RIKEN Accelerator-driven compact neutron systems , RANS project and their capabilities

14 June 2022 IPAC. Invited talk

RANS-RIKEN Accelerator-driven compact Neutron Sources-

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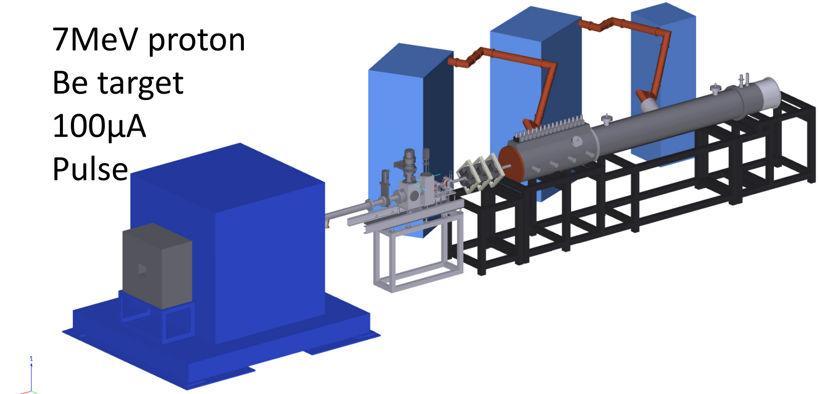
Technology Research Association for Neutron Next Generation System

RANS project

- In operation, RANS and RANS-II

RANS

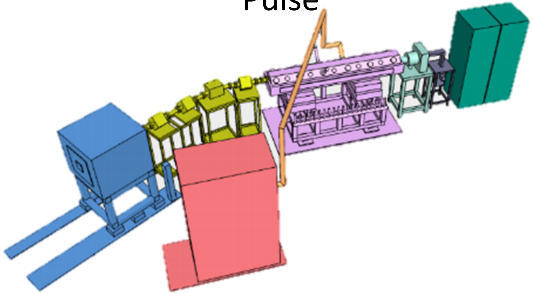
7MeV proton
Be target
100μA
Pulse



Up-grade of moderator-reflector system 2020-2021

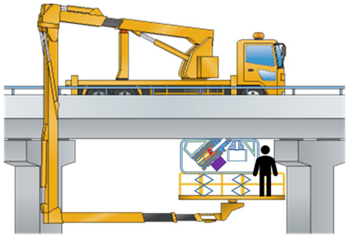
RANS-II

2.49MeV proton
Li target
100μA
Pulse



Under development

RANS-III



RANS-μ

RANS

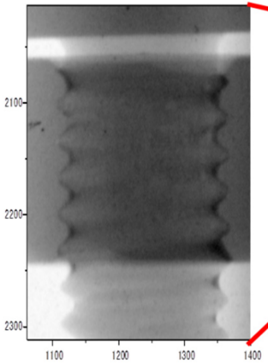
RAP

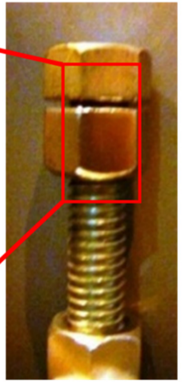
Neutron : Making the invisible visible nondestructively

- High penetration power
- High sensitivities for light elements, H, Li, B,
- Elemental analysis

Non-destructive imaging

Neutron imaging
(25meV)

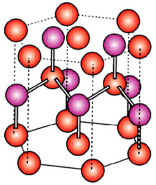


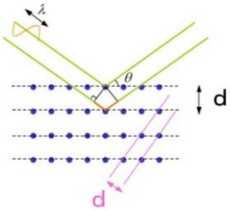


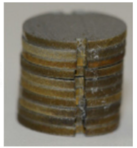
X-ray imaging
(450kV)

Structural Analysis
Lattice, iron, metal, concrete

neutron diffraction, small angle scattering



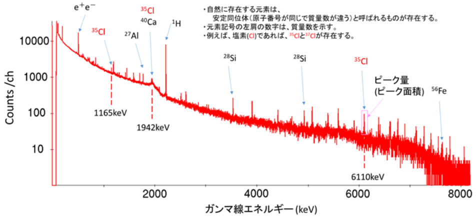




~1cm^3

Elemental analysis

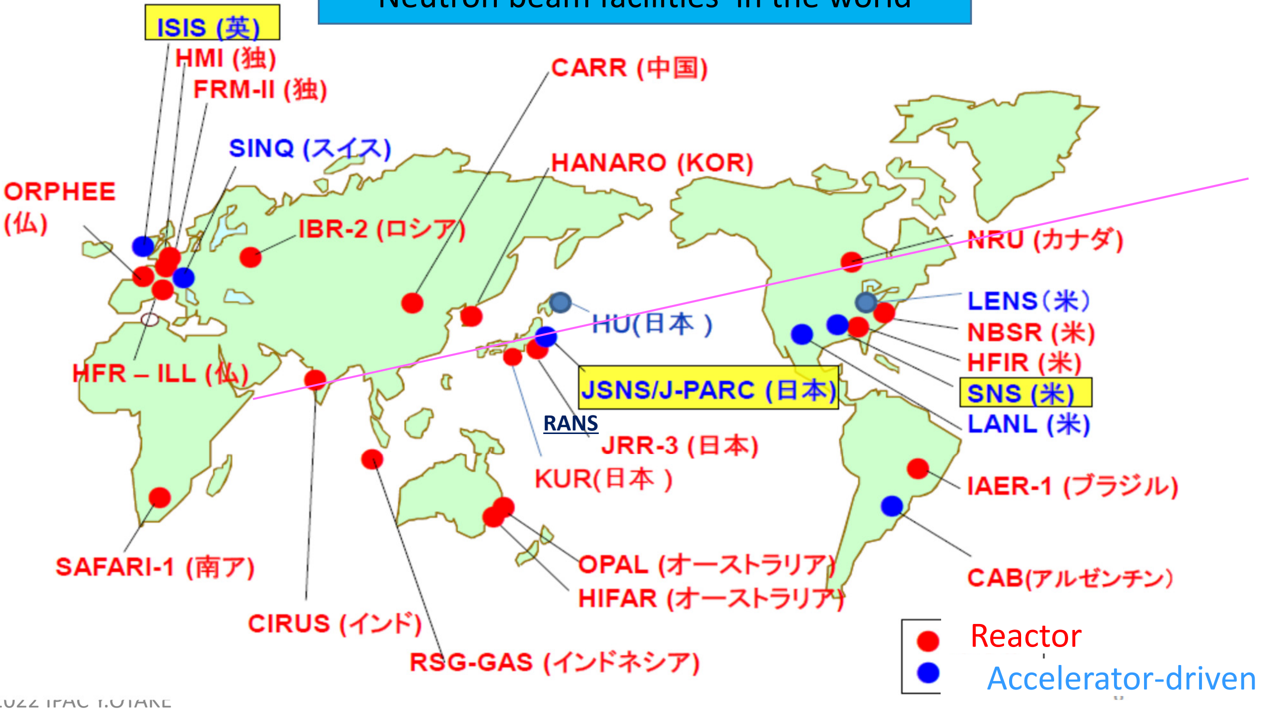
PGAA, NAA

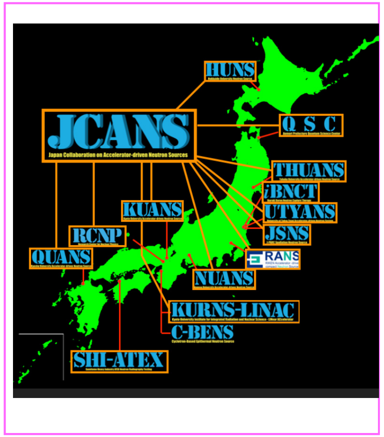


Evaluate inside the **bulk** samples with neutrons

Neutron facilities in the world
A few chances for non-destructive test users, and for new requests

