Radiopurity strategies and low background control in the JUNO experiment

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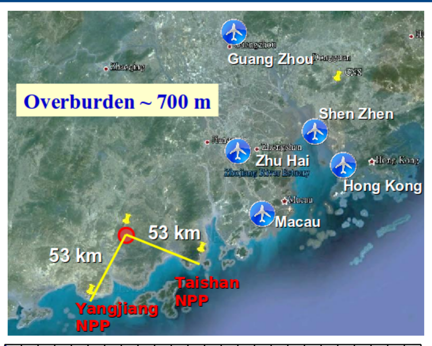
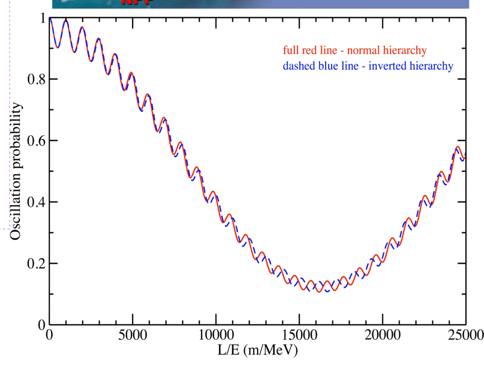
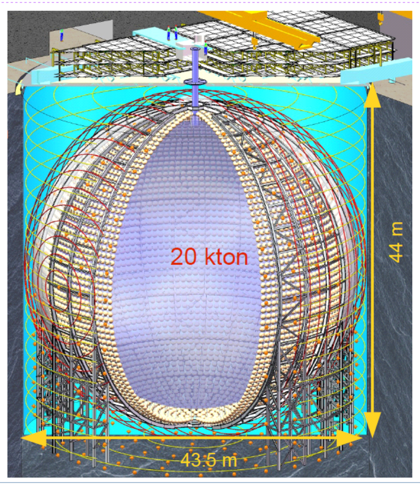
JUNO overview

- **Main JUNO physics goal : to determine the neutrino mass hierarchy at 3σ sensitivity within 6 years**
- Located at 53 km from nuclear power plants (26 GWth in 2020)
- Neutrino detected by Inverse Beta Decay on free protons
- Large scintillator detector (20 ktons) to detect 10^5 events in 6 years
- Largest PMT coverage ever built and high transparency liquid scintillator to reach 3% energy resolution at 1 MeV
  - → **Discrimination of normal or inverted mass hierarchy**
  - → Broad physics program: sub-percent sensitivity on solar oscillation parameters, study of neutrino supernovae, geo-neutrinos, proton decay...



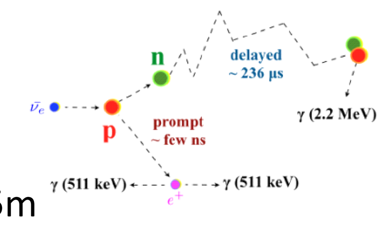


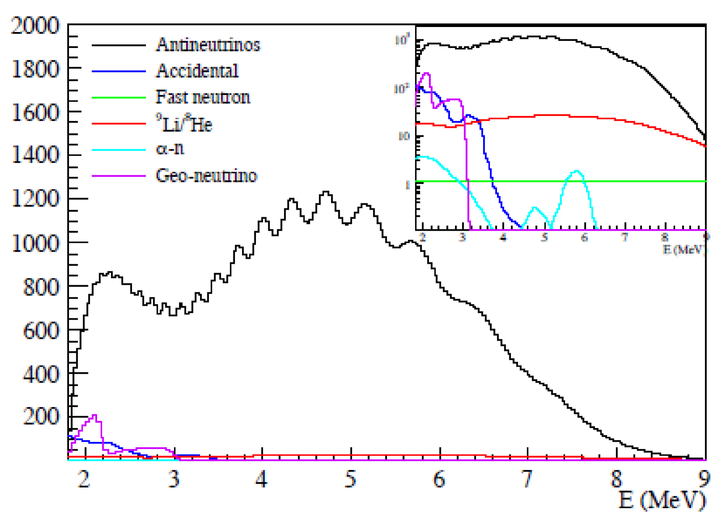


- **JUNO detector main features**
  - 20 ktons of LAB (+PPO+bis-MSB) in an acrylic sphere with R=17.7m
  - 18,000 20''PMTs (LPMT system)+ 25'000 3'' PMTs (SPMT system) on a stainless steel truss, with a total photocoverage of 75+2%
  - Compensation coil
  - Water Pool equipped with 2,000 20''PMTs and Top Tracker system for muons identification and rejection (after 700m overburden)

