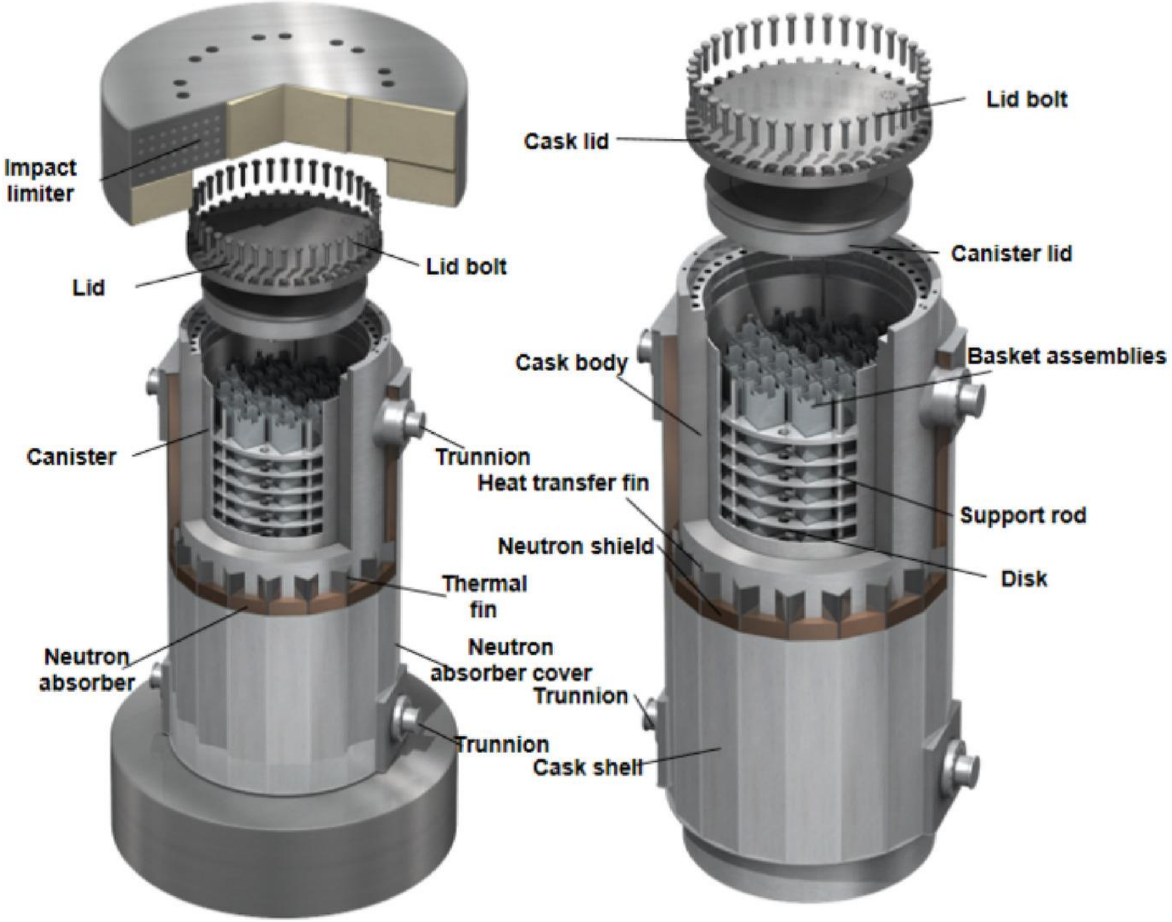
Spent Nuclear Fuel transport/storage system

Wet storage



Dry storage

KORAD-21 transportation cask



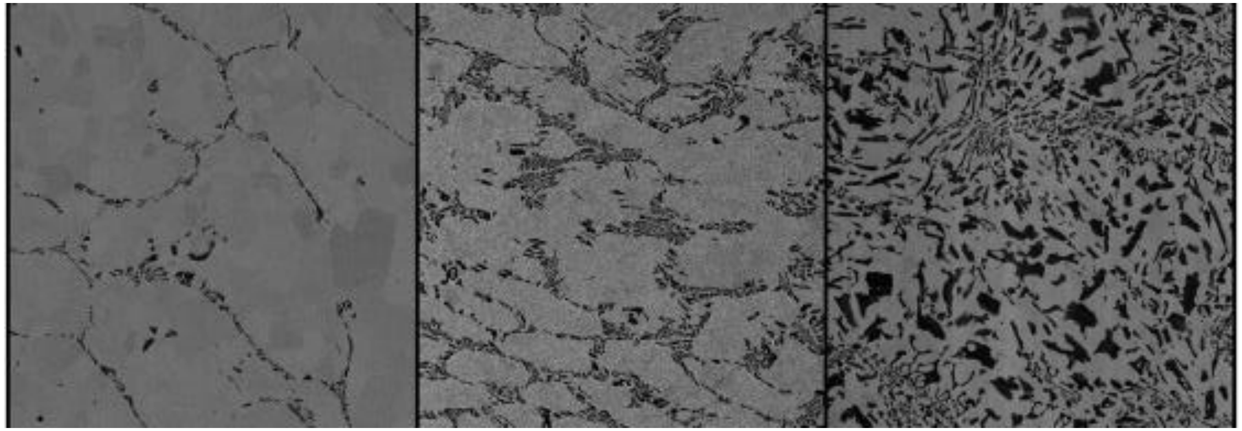
NET, 55(11), 4125, 2023

Neutron shielding materials in cask/canister systems

*Gd- and Cd-added materials are not included.

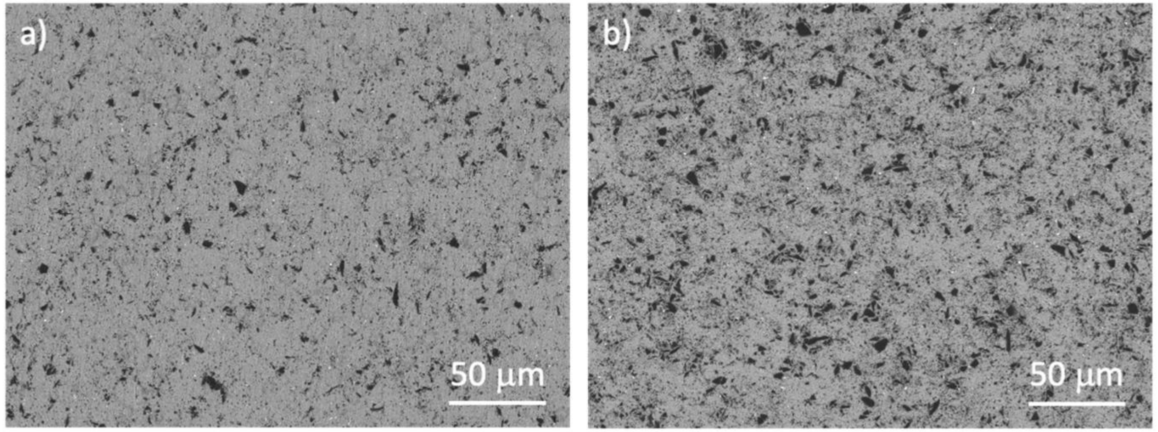
Items	Location	Material characteristics
Boron Stainless Steel (BSS)	Inside canister basket or rack structure	- High mech. strength - High corrosion resistance
B-Al (Al-B_4C plate)	Internal absorber plates btw fuel assy.	- Aluminum matrix & B_4C particles - Laminated structure
Metamic (Al-B_4C MMC)	Basket insert inside canister	- Homogeneous MMC - Uniform B_4C distr. - Isotropic properties
Boron Aluminum Alloy/ B_4C-Al composite	Internal absorber components	- High boron content - Lightweight composite