Neutron beam facilities in the world





RIKEN RANS Development

Compact neutron systems for practical use !

neutrons, anytime, anywhere

Source and instrumentation are inextricably associated

The development purpose

in order to respond to the needs! New needs

→Standard Model of non-destructive test as evaluation analyzer

Source development

Instruments design, analytical methods should be based on strong demand from the society

Infrastructure: non-destructive test

To meet needs ： preventive maintenance

Salt damage->bridges collapse

USA I-70 Concrete bridge collapse

Dec. 2005 , 45 years after the construction Pennsylvania. Rebar corrosion because of **ant freezing agent**

From ： Pittsburg Post-Gazette

Initial construction failure

Canada Collapse of a Portion of de la Concorde Overpass

Sept, 2006, 35 years after construction, Montreal

Initial construction failure

出典：落橋に関する委員会報告書

Message from Dr. Banthia to Japanese researchers:
The novel non-destructive test methods such as x-ray, electromagnetic induction method, elastic wave method.出典：六郷ら、カナダのデラコンコルド跨道橋の崩落事故に学ぶ、コンクリート工学,2008.12

From Mr. R.Ooishi (Institute Public Work)

Italy ·Moradi bridge collapse （14 Aug.2018.） Salt damage

Vigili del Fuoco/AFP

Taiwan bridge collapse1 Oct. 2019)

写真:https://udn.com/news/story/7321/4078135

NEED: Daily use of neutron non-destructive test

RANS: Neutron system at anytime, anywhere!
On-site compact instruments

Non-destructive observation, on-site: company site

New request : Preventive maintenance in, test:Manufacturingfrastructure, such as bridges (in Japan, more than 720,000)

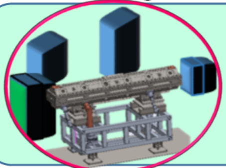
Neutron

OAK RIDGE NL HP

cooperation

J-PARC エンター HP

On-site usage : Evaluation analysis



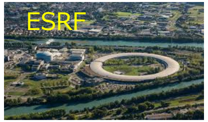
Floor-standing type
RANS-II Model

Transportable
Under development
RANS-III Model

Transportable

Large facilities

Synchrotron radiation, X-ray



ESRF HP

理研 HP

相補利用

Ibaraki center HP

X-ray CT
XRD,microstructure analysys
Compact, on-site

Large facilities

Nondestructive test **on site** use, **floor standing**, and **transportable compact system**

On-site non-destructive test

Floor-standing type

X -ray, Electron,
SEM, TEM,EBSD

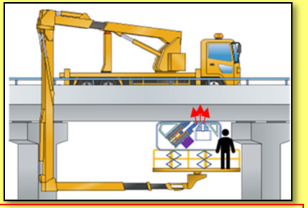
Neutron

RANS-II MODEL

RANS-II

On-site non-destructive test

Transportable type

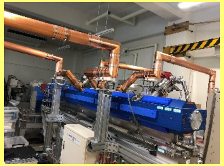


RANS-μ　Neutron Salt-meter

RANS-μ

RANS-III MODEL

RANS-III



1. Lower radiation level during operation
2. Easy to operate, and easy and safe for maintenance
3. Good S/N measurements for quantitative analysis (No powerful source, but proper technology for compact source including shielding design, pulse structure, etc.)
4. As few as possible of activation products

Why accelerator-driven neutron sources are needed?

- -Neutron intensity above about 10^{12} n/s = quantitative analysis evaluation.
- Radiation safety: neutron generation can be stopped by switching off.

  - Quantitative analysis
  - RANS, RANS-II, RANS-III are accelerator-driven neutron systems

  RANS development has started since 2011, and started operational since 2013.

  - The development of advanced measurement technology has been carried out using a RANS, and the results have enabled quantitative analysis to be carried out on an even smaller instrument with limited resolution, the RANS-μ.

RANS (RIKEN Accelerator -driven compact neutron sources)

RANS
RIKEN Accelerator - driven compact Neutron Sources

1.Proton 7MeV 100 μA (max. av.) Daily use

Be (p,n)reaction: Be (Dr. Y.Yamagata)

2012 7MeV proton linac was installed (Accsys co.)
2013 Operation starts with fast and thermal neutron

- Neutron max total flux ~10^{12}/sec

- 7MeV 100 μA 700W
- Pulse condition
- 10-180μs pulse width
- 20-180Hz repetition rate

Choose them under the condition 1.3 %duty, 100μA

2.compact and low cost

proton linac: in our case less than <2億円=2*10^8 yen=2 million US$

shielding design Multilayer shielding of target station

７MeV、100μA、Rf power supply.: 350kW(peak) duty 1.3%,Electric power peak 40kVA, Cooling water：75L/min ,**pulse width** (**30～200μs**)repetition frequency～**20～180Hz** RF power 425MHz, Injection energy0.030-3.5MeV

RANS

RAP

RANS-II: two function

・Proto-type of transportable compact neutron systems

・Standard Model of floor standing compact neutron system: can be easily introduced into public inspection stations, companies and universities.

Power	Neutron Yield @target	Target ST shielding	Beamline	Neutron @ sample position	Acce. Duty
RANS 7MeV 700W	10^{12} n s^{-1}	Volume：~ $8m^3$ weight～ 23ton	1.5m	*10^5 n cm^{-2} s^{-1}	RANS 1.3% (RF Duty cycle)
			5m	*10^4 n $cm^{-2}s^{-1}$	
RANS-II 2.49MeV 250W	*10^{11} n s^{-1}	V~$1m^3$ W~ 3.5ton	0.5m	*10^4~10^5 n cm^{-2} s^{-1}	RANS-II 3% (RF Duty cycle)
			1.5m	*10^4 n cm^{-2} s^{-1}	

RANS Comparison table : Compact Accelerator-driven Neutron Systems: CASNS

	RANS	**RANS-II**: Floor standing type, proto-type of transportable	**RANS-III (under construction)** (transportable)
Pulse	10-180μs 15-1800Hz	5μs-3ms 0.1-500Hz	
Particle	proton	proton	proton
Energy	7 MeV	2.49 MeV	2.49 MeV
Current	100 μA	100 μA	100 μA
Reaction	$^{9}Be(p, n)^{9}B$	$^{7}Li(p, n)^{7}Be$	$^{7}Li(p, n)^{7}Be$
frequency	425MHz	200MHz	500MHz
Accelerator	RFQ + DTL	RFQ	RFQ
RF amplifier	vacuum tubes	Solid state 200kW	Solid state 250kW
Weight (Accelerator)	5 t	2 t	700kg
Weight (Target Shield)	20 t	2 t	1.5t
Length	15 m	5 m	< 3 m
Neutron Yield	～10^{12} sec^{-1}	～10^{11} sec^{-1}	～10^{11} sec^{-1}
Ion source	Duo-plasma	ECR plasma	ECR plasma (Permanent magnet)
Drive mode	Pulse	Pulse	Pulse

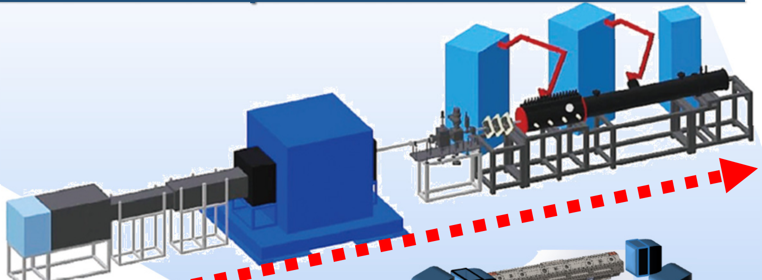
RANS

RAP

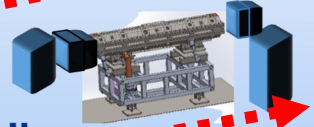
RANS challenge
to meet the needs for such non-destructive test with neutrons!