JUNO backgrounds

- **Inverse Beta Decay (IBD):** $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Prompt signal from positron ionization and annihilation
  - Delayed signal from neutron capture on 1H (2.2 MeV γ)
- **Criteria for IBD identification:**
  - Prompt signal: 0.7 < Ep < 12 MeV
  - Delayed signal: 1.9 < Ed < 2.5 MeV
  - Time Coincidence < 1 ms
  - Distance between two vertexes < 1.5m





Number of expected events per day before and after cuts for E > 0.7 MeV

Selection	IBD efficiency	IBD	Geo-νs	Accidental	^{9}Li/^{8}He	Fast n	(α, n)
-	-	83	1.5	$\sim 5.7 \times 10^4$	84	-	-
Fiducial volume	91.8%	76	1.4	410	77	0.1	0.05
Energy cut	97.8%	73	1.3		71		
Time cut	99.1%						
Vertex cut	98.7%			1.1			
Muon veto	83%	60	1.1	0.9	1.6		
Combined	73%	60	3.8				

→ Single trigger count rate from U/Th/K materials in JUNO must be below 100 evts/s (*10 evts/s*) in the full (*fiducial volume - R<17.2 m*) liquid scintillator volume

- **Main backgrounds**
  - Accidental background from natural radioactivity of materials in U/Th/K
  - Cosmogenic nuclei (^{9}Li/^{8}He) from μ's
  - Fast neutrons and (alpha,n) reactions
  - Geo-neutrinos

→ **Need for careful material selection, surface cleanliness, Radon emanation control and dust control!**

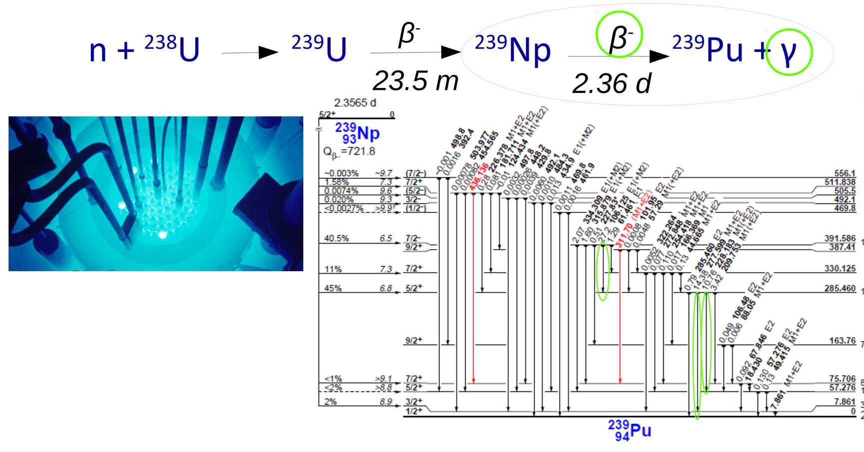
Liquid scintillator – Linear Alkyl Benzene (LAB)

Two underground purification systems (Water Extraction Plant and Stripping Plant) will be used for radioactive impurity removal from LAB. Baseline requirements for natural contaminants concentration in JUNO are: ^{232}Th < 10^{-15} g/g, ^{238}U < 10^{-15} g/g, ^{40}K < 10^{-16} g/g

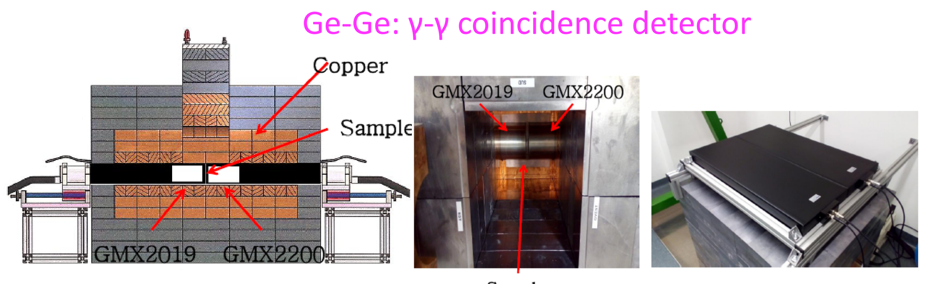
◆ **Two complementary assay techniques to certify the aimed purity level <u>during JUNO construction</u>:**

