RENO: Reactor Neutrino Experiment at Yonggwang

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What is RENO?

RENO = Reactor Experiment Neutrino Oscillation

![Diagram of Inverse Beta Decay and Survival Probability](image)

Survival Probability

$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2(2\theta_{13}) \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right)$

$\theta_{13}$ Dominant

$\theta_{12}$ Dominant

$E_\nu < 10$ MeV
Project Summary

• Feasibility study began in early 2004.
• Announced the intention for the project at FLENE05 workshop in Brazil in 2005.02.
• Submitted the proposal to MOST (Ministry of Science and Technology) in 2005.04 and it was approved with $10M (US).
• The budget was allocated in 2005.12
• The project began in 2006.03.
• Data-taking is expected to start in early 2010
• Technical Design Report will be ready in July 2007
• International collaborators are being invited
## Schedule

<table>
<thead>
<tr>
<th>Activities</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
<td>6</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>Detector Design &amp; Specification</td>
<td></td>
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<td></td>
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<tr>
<td>Geological Survey &amp; Tunnel Design</td>
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<tr>
<td>Detector Construction</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Excavation &amp; Underground Facility Construction</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Detector Commissioning</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
RENO Collaboration

12 Institutions/43 Collaborators

- Chonnam National University
- Dongshin University
- Gyeongsang National University
- Institute of Nuclear Physics RAS (Russia)
- Institute of Physical Chemistry and Electrochemistry RAS (Russia)
- Kyungpook National University
- Pohang Accelerator Laboratory
- Pusan National University
- Sejong University
- Seoul City University
- Seoul National University
- Sungkyunkwan University

4th Collaboration Meeting
Yonggwang Nuclear Power Plant

- Six ~1000 GWₑ class PWRs
- Total average thermal output of 16.4 GW (max 17.3 GW)
- Operational factor > 90
Reactor Operation History

Operation factor of Yonggwang nuclear reactors

\[
\text{operational factor} = \frac{\text{generated GWh in a year}}{365 \times 24 \times \text{GW of installed rated capacity}}
\]

![Graph showing operational factor of Yonggwang reactors from 2002 to 2006. Each reactor has a line indicating its operational factor, with a trend line indicating the average operational factor above 90%]

2007.06.10-13 DBD07 Int’l Workshop Osaka, Japan
Yonggwang Site

six reactors aligned in equal distance.
Yonggwang Site

~70 m

reactors

~200 m

~260 m

Near

Far
Detector Location

Two Plans for Far Detector

Plan B: 300m
Plan A: 600m

Experimental Hall

Access Tunnel
4 m x 4 m

Detector

Exp. hall@35 m AMSL

<table>
<thead>
<tr>
<th></th>
<th>Vertical Depth (m/mwe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near</td>
<td>35/93</td>
</tr>
<tr>
<td>Far A</td>
<td>225/596</td>
</tr>
<tr>
<td>Far B</td>
<td>165/437</td>
</tr>
</tbody>
</table>
Expected Inverse Beta Decay Event Rates

- Each reactor has power output of $2.73 \ text{GW}_{th} (=16.4/6)$
- $^{235}\text{U}; ^{238}\text{U}; ^{239}\text{Pu}; ^{241}\text{Pu}=0.556:0.071:0.326:0.047$

**near detector @ 150 m:**
8.12x$10^4$ IBD events/(10$^{29}$ protons·yr)

**far detector @ 1500 m:**
2.96x$10^3$ IBD events/(10$^{29}$ protons·yr)

15 ton targets with PC (20%) + Dodecane (80%)

**near detector:** 1.02x$10^6$ IBD events/yr

**far detector:** 3.73x$10^4$ IBD events/yr
Survival Probability

What effect on survival probability due to a wide spread reactor array?