BSS (B 0.19 w%) BSS (B 0.78 w%) BSS (B 1.76 w%)



J. Nucl. Mater., 515, 206, 2019

Al-B_4C 4 vol% Al-B_4C 10 vol%



J. Nucl. Mater., 565, 153724, 2022

Standards of assessment of neutron shielding

Designation: A887 – 20

Standard Specification for
Borated Stainless Steel Plate, Sheet, and Strip for Nuclear Application[1]

ASTM A887-20

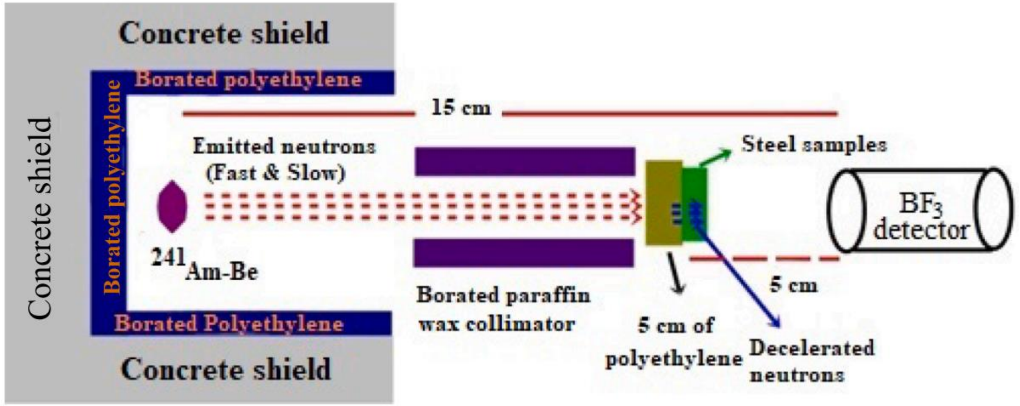
- Define chemical composition and mechanical properties of BSS (B contents 0.2 - 2.25 wt%)
- Ensures neutron absorption capability based on boron content

Designation: E2971 – 16

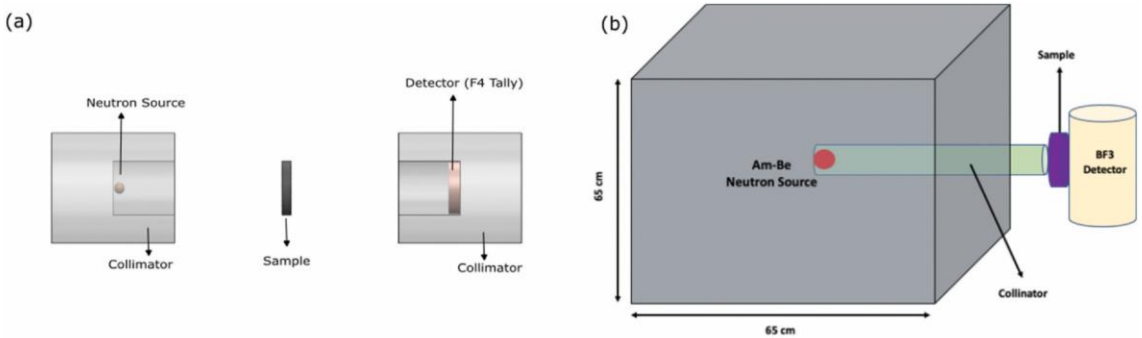
Standard Test Method for
Determination of Effective Boron-10 Areal Density in Aluminum Neutron Absorbers using Neutron Attenuation Measurements[1]

ASTM E2971-16

- Evaluate Al-based neutron absorber materials
- Specifies methods for thermal neutron absorption and areal density measurement
  - Thermal neutron sources: reactor beamline, NR facility w/ moderator
- Includes uniformity and quality verification procedures
  - Measure multiple positions



Nucl. Eng. Des.,413, 112515, 2023



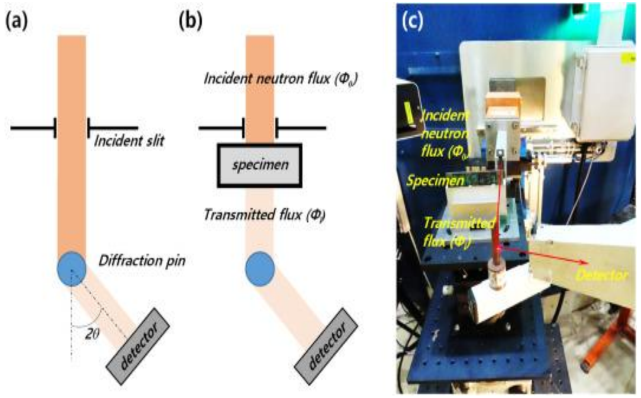
NET, 56(12), 5201, 2024

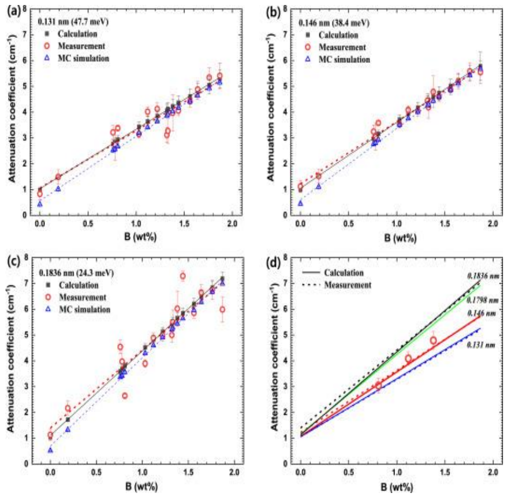
- Am-Be source
  - Fast neutrons: 4 - 5 MeV
  - Thermal neutrons decelerated by PE moderator (5 cm): ~25.3 meV (~1.8 Å)

Previous studies/research

Wanchuck Woo et al. / NET 58(1),103904, 2026

Correlation between boron content and thermal neutron attenuation coefficient in borated stainless steels analyzed by neutron diffraction



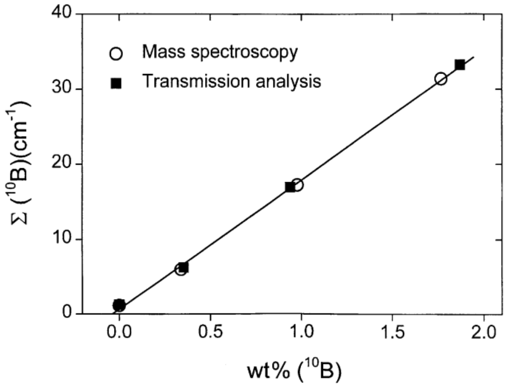


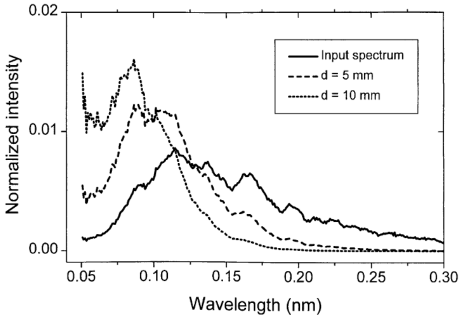
- Quantitative relationship btw B content and μ (@RSI, FCD, HRPD)
  - Neutron diffraction-based transmission
    → monochromatic beam (1.3Å, 1.5Å, 1.8Å)
  - Calculation using actual BSS alloy composition & density

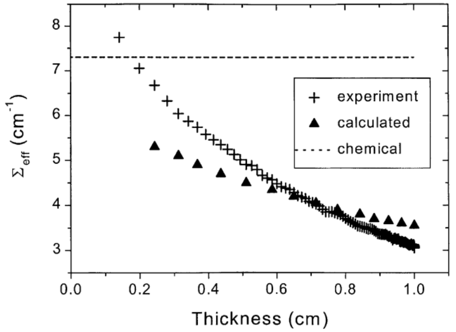
→ Engineering correlation w/ practical predictive modeling