- Dedicated test in one of the DayaBay detectors (AD1 – 20 ton of LAB) – *currently ongoing*
- Neutron Activation Analysis + β/γ and γ/γ coincidence measurements – *currently in progress*

Example: NAA on ^{238}U

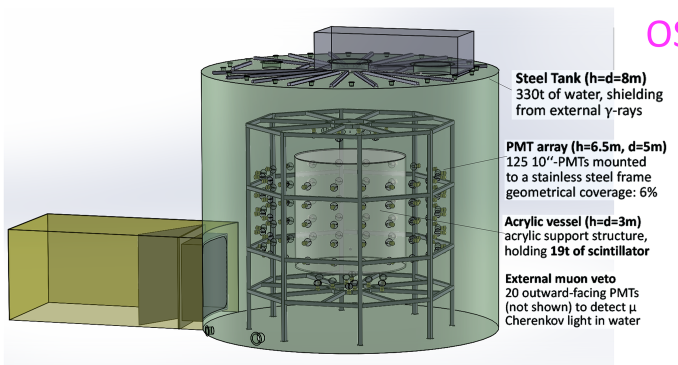


Ge-Ge: γ-γ coincidence detector



Ge-Spark: β-γ coincidence detector

◆ **<u>During JUNO operation</u>:**



OSIRIS: Online Scintillator Internal Radioactivity Investigation System

~ 20 ton of LAB scintillator with a design sensitivity of 10^{-16} g/g for ^{232}Th and ^{238}U in 1 day

currently in progress

To be installed as final step of the underground LAB purification system – just before JUNO Acrylic Sphere inlet – as online radiopurity monitor

Acrylic sphere

- **Careful selection of the raw material.** Measurements by Neutron Activation Analysis at the Pavia Triga Mark II reactor (Italy) and HPGe gamma spectroscopy:

Raw material is clean

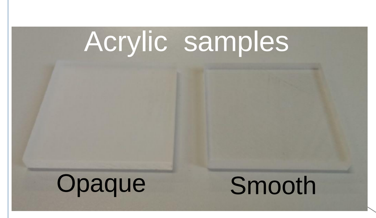
Measurements performed on samples produced by three different companies

To be repeated on final production samples

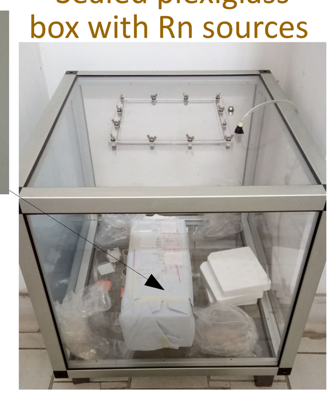
Acrylic sample	^{40}K [1E-12 g/g] (untreated)	^{40}K [1E-12 g/g] (after surface grating)	^{238}U [1E-12 g/g] (after surface grating)	^{232}Th [1E-12 g/g] (after surface grating)
Company A0	0.7 ± 0.3	< 0.1	< 2.0	< 2.9
Company B1	0.7 ± 0.2	< 0.5	< 3.2	< 2.4
Company B2	0.7 ± 0.2	< 0.4	< 2.0	< 2.5
Company C2	0.9 ± 0.2	< 0.1	< 0.7	< 1.4
JUNO requirement	< 1	< 1	< 1	< 1

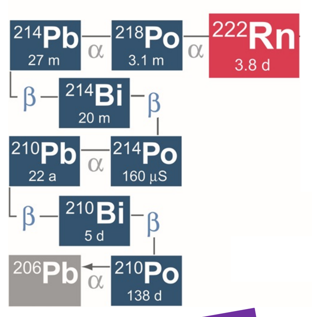
limits @ 90% C.L.

- **Close cooperation with Acrylic company to follow each step of the Acrylic sphere construction,** from flat panel production to final sphere assembly to avoid radioactive recontamination.
- **Acrylic panel surface will be covered by a thin film during the whole production process to protect it from radioactive isotope contamination.** Measurements on small Acrylic samples left for several weeks in Rn atmosphere show that the preferred ways of sample contamination are: 1) implantation of α-decaying nuclei and 2) dust deposition, while Rn diffusion seems not to play a role.