Baseline (m)

0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000

$\nu_e \rightarrow \nu_e P(0.9, 0.91, 0.92, 0.93, 0.94, 0.95, 0.96, 0.97, 0.98, 0.99, 1)$

$\theta^2 = 0.0015 \text{ eV}^2$

$\Delta m^2 = 7 \times 10^{-5} \text{ eV}^2$, $\sin^2(2\theta_{13}) = 0.8$

$\sin^2(2\theta_{13}) = 0.1$

0.99

0.98

0.97

0.96

0.95

0.94

0.93

0.92

0.91

0.9

0.9

P($\nu_e \rightarrow \nu_e$)

Baseline (m)

500 1000 1500 2000 2500 3000 3500 4000 4500 5000

$\Delta m^2 = 0.0015 \text{ eV}^2$

$\Delta m^2 = 0.0018 \text{ eV}^2$

$\Delta m^2 = 0.0024 \text{ eV}^2$

$\Delta m^2 = 0.0029 \text{ eV}^2$

$\Delta m^2 = 0.0034 \text{ eV}^2$

$\sin^2(2\theta_{13}) = 0.8$

$\sin^2(2\theta_{13}) = 0.1$
Working Group Activities

Civil Construction & Underground Facility
(geological survey, excavation, on-site lab utilities, etc.)
→ Negotiation with local government, residents, power company
→ Construction of underground facility (tunnel design & excavation)

MC & Detector Design
(MC, performance study, detector drawing, detector optimization, etc.)
→ Full detector simulator & analysis
→ Detector design

Gd+Liquid Scintillator R&D
(purification, selection, production & purchase, etc.)
→ R&D of recipe and study of characteristics

Prototype Detector
(PMT test, background study, construction scheme R&D, etc.)
→ Test of detection method using a prototype detector and a mockup version detector
On-Site Facility

- 2006.03-08 Townhall meetings with local residents, NGOs, and local government
- 2006.07 endorsement by local government
- 2006.11 endorsement by KHNP
- 2007.02 Contract awarded for geological survey and tunnel design
- 2007.03 Land usage agreement between KHNP and RENO
- 2007.05 Geological survey completed
- 2007.06 Tunnel design in progress
- 2007.10 Issue contract for tunnel construction
Borehole Rock Samples
MC Simulation

- Detector simulation based on GLG4sim.
- Used to determine detector geometry and size
- Detector performance
- Background studies
RENO Detector at a Glance

- Concentric cylindrical design
- 15 ton target
- 537 8” PMTs on the buffer vessel wall
  - 87x2 top/bottom
  - 363 on cylinder wall
- Solid angle coverage @ centre = 12.6%
- Undetermined number of undetermined size PMTs in VETO

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Inner Diameter (cm)</th>
<th>Inner Height (cm)</th>
<th>Vessel Thickness (mm)</th>
<th>Filled with</th>
<th>Volume (m³)</th>
<th>Mass (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>280</td>
<td>320</td>
<td>12</td>
<td>Gd(0.1%) + LS</td>
<td>19.7</td>
<td>15.4</td>
</tr>
<tr>
<td>Gamma catcher</td>
<td>400</td>
<td>440</td>
<td>8</td>
<td>LS</td>
<td>35.2</td>
<td>27.5</td>
</tr>
<tr>
<td>Buffer</td>
<td>540</td>
<td>580</td>
<td>4</td>
<td>Mineral oil</td>
<td>76.9</td>
<td>59.2</td>
</tr>
<tr>
<td>Veto</td>
<td>740</td>
<td>780</td>
<td>15</td>
<td>water</td>
<td>201.8</td>
<td>201.8</td>
</tr>
</tbody>
</table>
Gamma Catcher Thickness

Gamma catcher thickness determined by the efficiency of Gd captured neutron identification

60cm: (93.0+/-0.6)%
Event Reconstruction

- **Energy Reconstruction**

- 1 MeV (KE) $e^+$
  - ~200 photoelectrons per MeV

- Reconstructed vertex: $\sigma \sim 8$ cm at the centre of the detector

- $4$ MeV (KE) $e^+$

- Positron energy spectrum
  - Energy (MeV)
  - Events per 0.2 MeV

- Energy Reconstruction
  - $E_{vis}$ (MeV)
  - $|y|$ (mm)
  - $\sigma_y$ (mm)
  - $\sigma_{\theta}$ (mm)
  - $\sigma_1$ (mm)
  - $\sigma_2$ (mm)
  - $\sigma_3$ (mm)

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**Gamma Background from PMT**

- Used almost all energy lines from $^{40}$K, $^{232}$Th, and $^{238}$U decay chains