M. Zawisky et al. / Appl. Radiat. Isot. 61, 517-523, 2004

Non-destructive ^{10}B analysis in neutron transmission experiments







- Precise determination of ^{10}B using transmission measurements (@NEUTRA, PSI)
  - Monochromatic beam → ideal exponential law
  - Polychromatic beam → beam hardening effect

→ Physically rigorous ∑ determination vs real beam spectral effect

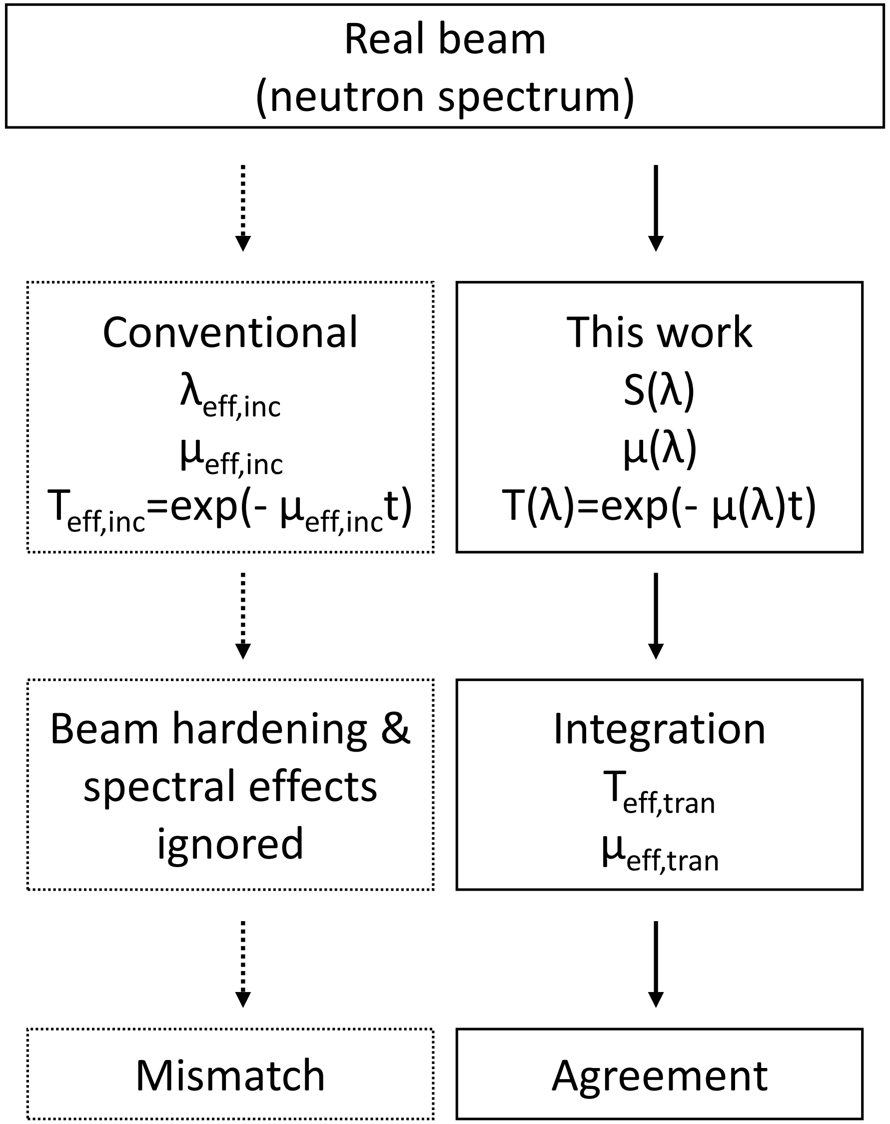
Objectives of this study

Context & Gap

- Real neutron beams (e.g. HANARO NIF) are polychromatic
- Conventional approach:
  - Monochromatic or singe effective wavelength
  - Count measurement at local volume
- Limitation:
  - Can not capture beam hardening and spectral effects
  - Face big discrepancy w/ thick and strong absorbing materials
  - Requires multiple repeated measurement for bulk samples

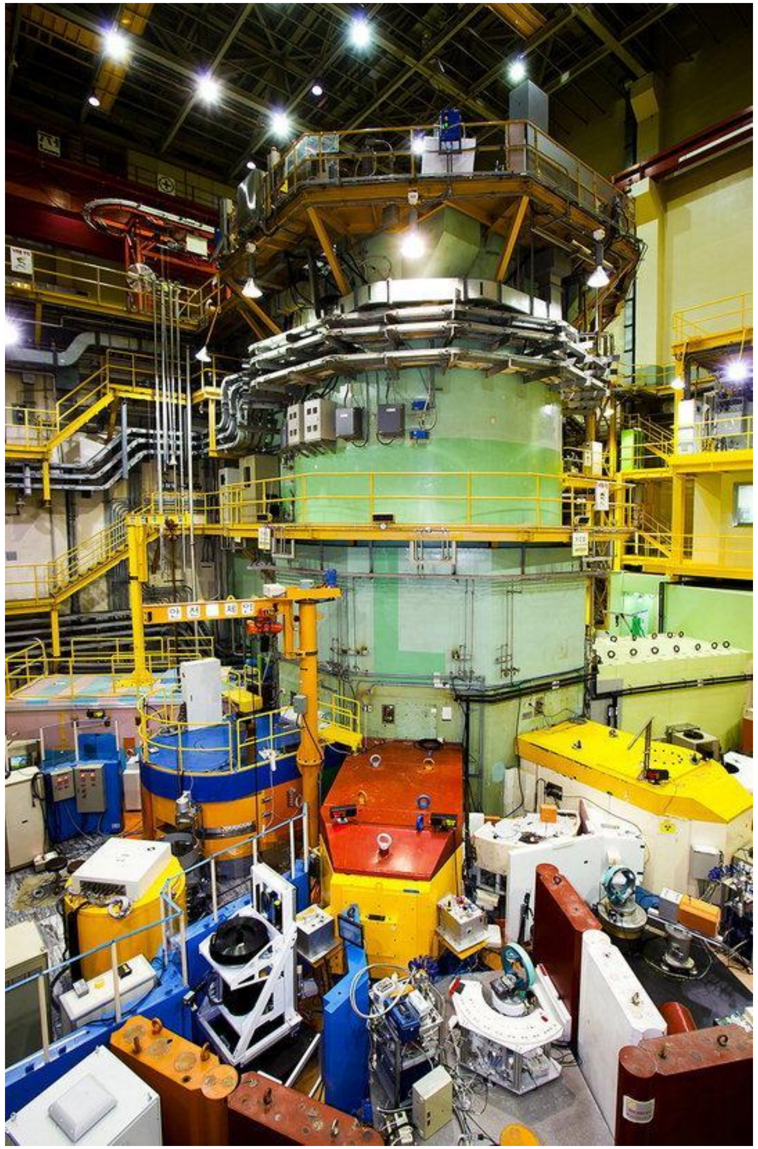
Objective & Approach

- Develop a spectrum-based framework for attenuation evaluation using imaging-based neutron transmission
- Define:
  - Effective transmission
  - Effective attenuation coefficient
- Validate using:
  - Borated Stainless Steel (BSS)
  - Boron Aluminum materials