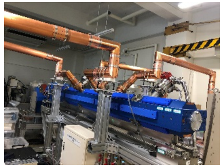
RIKEN Accelerator-driven compact Neutron Sources RANS

RANS: Research with neutron scattering at the institutes, universities, etc.

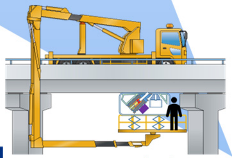


RANS-II: MODEL of non-destructive test instrument with neutrons on-site.
Ex. Neutron CT-instrument, (p-23 Takanashi)
Stress measurement instrument
-> Hungarian case: PHOTO (from Prof. Dr. F.Mezei)





RANS-III: Transportable neutron system out-side

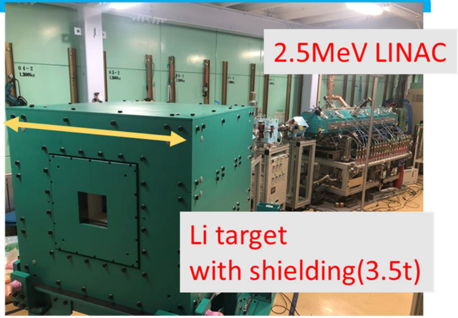


RANS-μ: Neutron salt meter with bridge inspection vehicle
It will be appeared in 2023 with T-RANS activities

Needs-based measurement results based on the characteristics of compact neutron sources.

RANS and RANS-II neutron instruments

RANS



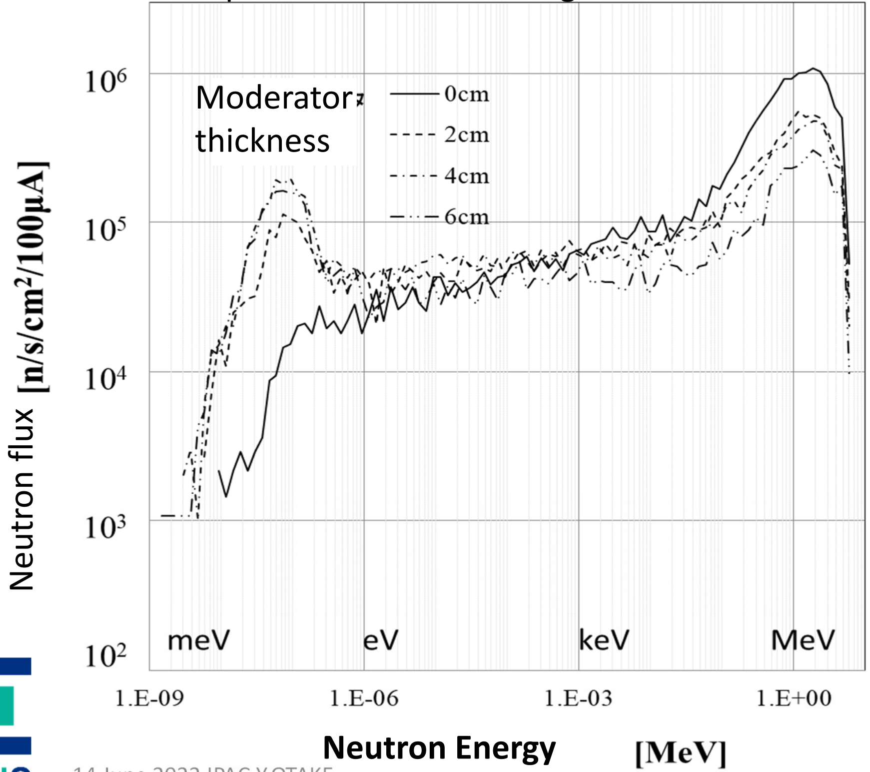
RANS-II

1. Imaging experiments special resolution, 0.5mm, 0.2mm, Non-destructive test
2. Diffraction, iron steel samples, residual **austenite phase fraction**
3. Prompt gamma-ray Neutron Activation Analysis, PGNAA, elemental analysis
4. SANS with Ibaraki Univ. (Small Angle Neutron Scattering) nano, sub-mic.
5. Fast neutron transmission imaging for thick samples
6. Fast neutron **scattered imaging** from the surface layer with 6~20cm
7. Phase contrast imaging with Tohoku Univ. Prof. A. Momose
8. Polarized neutron experiment for fundamental physics, with Nishina-center, Tohoku Univ. Kyushu- Univ.

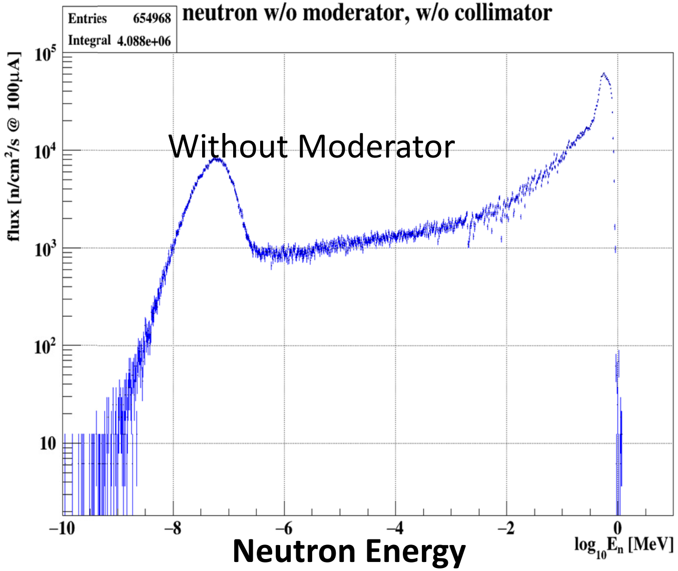
RANS, RANS-II Neutron Spectrum

RANS

Spectrum 1.5m from target (Target station exit)



RANS-II

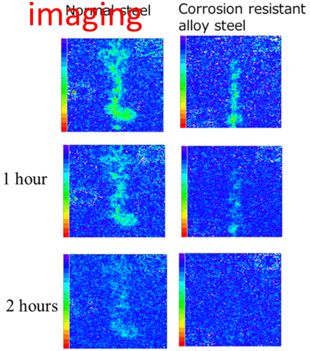


Corrosion imaging: Non-destructive test: industrial use:

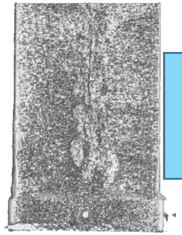
- Painted steel corrosion imaging Collaboration with Kobe Steel
- Cooperation together with large facility and compact neutron sources.