<table>
<thead>
<tr>
<th>Energy [MeV]</th>
<th>Arbitrary Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0.5</td>
<td>$10^2$</td>
</tr>
<tr>
<td>1</td>
<td>$10^3$</td>
</tr>
<tr>
<td>1.5</td>
<td>$10^4$</td>
</tr>
<tr>
<td>2</td>
<td>$10^5$</td>
</tr>
<tr>
<td>2.5</td>
<td>$10^6$</td>
</tr>
<tr>
<td>3</td>
<td>$10^7$</td>
</tr>
<tr>
<td>3.5</td>
<td>$10^8$</td>
</tr>
<tr>
<td>4</td>
<td>$10^9$</td>
</tr>
</tbody>
</table>

- $^{238}$U Chain
- $^{232}$Th Chain
- $^{40}$K Chain

- $\gamma$s from $^{214}$Bi decay

<table>
<thead>
<tr>
<th></th>
<th>$^{40}$K</th>
<th>$^{232}$Th</th>
<th>$^{238}$U</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bq/PMT</td>
<td>1.63</td>
<td>0.41</td>
<td>0.70</td>
<td></td>
</tr>
<tr>
<td>Rate (E&gt;1MeV)</td>
<td>1.5Hz</td>
<td>4.2Hz</td>
<td>5.5Hz</td>
<td>11.2Hz</td>
</tr>
</tbody>
</table>

Hamamatsu 8”

70 cm buffer

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Muon Rates

- Modified Gaisser parameterisation for muon flux @ sea level
- MUSIC for muon propagation
- Used site topology.

- Other background studies are in progress
Liquid Scintillator R&D

<table>
<thead>
<tr>
<th>Aromatic</th>
<th>Oil</th>
<th>Fluor</th>
<th>WLS</th>
<th>Gd-compound</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC(Pseudocumene), PXE, LAB</td>
<td>Mineral oil, Dodecane, Tetrdecan, LAB</td>
<td>PPO, BPO</td>
<td>Bis-MSB, POPOP</td>
<td>0.1% Gd compounds with CBX or BDK</td>
</tr>
</tbody>
</table>

Requirements:
- Should satisfy physical, technical characteristics:
  - high transparency, good scintillation properties, ease of purification
- Safety consideration: high flash point, low toxicity.
- easy availability,
- Gd-LS must have long attenuation length, good light yield, and be stable for several years

- Gd+LS R&D with the Russian INR/IPCE group
- Performance study of various recipes:
  - light yield
  - transmission & attenuation lengths
- Development of purification system
  - $\text{Al}_2\text{O}_3$ adsorption
  - Filtration
  - Vacuum distillation
  - Water extraction, etc
- Long-term stability test
- Reaction with acrylic, stainless steel
Baseline for Gd-loaded Liquid Scint.

- Baseline Recipe:
  - PC(20%) + Dodecane(80%) + (PPO with bis-MSB or BPO)
  - 0.1% Gd compounds with CBX or BDK
- Extensive study on LAB this year

Carboxylic acids

\[ \text{Gd}_{2}O_{3} \oplus \text{RC} - \text{C} - \text{C} - \text{O} \]

\[ \text{GdCBX} \]

\[ \text{GdBDK} \]

β-diketonates

\[ \text{Gd}_{2}O_{3} \oplus \text{R}_{1} - \text{C} - \text{CH}_{2} - \text{C} - \text{R}_{2} \]

Extensive study on LAB this year
Gd loading created degradation in light yield

<table>
<thead>
<tr>
<th></th>
<th>Chooz</th>
<th>Palo Verde</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gd</td>
<td>Gd(NO₃)₃</td>
<td>Gd₂O₃</td>
</tr>
<tr>
<td>Loading Methods</td>
<td>Dissolved in hexanol + LS</td>
<td>Converted to carboxylate + LS</td>
</tr>
<tr>
<td>Light yield degradation</td>
<td>0.4 % / day</td>
<td>0.03 % / day</td>
</tr>
<tr>
<td>Remarks</td>
<td>Unstable → Turned Yellow</td>
<td>Stable → still usable</td>
</tr>
</tbody>
</table>

Gd loading is not trivial:
- collaborating with experienced Russian groups (INR/IPCE)
  → 6 months stable Gd-LS

Two problems reported
- Degradation
- Yellowish problem
R&D with Linear Alkylbenzene (LAB)

LAB : \((C_6H_5)\text{C}_N\text{H}_{2N+1}\) (N=10~13)

**Pro**
- High light yield
- Good transparency: better than PC
- High flash point: \(~140 \, ^\circ\text{C} > \text{PC} \, 48 \, ^\circ\text{C}\)
- Environment friendly: PC is toxic
- Domestically available: Isu Chemical Ltd.
- VERY CHEAP!!!