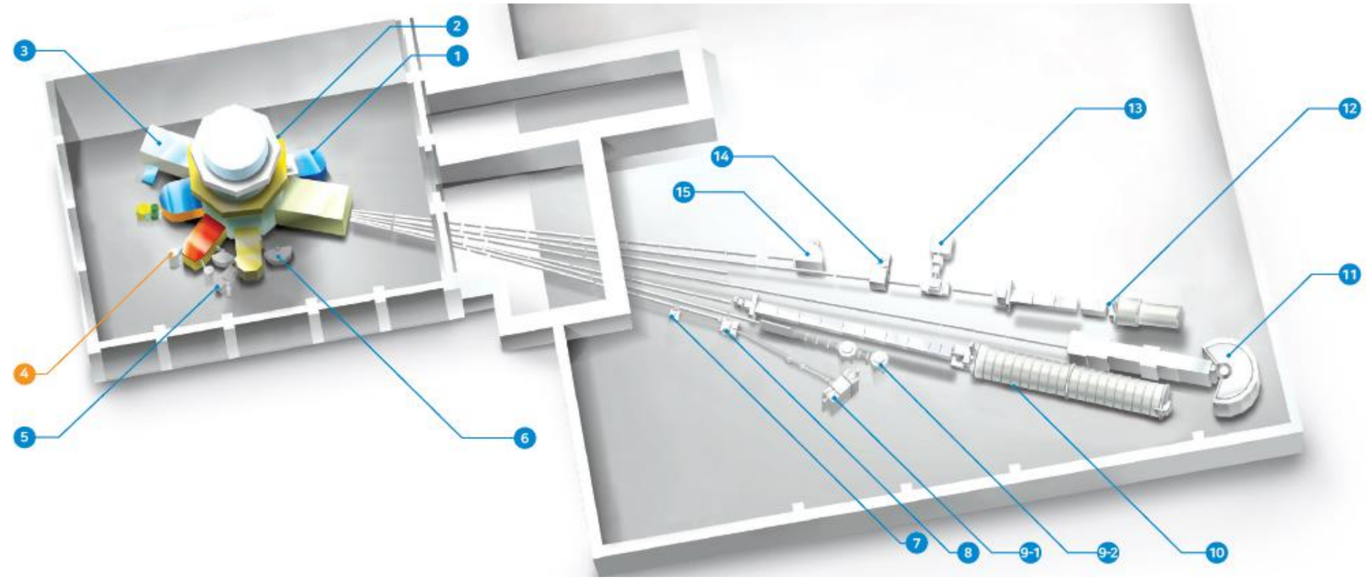


HANARO, High-flux Advanced Neutron Application Reactor

Visit HANARO



Beam instruments



01 Residual Stress Instrument	07 Guide Test Station
02 Ex-core Neutron irradiation Facility (ENF)	08 Vertical type REFlectometer
03 Neutron Radiography Facility (NRF)	+09 Cold Neutron Activation Station
*04 Bio-diffractometer with neutron image plate Camera(KRIBB)	10 40m Small Angle Neutron Scattering instrument
05 Four Circle neutron Diffractometer	11 Disk-Chopper Time-of-Flight spectrometer
06 High Resolution Powder Diffractometer	12 18m Small Angle Neutron Scattering instrument
	*13 KIST Ultra-Small Angle Neutron Scattering instrument
	14 Bio-REFlectometer
	15 Cold neutron Triple-Axis Spectrometer

Neutron Imaging facilities at HANARO

NRF (Neutron Radiography Facility)

- Thermal neutron flux
  - 2.0×10^7 n/cm^2·s (@beam shutter)
- Field of View (FoV)
  - 350×450 mm^2
- Polychromatic
- Fuel cell research w/ Hyundai-Motor and KATEC

ENF (Ex-core Neutron irradiation Facility)

- Thermal neutron flux
  - 1.5×10^9 n/cm^2·s (@beam shutter, max)
  - 5.1×10^8 n/cm^2·s (@beam shutter, 24MW opr.)
- Field of View (FoV)
  - ~150×150 mm^2
- Polychromatic (ToF measured)
  - Effective wavelength 2.7 Å
- Multipurpose: advanced neutron imaging, irradiation, etc.

Attenuation coefficient μ and Transmission

Sum of Macroscopic cross section (cm^{-1})

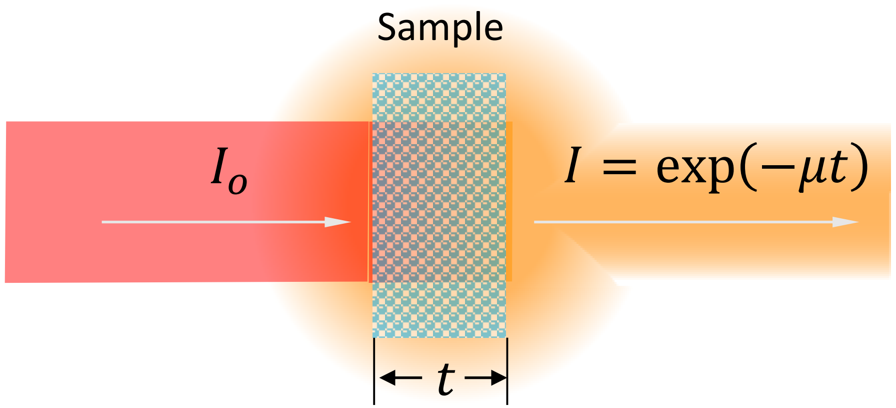
$$\mu = \bar{\Sigma}_{abs} + \bar{\Sigma}_{coh} + \bar{\Sigma}_{incoh}$$

- Σ_{abs} : absorption cross section
- Σ_{coh} : coherent scattering cross section
- Σ_{incoh} : incoherent scattering cross section

Alloy-based model

$$\bar{\Sigma} = \sum_i \sigma_i \cdot N_i = \sum_i \sigma_i \cdot \left(\frac{w_i N_A \bar{\rho}}{M_i}\right)$$

- σ_i : microscopic cross section of element i at energy
- N_i : atomic number density of element i
- w_i : weight fraction of element i
- N_A : Avogadro's number
- $\bar{\rho}$: mean alloy density $\left(= \frac{1}{\Sigma(w_i/\rho_i)}\right)$
- M_i : Atomic weight of element i



Transmission of Monochromatic ideal model

$$T = I/I_o = \exp(-\mu t)$$

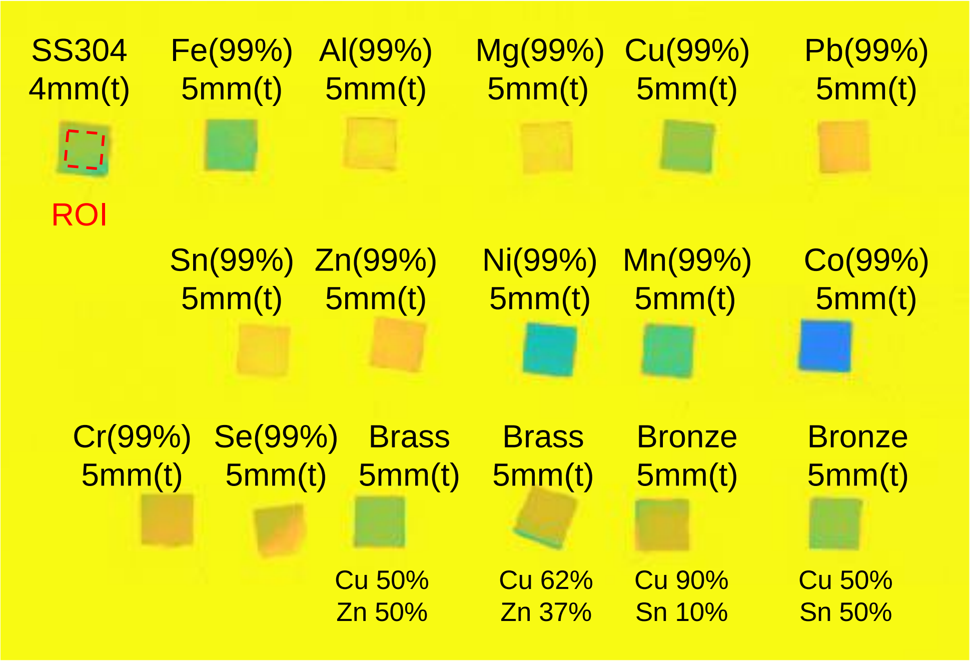
- I : intensity w/ sample
- I_o : intensity w/o sample
- t : thickness of sample