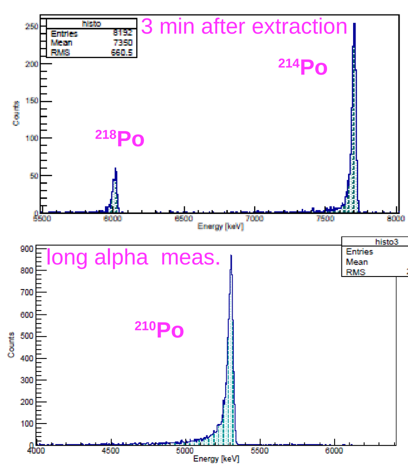


Sealed plexiglass box with Rn sources





A(^{222}Rn) = ~250 kBq/m^3 in secular equilibrium with daughters



^{210}Pb activity as extracted

^{210}Pb activity remaining after surface cleaning

Alpha measurements

Alpha activity at the time of extraction:

Sample	A^0_{218Po} [Bq]	A^0_{214Pb} [Bq]	A^0_{214Bi} [Bq]
Smooth Acrylic	48 ± 3	79.8 ± 0.8	80 ± 1
Opaque Acrylic 2	38 ± 1	54.3 ± 0.7	55.7 ± 0.9
Opaque Acrylic 3	50 ± 3	74.8 ± 0.8	76 ± 1
Opaque Acrylic 4	44 ± 3	65.7 ± 0.7	68 ± 1

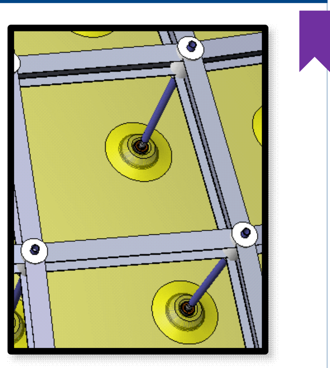
Gamma measurements (and dust removal)

^{210}Pb gamma peak activity:

Sample	Total activity [Bq]	Deep activity [Bq]
Smooth Acrylic	0.61 ± 0.03	0.40 ± 0.02
Opaque Acrylic 2	0.68 ± 0.04	0.49 ± 0.03
Opaque Acrylic 3	0.89 ± 0.05	0.56 ± 0.03
Opaque Acrylic 4	0.38 ± 0.02	0.25 ± 0.02

Connecting nodes and other SS components

- Stainless steel (SS) will be used for several purposes in JUNO: connecting nodes to the acrylic sphere, stainless steel truss to support the 20" and 3" PMTs,...
- **Total mass is ~500 tons --> must be radiopure enough**