**Con**
- Composition variation
Composition of LAB

**Gas Chromatography/Mass Spectroscopy**

LAB : \((C_6H_5)C_NH_{2N+1}\) (N=10~13)

<table>
<thead>
<tr>
<th>C_{16}H_{26}</th>
<th>C_{17}H_{28}</th>
<th>C_{18}H_{30}</th>
<th>C_{19}H_{32}</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.2%</td>
<td>27.6%</td>
<td>35.0%</td>
<td>30.2%</td>
</tr>
</tbody>
</table>

# of H = 0.631 \times 10^{29}/m^3
H/C = 1.66
R&D with Linear Alkylbenzene (LAB)

Gd loaded LS Light yield measurements

Using $^{137}$Cs.

Purification by $\text{Al}_2\text{O}_3$ adsorption

<table>
<thead>
<tr>
<th></th>
<th>Attenuation Length (m)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Before</td>
</tr>
<tr>
<td>PXE</td>
<td>1.0</td>
</tr>
<tr>
<td>Dodecane</td>
<td>15.2</td>
</tr>
<tr>
<td>PC</td>
<td>5.9</td>
</tr>
<tr>
<td>MO</td>
<td>9.7</td>
</tr>
<tr>
<td>LAB (batch1)</td>
<td>9.5</td>
</tr>
<tr>
<td>LAB (batch2)</td>
<td>7.7</td>
</tr>
</tbody>
</table>

UV/Vis Spectrometer
PMT Test

- PMTs considered.
  - Hamamatsu: R5912 (8"), R7081 (10"")
  - Photonis: XP1806 (8"), XP1804 (10.6"")
  - ETL: 9354 (to be tested)

Tested single photoelectron resolution and radioactive background

\[ {^{238}}U \text{ Radioactivity} \]

HPGe measurements show that backgrounds are secular equilibrium.

\[
\begin{array}{c|c|c|c|c|c|c|c|c}
\text{Energy (keV)} & 400 & 600 & 800 & 1000 & 1200 & 1400 & 1600 & 1800 \\
\hline
\text{Bq/PMT} & 1 & 1.5 & 2 & 2.5 & 3 & & & \\
\end{array}
\]
## Comparison between PMTs

<table>
<thead>
<tr>
<th></th>
<th>R9512</th>
<th>R7081</th>
<th>XP1806</th>
<th>XP1804</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gain (X10^7)</strong></td>
<td>1.0 @1500V</td>
<td>1.0 @1500V</td>
<td>1.0 @1600V</td>
<td>1.0 @1600V</td>
</tr>
<tr>
<td><strong>QE @ peak</strong></td>
<td>22% @390</td>
<td>25% @390</td>
<td>24% @420</td>
<td>24% @420</td>
</tr>
<tr>
<td><strong>DC (nA)</strong></td>
<td>50</td>
<td>50</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td><strong>Size (inch)</strong></td>
<td>8</td>
<td>10</td>
<td>8</td>
<td>10.6</td>
</tr>
<tr>
<td><strong>Weight (g)</strong></td>
<td>720</td>
<td>1150</td>
<td>880</td>
<td>1744</td>
</tr>
<tr>
<td><strong>Rise Time (ns)</strong></td>
<td>3.8</td>
<td>4.3</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td><strong>TTS (ns)</strong></td>
<td>2.4</td>
<td>2.9</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td><strong>Afterpulse</strong></td>
<td>2%</td>
<td>2%</td>
<td>12%</td>
<td>12%</td>
</tr>
<tr>
<td><strong>Peak/Valley ratio</strong></td>
<td>~4</td>
<td>~3.5</td>
<td>~3.5</td>
<td>~3.5</td>
</tr>
<tr>
<td><strong>Radioactivity (Bq/PMT)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>2.1</td>
<td>8.3</td>
<td>3.12</td>
<td>6.1</td>
</tr>
<tr>
<td>Th</td>
<td>0.52</td>
<td>1.14</td>
<td>0.22</td>
<td>0.32</td>
</tr>
<tr>
<td>U</td>
<td>0.78</td>
<td>2.68</td>
<td>1.57</td>
<td>3.26</td>
</tr>
<tr>
<td><strong>Bg (E&gt;1MeV) (Hz) With G4 simulation</strong></td>
<td>12.4</td>
<td>37.5</td>
<td>16.2</td>
<td>32.1</td>
</tr>
</tbody>
</table>
“Prototype” Detector