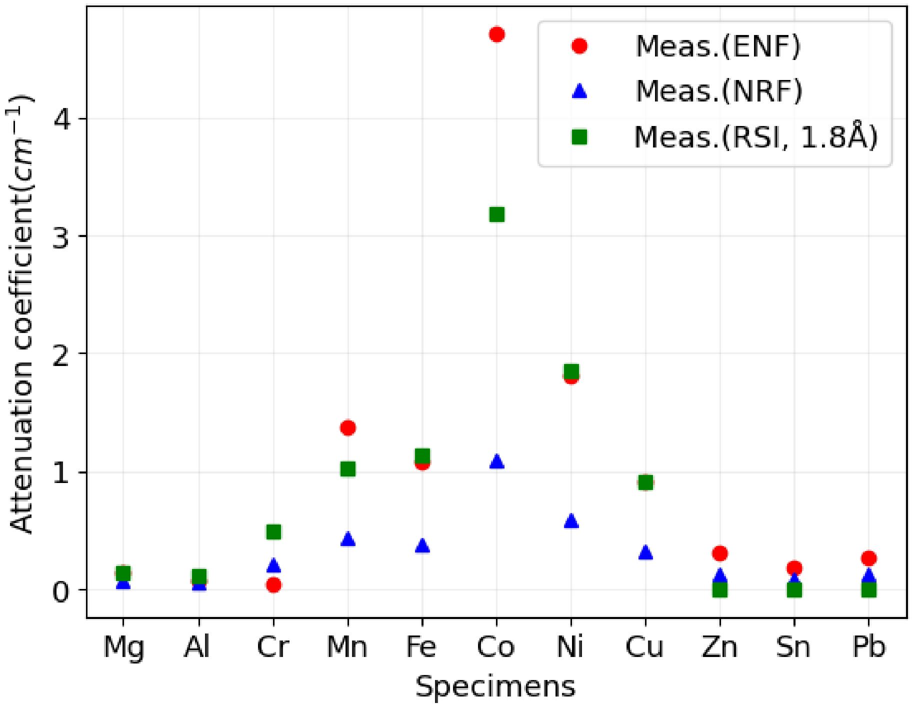
Measured attenuation coefficient

$$\mu_{meas} = -\frac{1}{t}\ln(T_{meas}) = -\frac{1}{t}\ln\left(\frac{I_{meas}}{I_{o,meas}}\right)$$

Experiments: Validation of Trans. measurement w/ pure metals

Transmission image (TI) @NRF



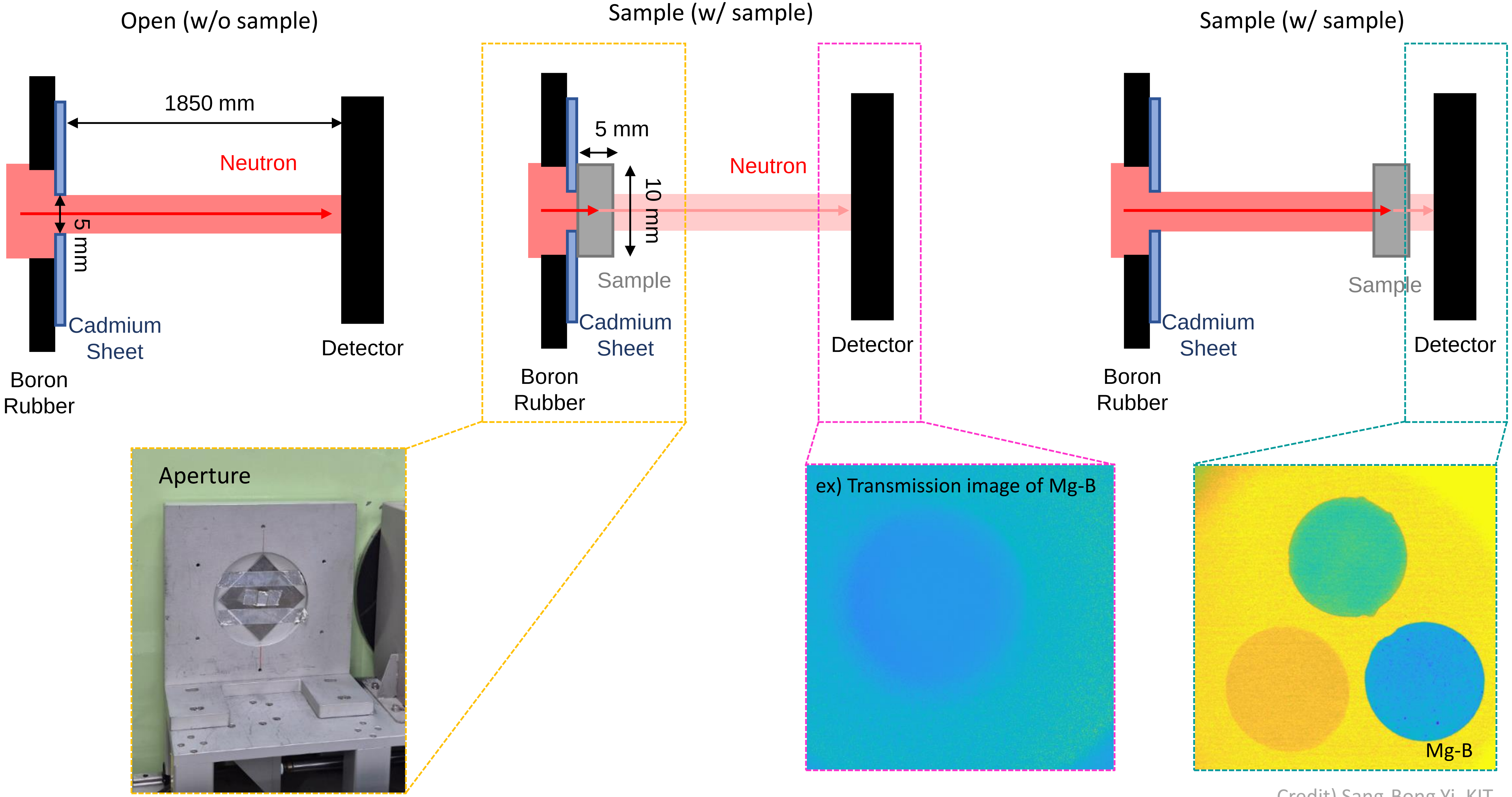


- Pure metals (purity > 99 %) 12 ea & few alloys
- Compared attenuation coefficients μ measured at ENF, NRF, RSI
  - Assumed ENF and NRF have similar polychromatic neutron spectrum
  - Relatively lower μ measured @ NRF due to large beam size may cause neutron scattering
  - Violated ASTM E2971-16 1.1.4: The test specimen has a testing surface area at least twice that of the thermal neutron beam's surface cross-sectional area.