Normal steel | Anti-corrosion alloy

Time dependent water movement imaging



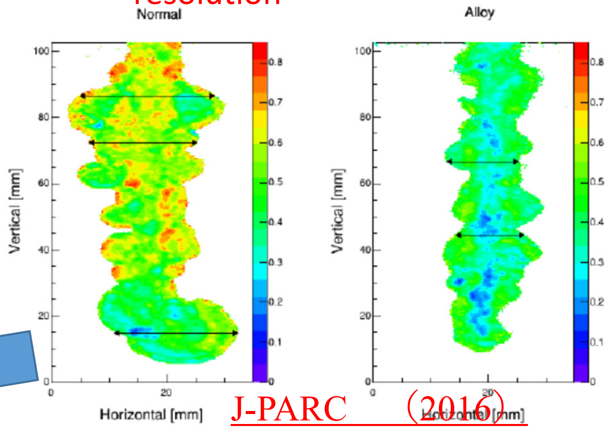
3D imaging



RANS (2013)

Large F. J-PARC

Time dependent water movement imaging with high resolution



J-PARC (2016)

Large facility

RANS (2019-)

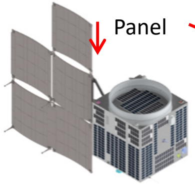
Cooperation of compact and large facility, imaging analytical technology development:

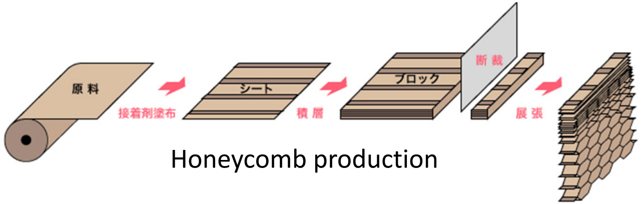
RANS-> J-PARC -> RANS : ~20μm thin water detection

Glue visualization: Non-destructive test Aluminum panel, honeycomb and glue: Space application JAXA, Satellite 1

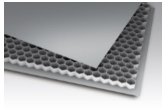
小型実証衛星１号機（RAPIS-1：RAPid Innovative payload demonstration Satellite 1）

JAXA
Dr. Kagawa

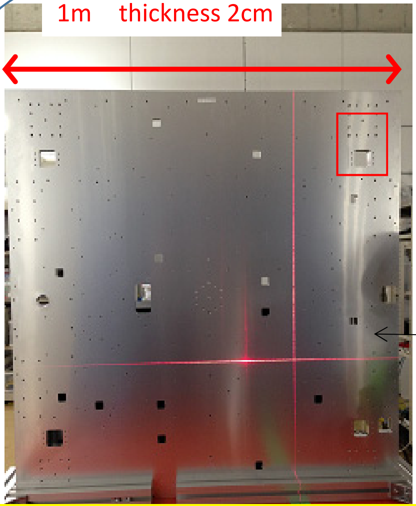


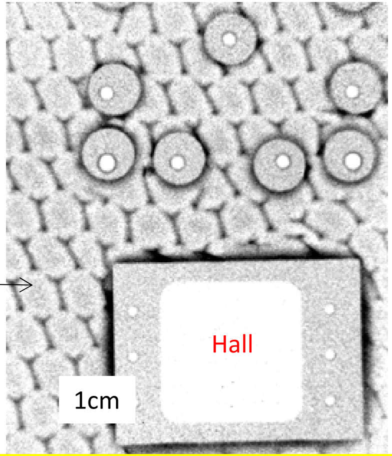


Honeycomb production

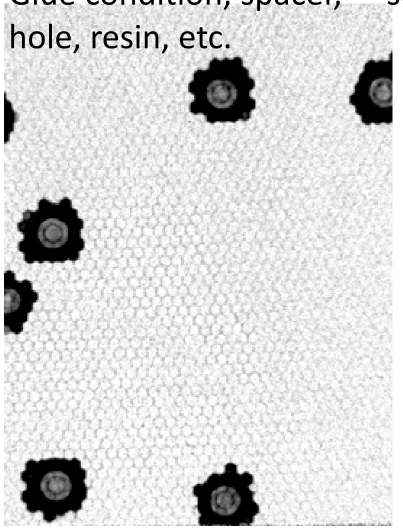


RANS non-destructive test





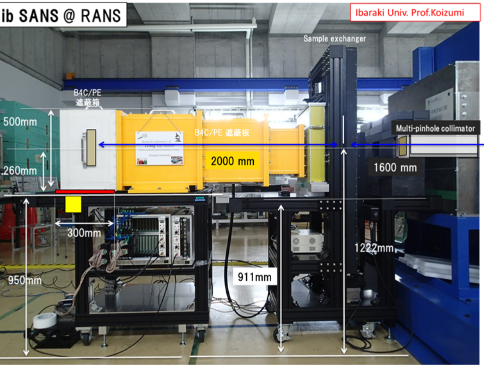
Inside the panel observation,
Glue condition, spacer, screw hole, resin, etc.



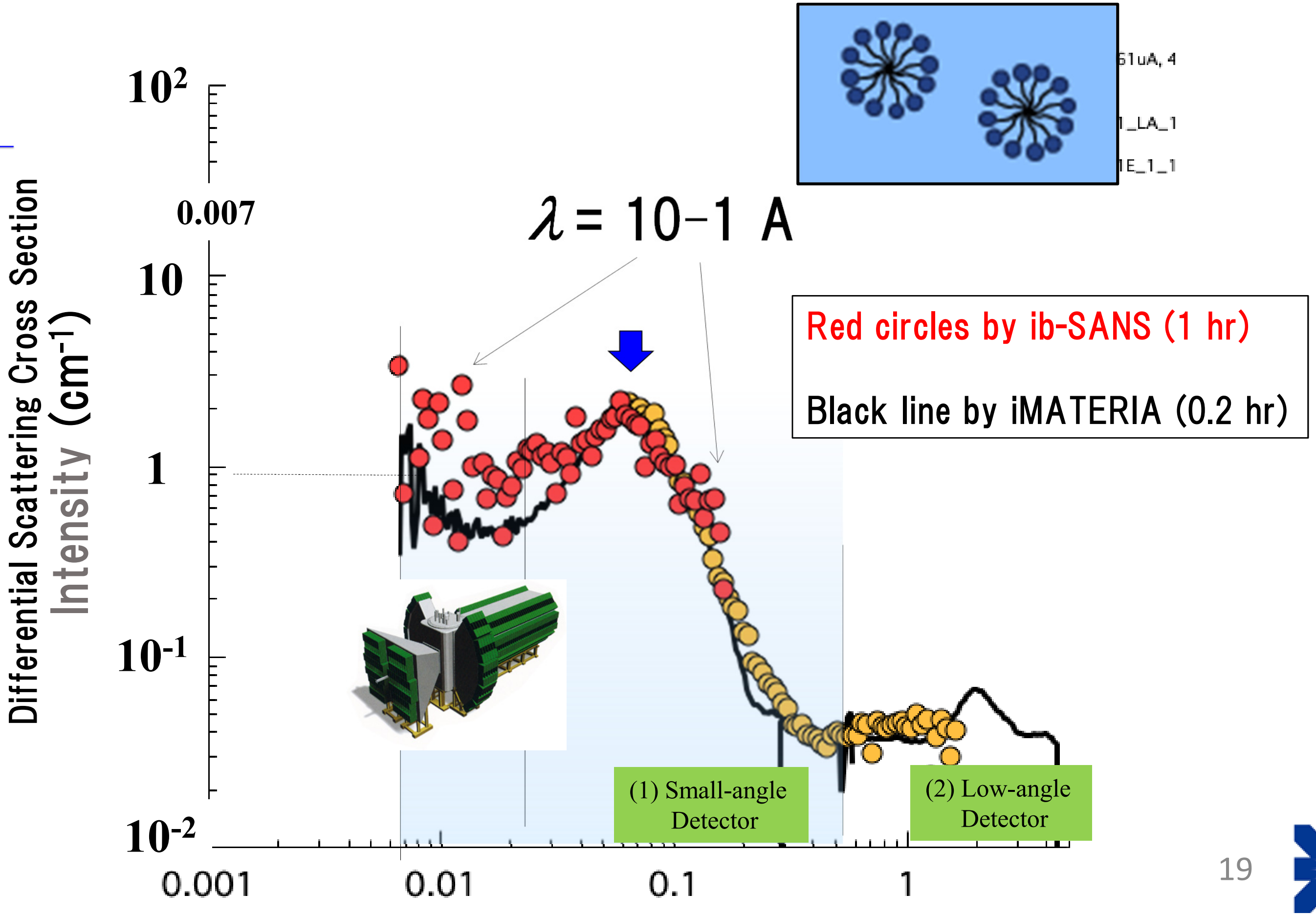
Success of launch 18 Jan.2019

Ib-SANS on SDS micelle solution with a cold source (before up-grade)