- Small size working detector for
  - Checking the validity of MC and tuning it
  - Developing data analysis method
  - R&D of detector structure
  - PMT performance test and background studies
  - Optical properties of acrylic vessel

### Liquid Scintillator mixture

<table>
<thead>
<tr>
<th></th>
<th>Target</th>
<th>γ catcher</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>1.6 L</td>
<td>56 L</td>
</tr>
<tr>
<td>MO</td>
<td>2.4 L</td>
<td>84 L</td>
</tr>
<tr>
<td>PPO</td>
<td>3 g/L</td>
<td>3 g/L</td>
</tr>
<tr>
<td>Bis-MSB</td>
<td>0.05 g/L</td>
<td>0.05 g/L</td>
</tr>
<tr>
<td>Gd</td>
<td>1 g/L</td>
<td>0</td>
</tr>
</tbody>
</table>

\[
\gamma\text{catcher} \quad 140\ell \quad \text{GdLS} \quad 42
\]
Prototype Construction

Acrylic vessels

Inner acrylic vessel

Mounting PMTs

Nitrogen flushing of LS

Filling with liquid scintillator

assembled prototype
Calibration of Prototype Detector

Data flow chart

Any 2 out of 10 PMTs

Calibration of Prototype Detector

Data flow chart

Any 2 out of 10 PMTs

Radioactive sources

<table>
<thead>
<tr>
<th>isotope</th>
<th>activity (μCi)</th>
<th>$E_{\text{particle}}$ (MeV)</th>
<th>$E_{\gamma}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{60}$Co</td>
<td>9.79</td>
<td>1.173, 1.333</td>
<td></td>
</tr>
<tr>
<td>$^{60}$Cs</td>
<td>2.47</td>
<td>0.662</td>
<td></td>
</tr>
<tr>
<td>$^{22}$Na</td>
<td>1.00</td>
<td>$E_{\gamma}$, 0.545</td>
<td></td>
</tr>
<tr>
<td>$^{252}$Cf</td>
<td>0.1</td>
<td>$4 \times E_{\gamma}$, 2.14</td>
<td></td>
</tr>
</tbody>
</table>

Sum ADC(data)

Events/(12 channel)

$^{60}$Co

- Data
- MC

ADC channel

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DBD07 Int’l Workshop
Osaka, Japan
Working “Mock-up” Detector

- Smaller size fully functioning detector (sans veto).
- Exercise for building and running a sizable scale detector
  - fluid handling
  - electronics
  - data handling
- basis for very near detectors?
- will start construction shortly

- 45 8” PMTs
- target 17 l
- γ catcher 199 l
- buffer 621 l

Expected Gd captured neutron tagging efficiency
Eff. = 73.5 +/- 1.5%
90%CL sensitivity after 3 years of data taking

(rate only analysis)

$90\%$ CL (3 yr)
$\Delta m^2_{31} = 0.00007$ 
$\sin^2(2\theta_{13}) = 0.8$

$SK \Delta m^2_{31}$

$\text{CHOOZ}$

Syst. = 1.0%
Syst. = 0.5%

Best constraint
$\sigma_{\text{rel}} = 0.38\%$
$\epsilon_{\text{eff}} = 10^4$

Worst constraint
$\sigma_{\text{rel}} = 0.6\%$
$\sigma_{\text{pwf}} = 3.0\%$
$\sigma_{\text{abs}} = 3.0\%$

GLoBES group workshop@Heidelberg
- Mention's talk

2007.06.10-13

DBD07 Int'l Workshop
Osaka, Japan

34
Summary

- Project was approved for funding in 2005.
- Experiment site usage has been approved.
- Geological survey carried out and rock samples obtained.
- Technical Design Report is expected to be ready by July 2007.
- Detector Construction will begin in Oct. 2007.
- Data taking expected to start in early 2010.
- International Collaborators are being invited.
Backup Slides
Attenuation Lengths of different solvents before/after purification

<table>
<thead>
<tr>
<th>Solvent</th>
<th>Before (m)</th>
<th>After (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PXE</td>
<td>1.0</td>
<td>1.3</td>
</tr>
<tr>
<td>Dodecane</td>
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<td>LAB (batch2)</td>
<td>7.7</td>
<td>14.7</td>
</tr>
</tbody>
</table>