Experiments: Re-formation of Trans. measurement

Quantitative Transmission Measurement

Qualitative Transmission Measurement



Credit) Sang-Bong Yi, KIT

Samples: BSS and B-Al

Samples	Elements (wt.%)								Thickness (cm)
	Fe	C	Si	Mn	Cr	Ni	Al	B	
SS304	72.29	0.04	0.42	1.18	18.05	8.02	0	**0**	0.413
BSS1	68.53	0.06	0.25	1.35	17.7	11.9	0.02	**0.19**	0.513
BSS2	64	0.05	0.59	1.6	19.9	13.1	0	**0.76**	0.575
BSS3	66.61	0.07	0.26	1.55	18.4	12.3	0.04	**0.78**	0.517
BSS4	65.7	0.03	0.25	0.75	18.12	14.35	0	**0.81**	0.432
BSS5	66.01	0.01	0.37	0	18.38	14.2	0	**1.03**	0.524
BSS6	65.63	0.04	0.27	0.78	18.27	13.89	0	**1.12**	0.403
BSS7	66.7	0.02	0.31	0.75	18.4	12.6	0	**1.22**	0.535
BSS8	66.79	0.07	0.4	1.22	18.2	12	0	**1.32**	0.493
BSS9	66	0.02	0.27	0.76	18.16	13.41	0	**1.38**	0.425
BSS10	66.12	0.01	0.31	1.1	18.6	12.3	0	**1.56**	0.55
BSS11	65.58	0.07	0.28	1.57	18.3	12.4	0.04	**1.76**	0.512
BSS12	64.7	0.01	0.26	1.16	19.4	12.6	0	**1.87**	0.533

BSS

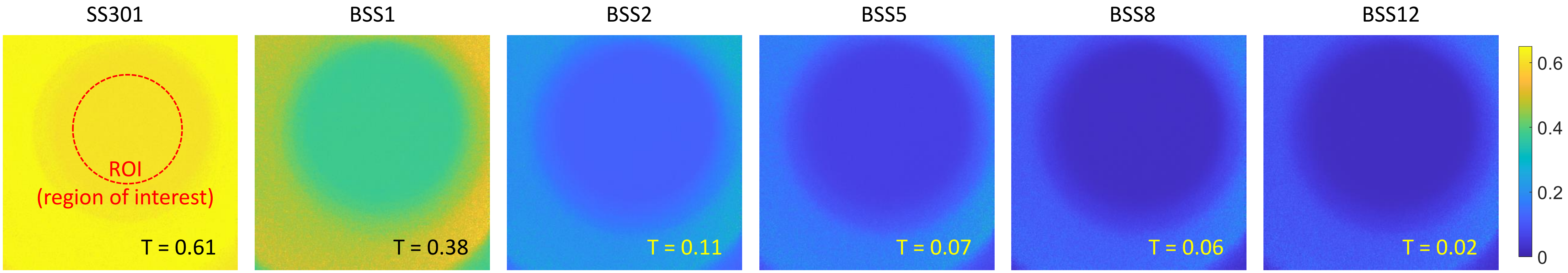
- B contents ~1.87 wt%
- Conventional melting and ingots of ~ 50 kg
- Heat-treated at 1150 °C for 1 h & hot-rolled into thickness of ~ 40 mm
- Cut plate to 10 mm x 10 mm x 5 mm
- BSS4, BSS6, BSS10 large scale ingot (up to 10 ton for industrial appl.)

Samples	Elements (wt.%)									Thickness (cm)
	Al	Mg	Si	Cu	Cr	Fe	Zn	Ti	Mn	B	
B-Al	97.2	1	0.6	0.3	0.2	0.4	0.1	0.1	0.1	**0**	0.5
B-Al04	93.31	0.96	0.58	0.29	0.19	0.38	0.1	0.1	0.1	**4**	0.5
B-Al05	92.34	0.95	0.57	0.29	0.19	0.38	0.1	0.1	0.1	**5**	0.5
B-Al10	87.48	0.9	0.54	0.27	0.18	0.36	0.09	0.09	0.09	**10**	0.5
B-Al20	77.76	0.8	0.48	0.24	0.16	0.32	0.08	0.08	0.08	**20**	0.5
B-Al30	68.04	0.7	0.42	0.21	0.14	0.28	0.07	0.07	0.07	**30**	0.5
B-Al50	48.6	0.5	0.3	0.15	0.1	0.2	0.05	0.05	0.05	**50**	0.5

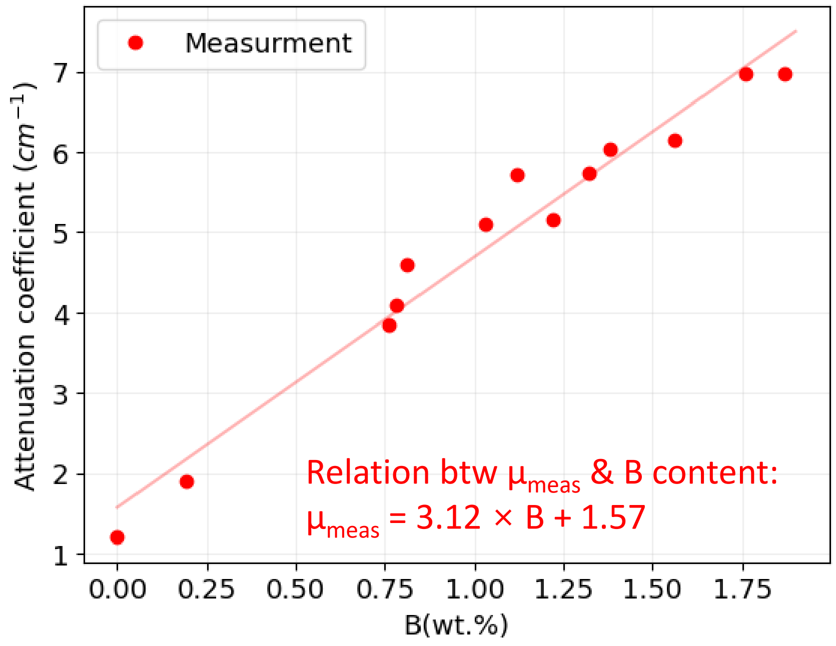
B-Al

- B contents ~50 wt%
- Al6061 alloy
- Cold compaction & sintering
- Hot-rolled & T6 heat treatment

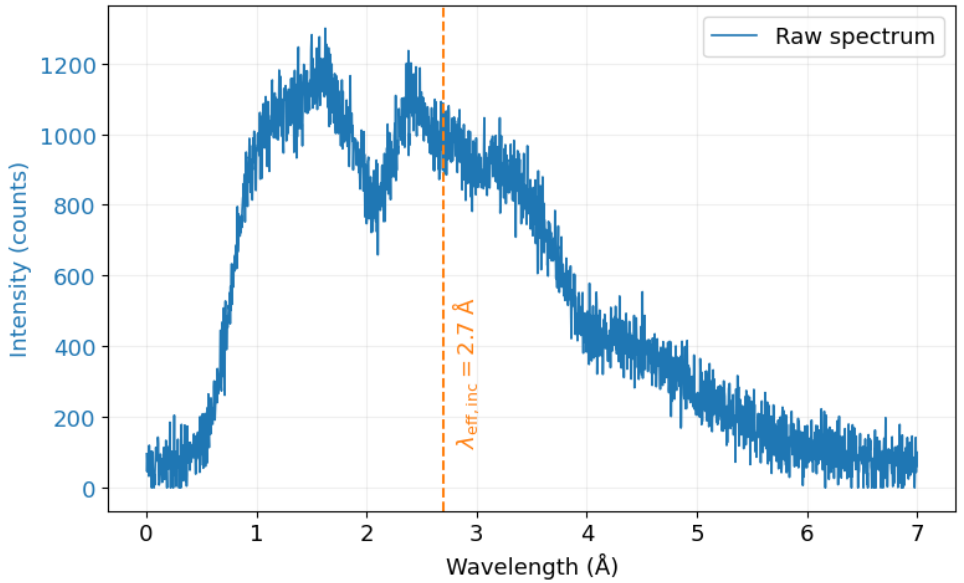
BBS results: Transmission images and μ_{meas}