Developed by Prof.S.Koizumi, Ibaraki University



RANS



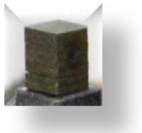
Volume fraction estimation with RANS engineering diffraction

RANS

retained **austenite** evaluation

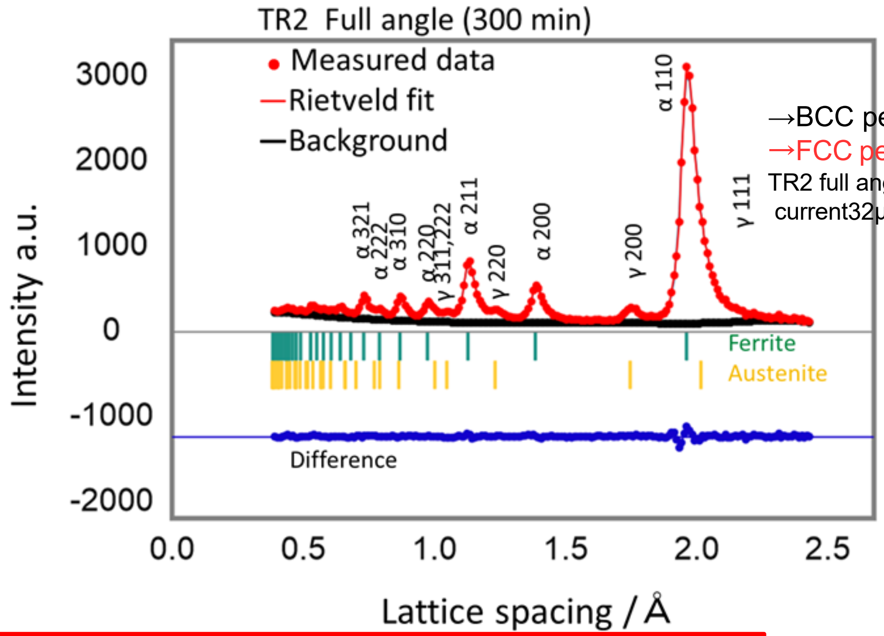
Controlled samples produced

9mm×10mm×9.5mm



Austenite：13.1%

J-PARC Takumi: 13.9%



→BCC peaks

→FCC peaks

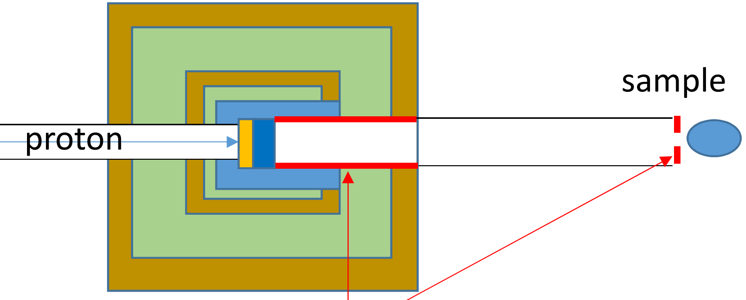
TR2 full angle(300min, current32μA)

The result of measurement during uniaxial rotation (30 min) for round robin sample is consistent with J-PARC measurement within 1%

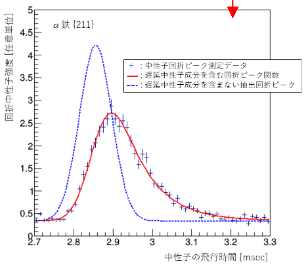
-> Compact source has high potential to use on-site

Y.Ikeda et al, Tetsu to Hagane **vol.104, No.3** (2018) pp.18-24

Towards stress measurement: decoupled collimator + de-convolution method-> higher resolution and intensity



Decoupled collimator system +
deconvolution method



$$F(t) = \int_{-\infty}^{+\infty} f(t')g(t-t')dt'$$

$$= A\exp(-\beta t)\,\mathrm{erfc}\left(\frac{-(t-(t_c+\sigma^2\beta))}{\sqrt{2}\sigma}\right) + C \quad (5.1)$$

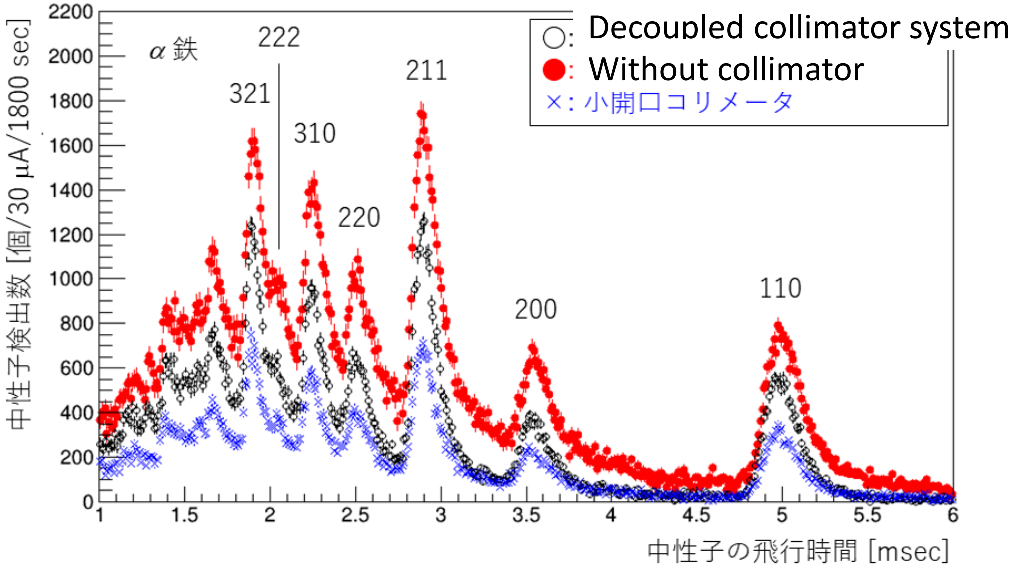
$$f(t) = \begin{cases} 0 : t < 0 \\ \beta\exp(-\beta t) : t \geq 0 \end{cases} \quad (5.2)$$

$$g(t) = \frac{I}{\sqrt{2\pi}\sigma}\exp\left(\frac{-(t-t_c)^2}{2\sigma^2}\right) \quad (5.3)$$