Absorption Measurement

Purification by $\text{Al}_2\text{O}_3$ adsorption
Optimization of PPO, bis-MSB Concentration for LAB

Solvent: LAB

- 1g PPO
- 2g PPO
- 3g PPO
- 4g PPO
- 5g PPO
- 6g PPO
- 7g PPO
- 10g PPO
- 20g PPO

Purified LAB(100) + varying PPO

- PPO 3g/l: LY maximum

LAB100+PPO3g/l+bis-MSB30mg/l
**Measurement of Gd Concentration**

1. For PH > 5, Gd reacts with EDTA

2. EDTA reacts with indicator, then violet color changes into yellow

3. \( V_{EDTA} \times C_{EDTA} = V_{sample} \times C_{sample} \)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Composition (ligand)</th>
<th>Date of preparation</th>
<th><a href="%25">Gd</a></th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>*3HR</td>
<td>2007.03.03</td>
<td>0.109</td>
<td>HR(0.92m)</td>
</tr>
<tr>
<td>2</td>
<td>*3TBP</td>
<td>2007.03.06</td>
<td>0.108</td>
<td>TBP(0.5m)</td>
</tr>
<tr>
<td>3</td>
<td>*2TOPO</td>
<td>2007.03.07</td>
<td>0.118</td>
<td>TOPO(99%)</td>
</tr>
<tr>
<td>4</td>
<td>*3TOPO</td>
<td>2007.03.07</td>
<td>0.110</td>
<td>TOPO(99%)</td>
</tr>
</tbody>
</table>
## Characteristics of Various Solvents

<table>
<thead>
<tr>
<th>Chemical elements</th>
<th>H:C</th>
<th>M.W. (g/mol)</th>
<th>Density (g/ml)</th>
<th>Boiling Point</th>
<th>Flash Point</th>
<th>Viscosity @20℃</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>decane C10H22</td>
<td></td>
<td>142.29</td>
<td>0.73</td>
<td>174</td>
<td>46</td>
<td>0.92cps</td>
<td>Domestically available</td>
</tr>
<tr>
<td>dodecane C12H26</td>
<td>2.17</td>
<td>170.34</td>
<td>0.7493</td>
<td>216.2</td>
<td>71</td>
<td>Expensive</td>
<td></td>
</tr>
<tr>
<td>tetradecane C14H30</td>
<td></td>
<td>198.3922</td>
<td>0.767</td>
<td>253</td>
<td>99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC(-TMB) C9H12</td>
<td>1.33</td>
<td>120.2</td>
<td>0.89(0.876)</td>
<td>169</td>
<td>48</td>
<td></td>
<td>Toxic Low FP</td>
</tr>
<tr>
<td>LAB C6H5 (CnH2n+1)</td>
<td></td>
<td>233-237</td>
<td>0.86</td>
<td>275-307</td>
<td>130</td>
<td>5-10cps</td>
<td>R&amp;D in progress Non-toxic Inexpensive</td>
</tr>
<tr>
<td>PXE C16H18</td>
<td>1.12</td>
<td>210.3</td>
<td>0.988</td>
<td>295</td>
<td>145</td>
<td>5.2cSt@40</td>
<td>Less toxic Supply limited</td>
</tr>
<tr>
<td>MO CnH2n+2, n=10-44</td>
<td></td>
<td>~0.8</td>
<td>~110</td>
<td>10-80cSt@40</td>
<td></td>
<td>Uncertainty in no. of protons</td>
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</tr>
<tr>
<td>PC20dod80</td>
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<td>2</td>
<td>0.78</td>
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<tr>
<td>PXE20dod80</td>
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<td>1.96</td>
<td>0.80</td>
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<td>&gt;80</td>
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<td>PC20MO80</td>
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<td>0.857</td>
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<tr>
<td>PC40MO60</td>
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<td>0.866</td>
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</tr>
</tbody>
</table>
Performance of Gd in PC & LAB

Absorption spectra

- LAB has lower optical absorption, better attenuation length
- 100% LAB and PC have similar light outputs
- We got similar results with BNL & Daya Bay experiment
- Nitrogen flushing effect is seen

Light output spectra

N₂ flushing effect

2007.06.10-13