Sample	B (wt.%)	t (cm)	I_o	I	T (I/I_o)	μ (cm^{-1})
SS304	0	0.413	4799.67	2916.32	**0.61**	**1.21**
BSS1	0.19	0.513	4799.67	1819.48	**0.38**	**1.89**
BSS2	0.76	0.575	4799.67	523.40	**0.11**	**3.85**
BSS3	0.78	0.517	4799.67	578.27	**0.12**	**4.09**
BSS4	0.81	0.432	4799.67	659.60	**0.14**	**4.59**
BSS5	1.03	0.524	4799.67	331.58	**0.07**	**5.10**
BSS6	1.12	0.403	4799.67	479.69	**0.10**	**5.72**
BSS7	1.22	0.535	4799.67	303.09	**0.06**	**5.16**
BSS8	1.32	0.493	4799.67	284.00	**0.06**	**5.73**
BSS9	1.38	0.425	4799.67	368.61	**0.08**	**6.04**
BSS10	1.56	0.55	4799.67	163.74	**0.03**	**6.14**
BSS11	1.76	0.512	4799.67	135.57	**0.03**	**6.97**
BSS12	1.87	0.533	4799.67	116.36	**0.02**	**6.98**



ENF neutron spectrum S(λ) and μ_{cal}

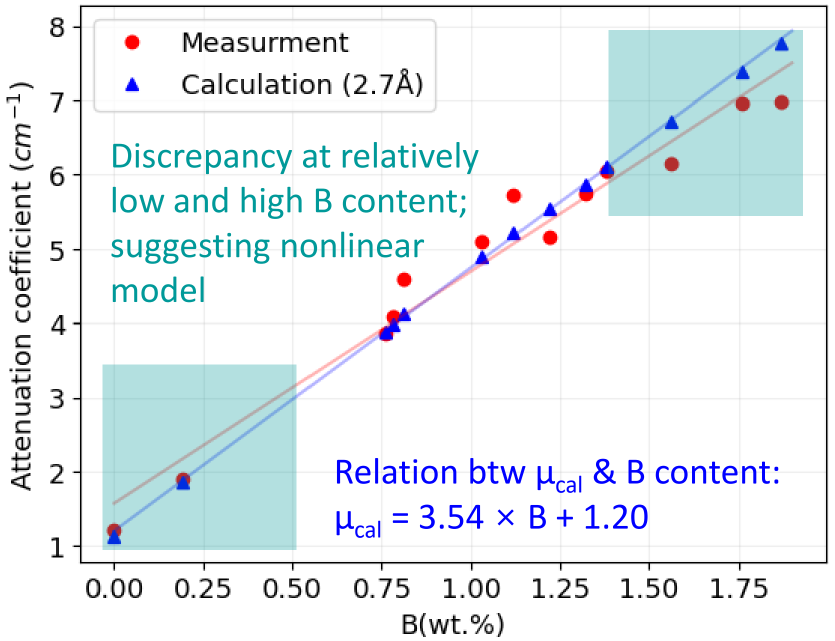


- ToF (Time-of-flight):
  - Chopper frequency: 100 Hz
  - Chopper-to-detector distance: 1200 mm
  - Direct beam position
- Effective Wavelength: 2.7 Å

$$\lambda_{eff} = \frac{\int \lambda S(\lambda) d\lambda}{\int S(\lambda) d\lambda} \rightarrow \mu_t = \bar{\Sigma}_t = \sum_i \sigma_{t,i}(\lambda_{eff}) \cdot \left(\frac{w_i N_A \bar{\rho}}{M_i}\right)$$

*Data from python packages: periodictable, pymatgen

Element	Atomic weight (M_i, g/mole)	Element density (ρ_i, g/cm$_3$)	Attenuation coefficient (μ_t, cm^{-1})
C	12.011	2.20	**0.613**
Si	28.085	2.33	**0.121**
Mn	54.938	7.33	**1.777**
Cr	51.996	7.19	**0.672**
Ni	58.693	8.90	**2.306**
B	10.810	2.34	**150.828**
Al	26.981	2.70	**0.111**
Fe	55.845	7.87	**1.313**



Re-definition of effective wavelength and μ_{eff}

Effective Incident wavelength

$$\lambda_{eff,inc} = \frac{\int \lambda S(\lambda) d\lambda}{\int S(\lambda) d\lambda}$$

- Beam property
- Depends only on: spectrum, $S(\lambda)$

→ $S(\lambda)$ integration

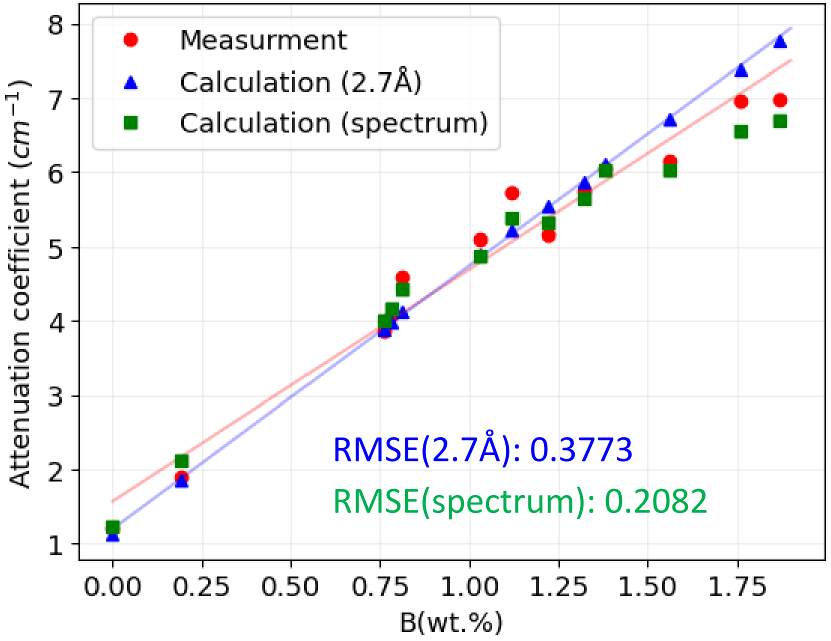
Effective Transmitted wavelength

$$\lambda_{eff,tran} = \frac{\int \lambda S(\lambda) \exp[-\mu(\lambda)t]\, d\lambda}{\int S(\lambda) \exp[-\mu(\lambda)t]\, d\lambda}$$

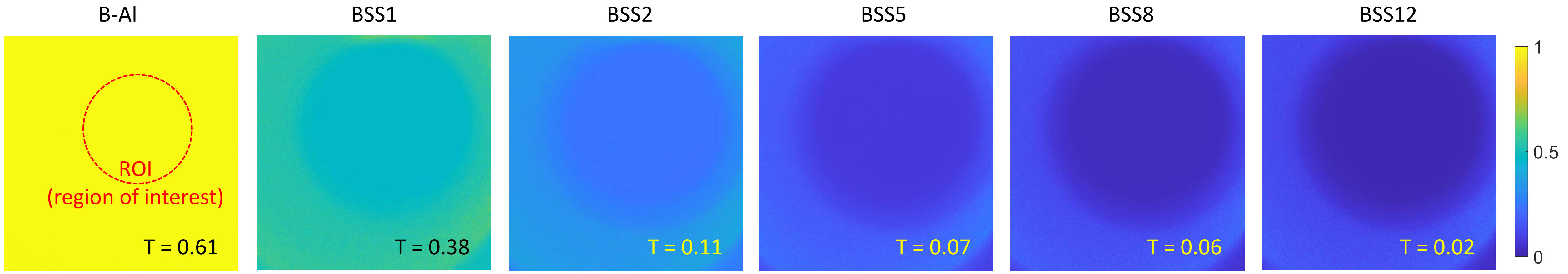
- Depends on:
  - Spectrum, $S(\lambda)$
  - Material and thickness, μ and t