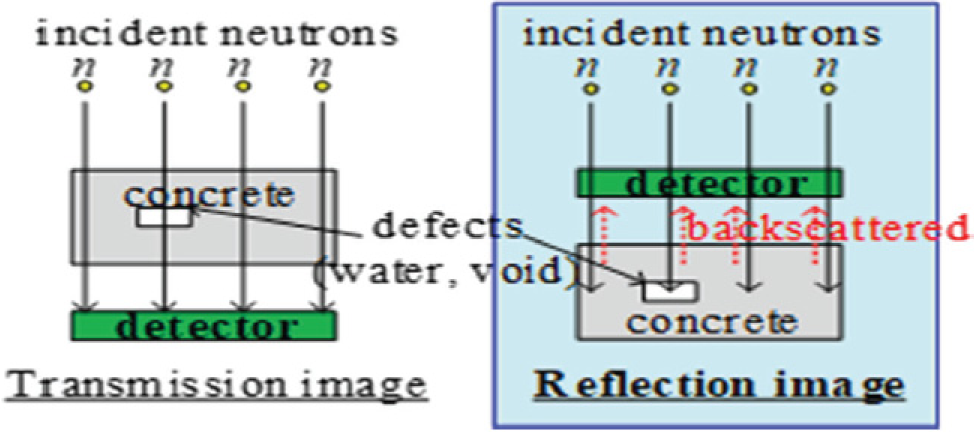
$$A = \frac{I\beta}{2}\exp\left(\frac{\sigma^2\beta^2}{2} + \beta t_c\right) \quad (5.4)$$

$$h(t) = \frac{I}{\sqrt{2\pi}\sigma}\exp\left(\frac{-(x-t_c')^2}{2\sigma^2}\right) \quad (6.1)$$

$$t_c' = t_c + \sigma^2\beta \quad (6.2)$$

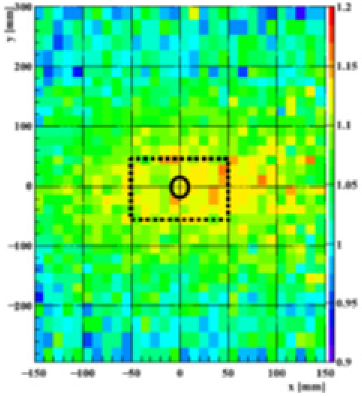


Back-scattering (reflection imaging) fast neutron time of flight imaging method

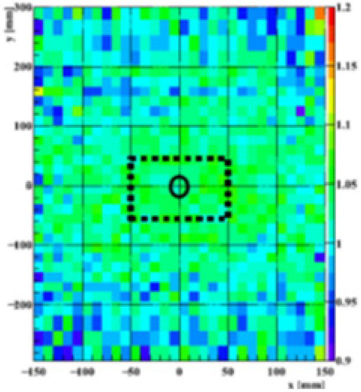


Comparison with normal transmission imaging set-up and the reflection (back-scattered neutron) image method for infrastructure (left), and the vision of future on-site use with a compact neutron source (right).

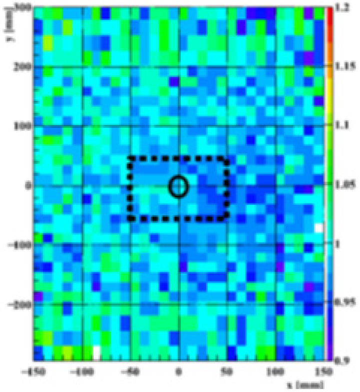
RANS-II Visualization of degradation,



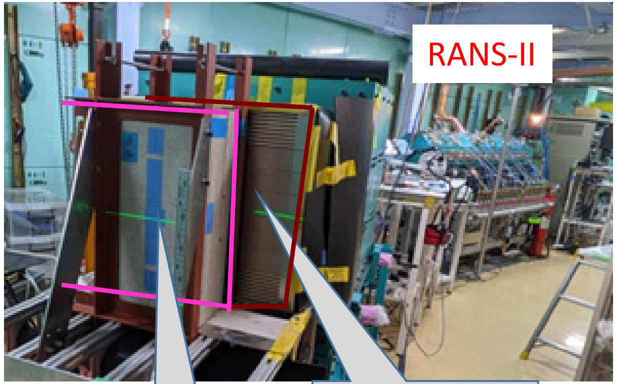
5mm water



wet sedimentation



dry sedimentation

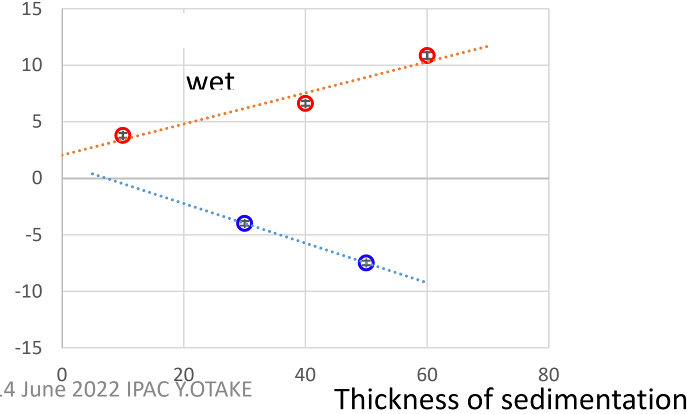


PSD Detector (ToF)

Floor slab With inside degradation

Degradation samples

- quantitative identification in terms of thickness of sedimentation



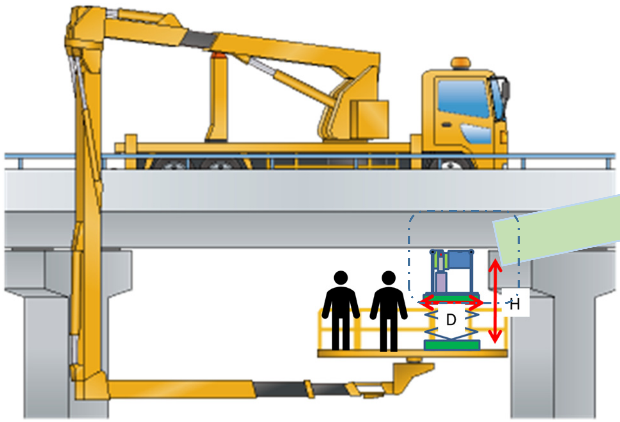
RANS−μ salt meter : Development in response to urgent requests

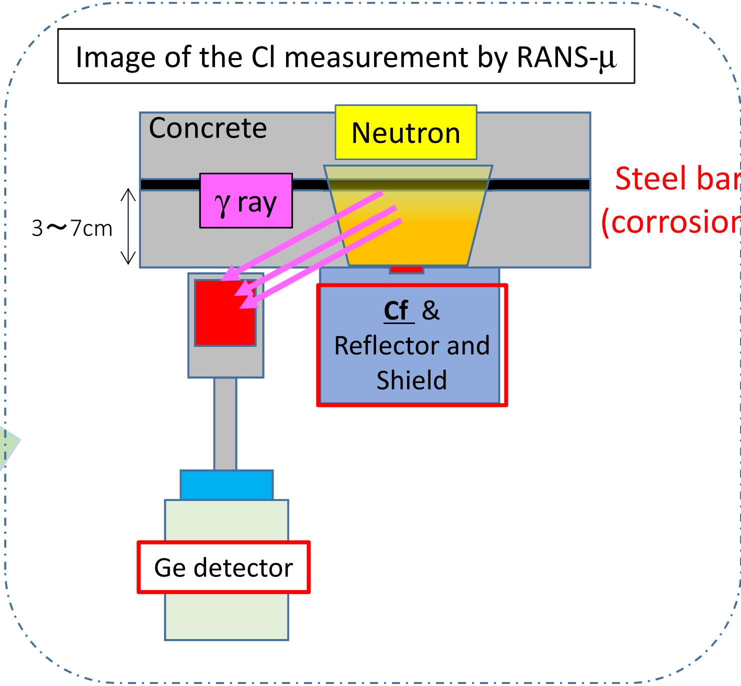
Non-destructive testing of salinity behind slabs and girders.