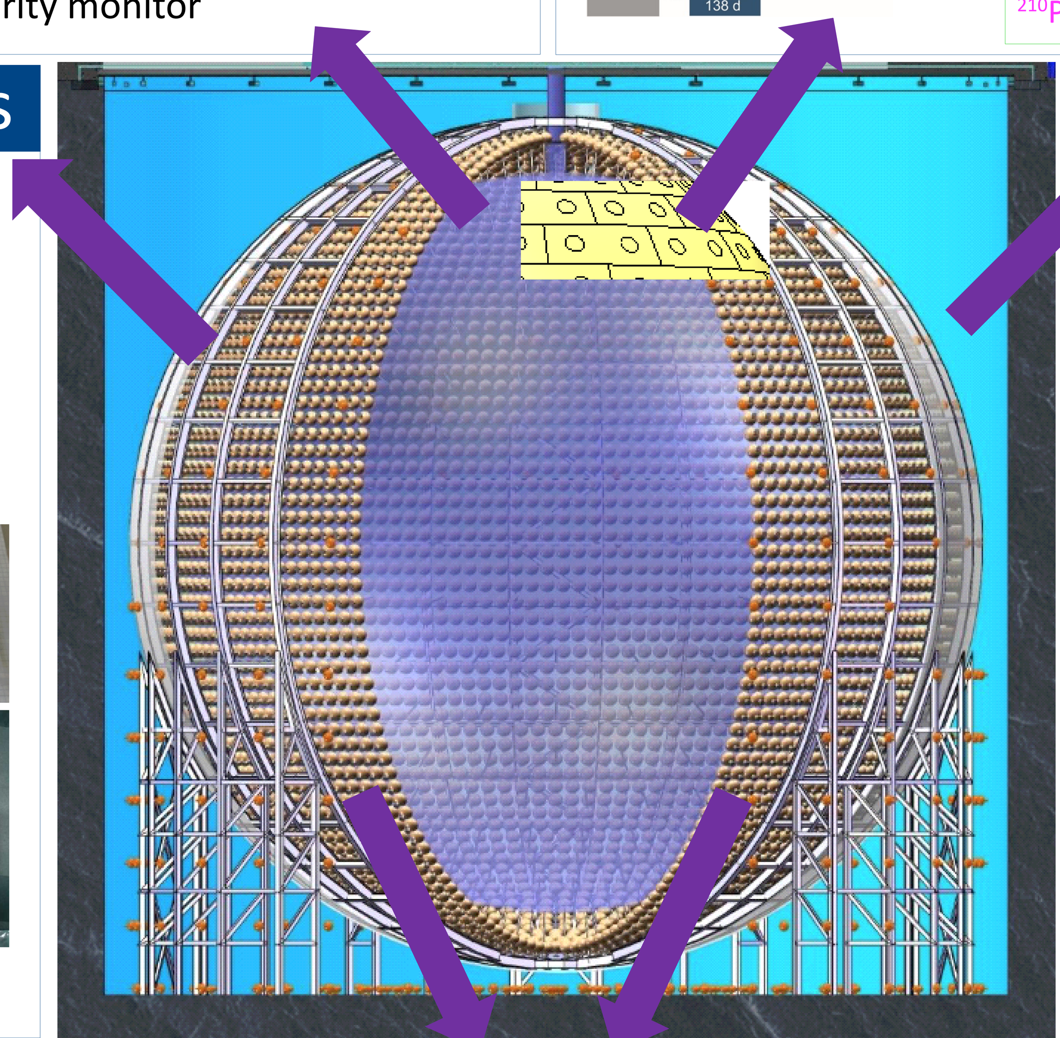


- Two techniques used to screen stainless steel samples:
  - → Low background spectrometry with HPGe detector (to have access to ^{226}Ra chain and ^{60}Co)
  - → Inductively Coupled Plasma Mass Spectrometry (ICP-MS) for U/Th

Sample SS 304L	^{40}K (ppb)	^{238}U (ppb)	^{232}Th (ppb)	^{60}Co (mBq/kg)
Sample 1 (HPGe)	<0.04	<0.07*	1.3±0.2	<0.3
Sample 2 (ICPMS)	-	<0.54	<0.12	-
Requirement	<0.2	<1	<5	<2

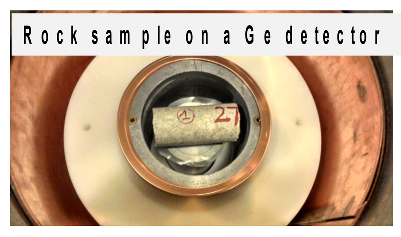
* derived from ^{226}Ra activity assumed in secular equilibrium with ^{238}U

→ some samples fulfilled the JUNO requirements for SS



Rock activity & Radon in Water

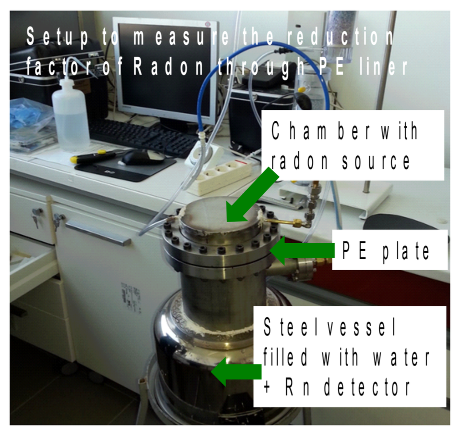
Several rock samples measured at different depths of the JUNO site by low-background gamma spectrometry.