Effective attenuation coefficient w/ Spectrum

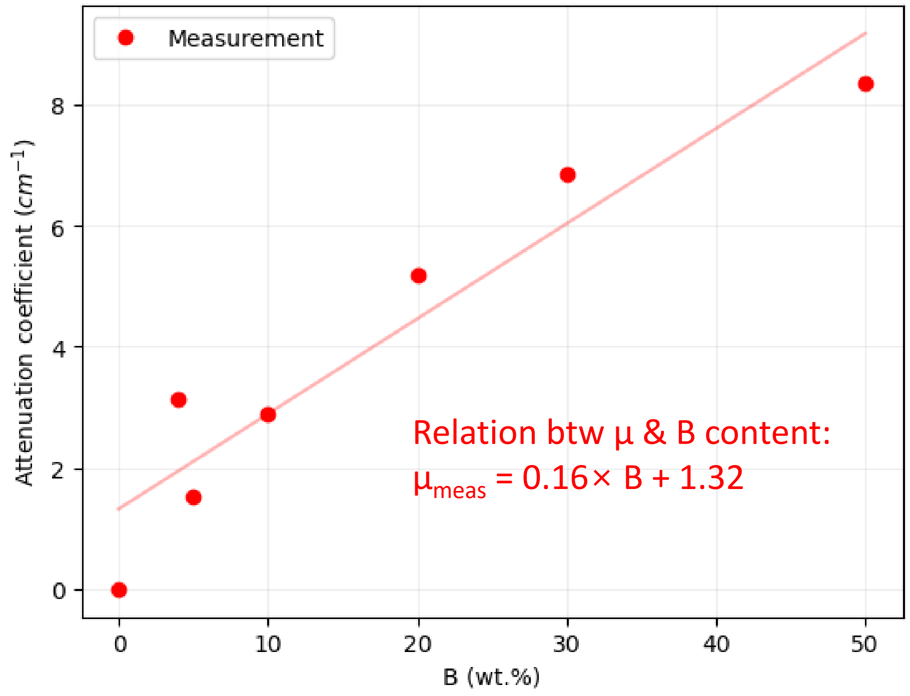
- Wavelength-dependent attenuation coefficient $$\mu(\lambda) = \sum_i \sigma_i(\lambda) \cdot N_i$$
- Transmission calculation $$T(\lambda) = \exp[-\mu(\lambda)t]$$
- Spectrum integration (effective transmission) $$T_{eff,tran} = \frac{\int S(\lambda) T(\lambda) d\lambda}{\int S(\lambda)\, d\lambda}$$
- Effective attenuation coefficient $$\mu_{eff,tran} = -\frac{1}{t} \ln(T_{eff,tran})$$



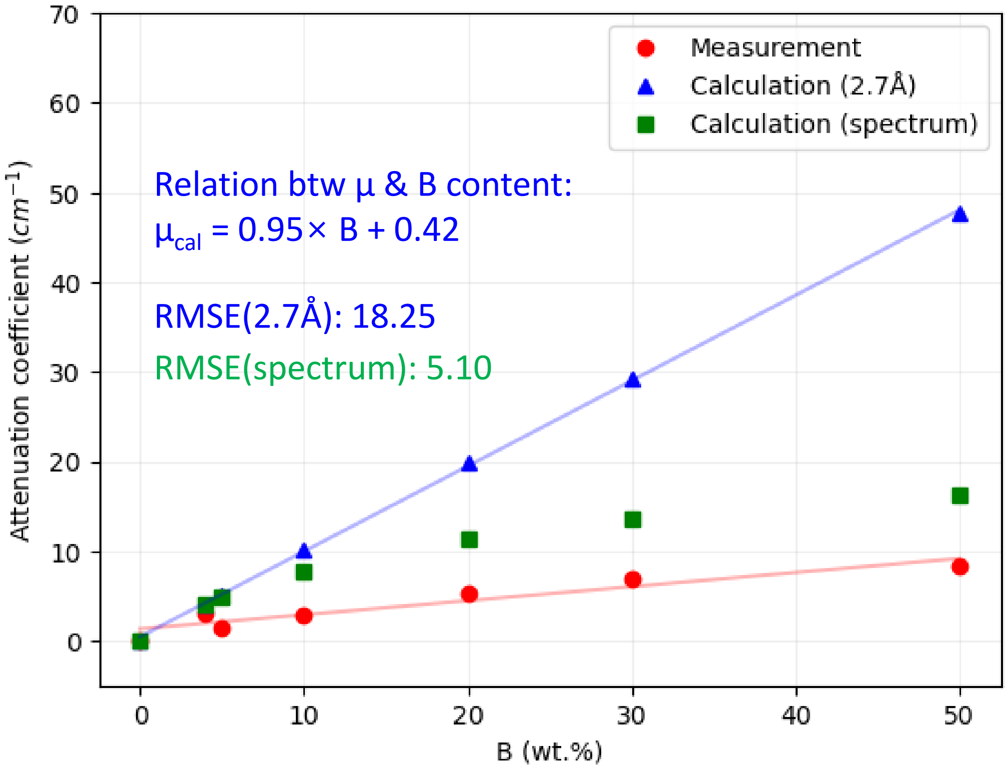
B-Al results: Transmission images and μ_{meas}



Sample	B (wt.%)	t (cm)	I_o	I	$T(I/I_o)$	$\mu(cm^{-1})$
B-Al	0	0.5	5155.75	5189.70	**1.01**	**-0.01(~0)**
B-Al04	4	0.5	5155.75	2396.28	**0.24**	**3.15**
B-Al05	5	0.5	5155.75	1215.98	**0.07**	**1.53**
B-Al10	10	0.5	5155.75	384.08	**0.03**	**2.89**
B-Al20	20	0.5	5155.75	167.08	**0.02**	**5.19**
B-Al30	30	0.5	5155.75	79.04	**0.21**	**6.86**
B-Al50	50	0.5	5155.75	1069.76	**0.46**	**8.36**



B-Al results: Transmission images and μ_{meas}



- Calculate density (ρ) of B contents in B-Al material
  - ρ_{Al}: 2.70 g/cm^3 & ρ_B: 2.34 g/cm^3

$$\rho_{alloy} = \frac{1}{\frac{w_B}{\rho_B} + \frac{w_{Al}}{\rho_{Al}}}$$

$$\rho_B^{(alloy)} = w_B \cdot \rho_{alloy}$$

- Areal density (A) of B content in B-Al material
  - Relation btw μ_{meas} and $\mu_{cal,spectrum}$:

$$\mu_{meas} = \mu_{cal} \cdot R \rightarrow A_{meas} = A_{cal} \cdot R$$

	0	4	5	10	20	30	50
Alloy density (g/cm^3)	2.700	2.679	2.674	2.648	2.598	2.549	2.454
B density in alloy (g/cm^3)	0.000	0.107	0.134	0.265	0.520	0.765	1.227
B areal density (A_{cal}) (g/cm^3)	0.000	0.054	0.067	0.132	0.260	0.382	0.613
B areal density (A_{meas}) (g/cm^2)	0.000	-	0.027	0.057	0.124	0.191	0.323

Summary

- Measured transmission and attenuation coefficients over a broad neutron energy range using imaging facility at HANARO

- Established the relationship btw B content and thermal neutron attenuation in BSS and B-Al alloys

- Spectrum-integrated effective transmission and attenuation showed good agreement w/ measurements

- Estimated real B areal density in B-Al alloys