Setting of goals for RANS-μ salt meter;

- Total size &weight : W<700 x D<700 x H～1800(adjustable) weight : <100kg
- Operator : 2 persons (1 for Salt meter + 1 for Bucket or Corridor)

- Cl detection : 1.0 ± 0.2 kg/m³ at 7cm depth from concrete surface
- Non-destructive measurement

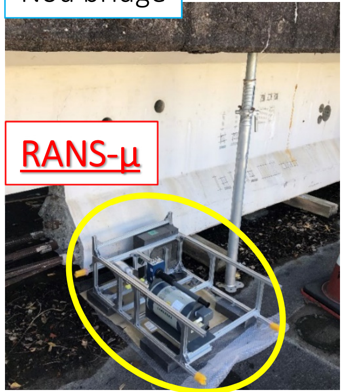




RANS−μ salt meter on-site measurement using removal damaged bridge at Public Work Research Institute

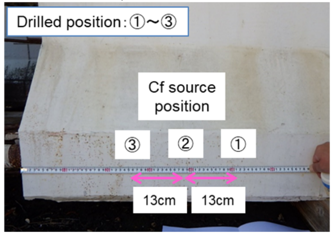
・Verification of average salinity using two demolished bridges: successful quantitative assessment.

Nou bridge



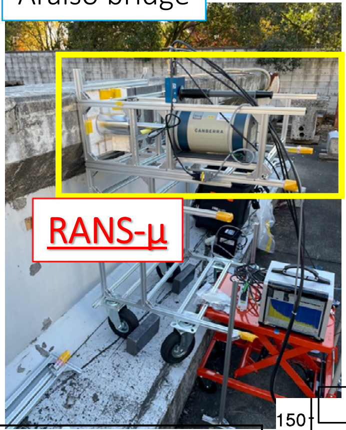
Conventional method

Drilled powder collection near RANS-μ measurement area

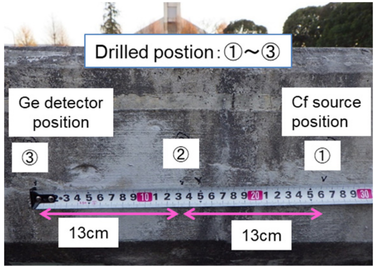


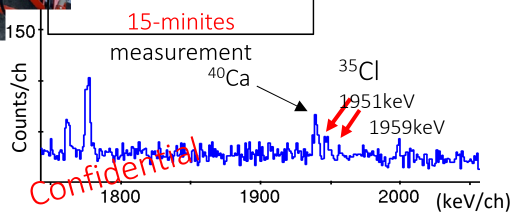
Total average of 9 points

Araiso bridge



Conventional method





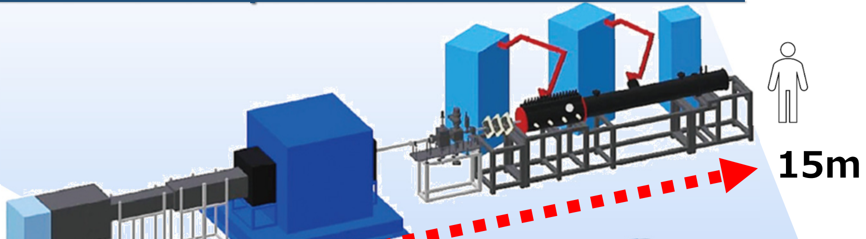
	Cl density (kg/m^3) ←Average	
	Nouu Bridge (Niigata)	Araiso Bridge
RANS-μ (non-destructive)	3.1 ± 1.1kg/m^3	5.7 ± 1.5kg/m^3
Conventional method (destructive)	3.27kg/m^3 (drill)	**5.72kg/m3 (drill)**

First success for non-destructive Cl measurement at on-site use by PGNAA with Cf source.

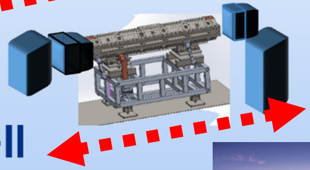
The method to deduce the depth profile will be verified.

RANS challenge
to meet the needs for such non-destructive test with neutrons!

RIKEN Accelerator-driven compact Neutron Sources RANS



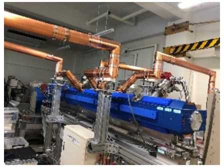
RANS: Research with neutron scattering at the institutes, universities, etc.



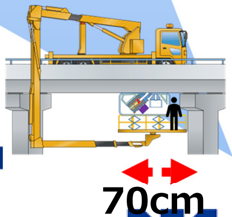
RANS-II

RANS-II: MODEL of non-destructive test instrument with neutrons on-site.
Ex. Neutron CT-instrument, (p-23 Takanashi)
Stress measurement instrument
-> Hungarian case: PHOTO (from Prof. Dr. F.Mezei)

RANS-III



RANS-III: Transportable neutron system out-side



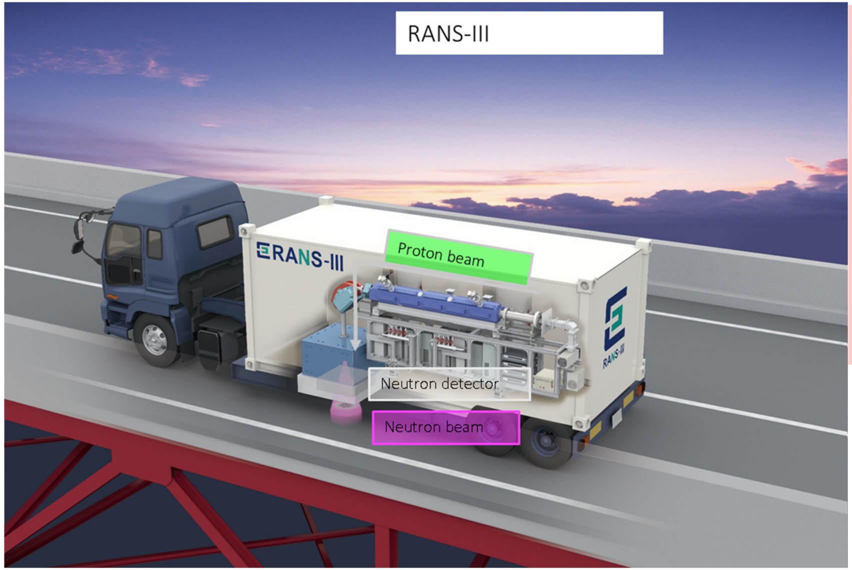
RANS-μ

RANS-μ: Neutron salt meter with bridge inspection vehicle
It will be appeared in 2023 with T-RANS activities

Japanese radiation regulation Transportable compact neutron system for bridge inspection with accelerator

The Japanese radiation regulations set the law on changing the location where accelerators are used only for bridge inspections.(Excluding deuterium)

- Linear accelerators only.
- Accelerated particle energy: less than 4 MeV.