	^{40}K	^{238}U	^{232}Th
Bq/kg	1340±50	110±10	105±10
ppm	4.9±0.2	8.9±0.8	25.9±2.5

→ high activity of the rocks led to a larger water thickness design for an efficient γ attenuation

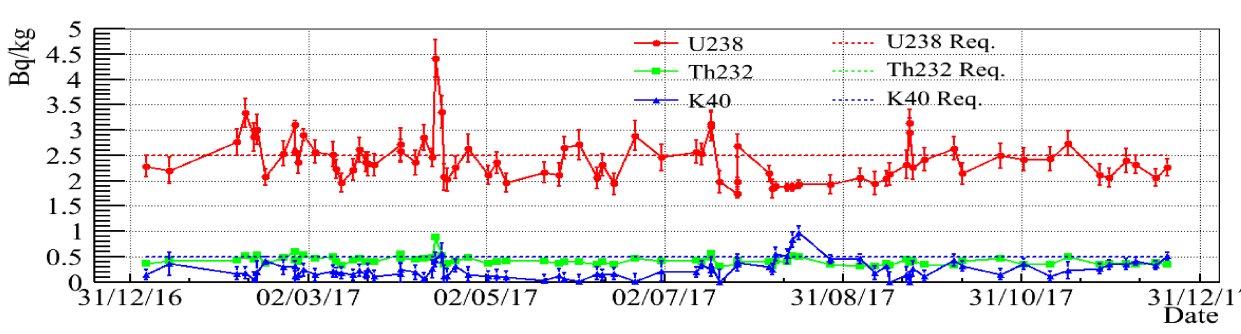
- **Risk of Radon diffusion from rock to the water pool.**
- **Requirement for ^{222}Rn activity in water: A < 0.2 Bq/m^3**
- Several strategies adopted:
  - 5mm PE liner around the walls of the water pool to prevent Rn diffusion in water
  - Circulation of water at ~100 t/h and removal of Radon thanks to a vacuum degaser device



20" & 3" Photomultiplier Tubes

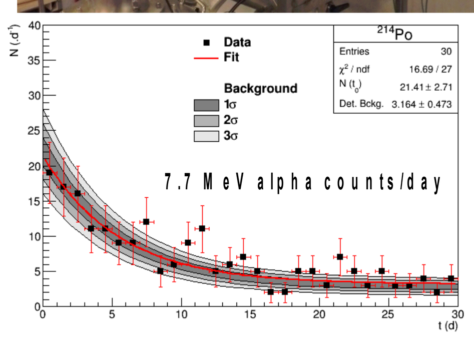
20" MCP-PMTs produced by NNVT

- PMT glass is usually the bottleneck of a low background experiment
- **Huge efforts achieved to improve the radiopurity of the glass bulbs**
- Glass samples measured every week by gamma spectrometry
- Samples exceeding the radiopurity requirements are rejected



- Transient section and stem glass measured every month
  - → **Glass production over 12 months under control !**

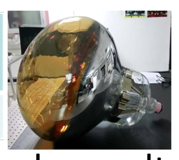
- 2 NNVT PMTs measured using a high sensitivity Radon emanation facility (~400 atoms/m2/s) and α spectrometry

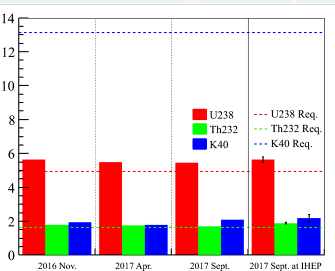


- → Data consistent with the background → A < 3mBq/PMT
- → **Contribution of the 15,000 NNVT PMTs to Rn activity in water is at least ~100 times lower than the 0.2 Bq/m^3 required level**

20" PMTs produced by Hamamatsu

Hamamatsu glass bulb	^{40}K (ppb)	^{238}U (ppb)	^{232}Th (ppb)
Requirement	<40	<400	<400





- → Glass sample results consistent between vendor and JUNO
- → Requirements are fulfilled (need to test a final glass bulb)

- → 1 PMT measured by Radon emanation
- → Radon contribution of the 5,000 Hamamatsu PMTs is also negligible

3" PMTs produced by HZC

- → 25,000 3" PMTs with a total mass of glass 60 times lower compared to LPMT → less risk

- Raw material selected for a new 3" glass bulb radiopure

	^{40}K (ppb)	^{238}U (ppb)	^{232}Th (ppb)
Glass with acid-washed sand	10.0±0.7	154±27	259±13
Requirement	<40	<400	<400

- → **Glass bulb requirements are fulfilled for the mass production**

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