- 放射性同位元素等規制法第11条　および　関連規定（平成１７年７月改定）Japanese regulation 4MeV>linac
  – 橋梁等の非破壊検査に用いる**直線加速器で４メガ電子ボルト**以上のエネルギーを有する放射線を発生しないものは、放射線発生装置の使用の場所の変更を都度許可を得る必要がなく届出で足りることとする。（ただし、設備については、事前に原子力規制委員会原子力規制庁の届け出許可が必要。）

T-RANS: Towards Standardization of non-destructive test method with neutrons

- Periodic inspections of infrastructure are regulated by inspection guidelines, which specify the methods and values to be measured.

R&D, proof of concept→ On-site demonstrations

RANS@RIKEN

- **MLIT** Ministry of Land, Infrastructure, Transport and Tourism
- **PWRI** Institute of Public work, Center for Advanced Engineering Structural Assessment and Research
- **TITECH** Tokyo Institute of Technology

- Proof → **On-site demonstrations**

Technology Research Association for Neutron Next Generation System (Licensed by MLIT)

T-RANS
Technology Research Association for Neutron Next Generation System

Standardization

★**Performance Catalogue of Inspection Support Technologies** (publication in it un

★Specific Inspection Guidelines for Salt Damage to Concrete Bridges (Draft)

Neutron measurements at regular inspections every 5 years

T-RANS members
9 (7companies) : June, 2021
- RIKEN
- TITECH
- Oriental Shiraishi Co.
- TIME Co.
- Clear-plus Co.（株）
- Chiyoda Technol
- COFUKUYAMA CONSULTANTS CO.
- PACIFIC CONSULTANTS CO.
- CONIPPON ENGINEERING CONSULTANTS CO.

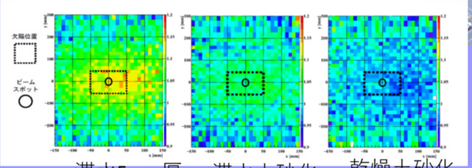
RANS

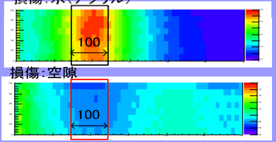
RAP

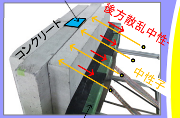
RANS RIKEN Accelerator-driven compact Neutron sources RANS, RANS2, 3, μ

Non-destructive inspection; infrastructure

In the pavement : back-scattered imaging



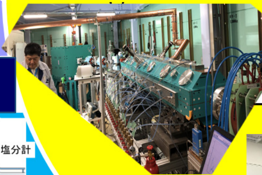




Compact Neutron

Anytime,

RANS : 15m, 25ton MeV～



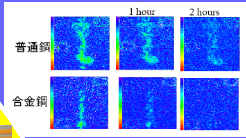
RANS-II : ~5m

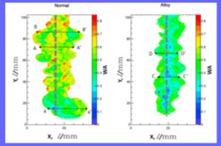
Floor-standing

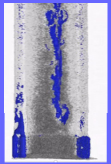
RANS-III

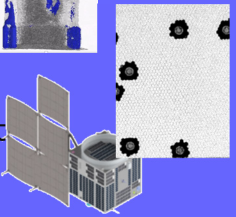
Non-destructive visualization

Visualization of the corrosion and its related water movement of the painted steel

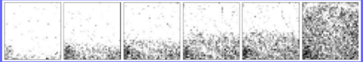






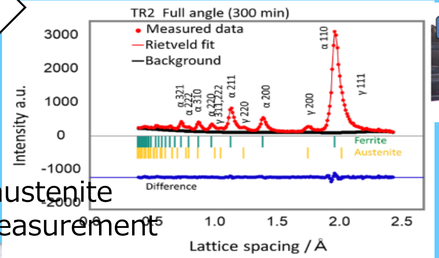


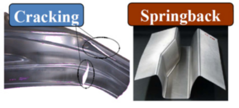
Visualization of water movement of the concrete



JAXA Satellite 1

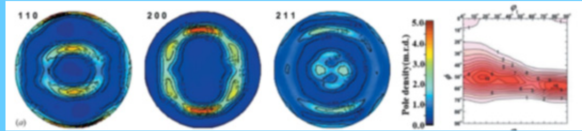
Diffractometer volume fraction, texture evaluation





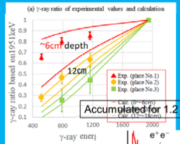
retained austenite fraction measurement

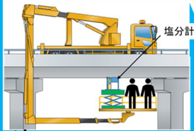
Texture evolution



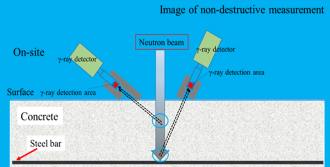
PGAA Salt detection of concrete

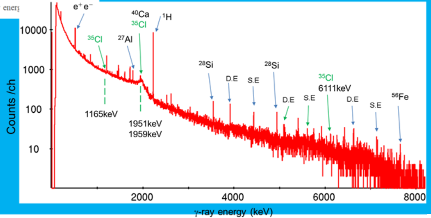
Element analysis on site





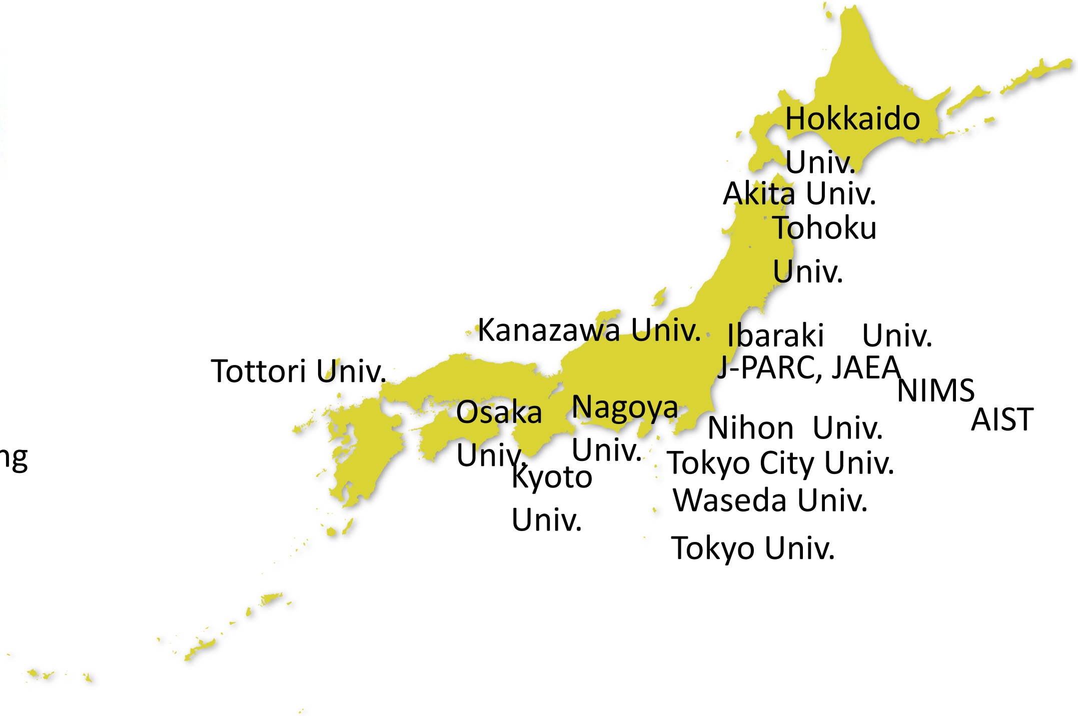
Salt distribution





Cooperation, collaboration

Xi'an Jiaotong University



Companies:
Iron and steel, Highway, and so on….

Thank you very much for your kind attention