The Daya Bay Antineutrino Detectors

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US Antineutrino Detector System Manager

BNL
CD-2/3a Review
January 8, 2008
Outline

1. Scope of Task

2. Requirements & Design Overview

3. Main AD Subsystems
   - Detector Tank (PRC)
   - Acrylic Vessels (US/Taiwan)
   - Lifting (PRC)
   - Liquid Scintillator (PRC, US, Russia)
   - PMT AD Mechanical Systems (US)
   - AD Instrumentation (PRC, US)
   - AD Filling and Target Mass (US)
   - Assembly&Installation (PRC, US)

4. US cost, schedule, summary
Antineutrino Detector Task - Overview & Scope

design & fabrication of all detector elements and instrumentation
Antineutrino Detector Task - Overview & Scope

design & fabrication of all detector elements and instrumentation

assembly
Antineutrino Detector Task - Overview & Scope

- design & fabrication of all detector elements and instrumentation
- assembly
- filling & target mass measurement
- scintillator preparation

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Antineutrino Detector Requirements

Physics Design Criteria
3-zone detector with the following general characteristics

<table>
<thead>
<tr>
<th>Item</th>
<th>Requirement</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target mass at far site</td>
<td>$\geq 80$ T</td>
<td>Achieve sensitivity goal in three years over allowed $\Delta m_{31}^2$ range</td>
</tr>
<tr>
<td>Precision on target mass</td>
<td>$\leq 0.3%$</td>
<td>Meet detector systematic uncertainty baseline per module</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>$\leq 15%/\sqrt{E}$</td>
<td>Assure accurate calibration to achieve required uncertainty in energy-threshold cuts (dominated by energy threshold cut)</td>
</tr>
<tr>
<td>Detector efficiency error</td>
<td>$&lt; 0.2%$</td>
<td>Should be small compared to target mass uncertainty</td>
</tr>
<tr>
<td>Positron energy threshold</td>
<td>$\leq 1$ MeV</td>
<td>Fully efficient for positrons of all energies</td>
</tr>
<tr>
<td>Radioactivity singles rate</td>
<td>$\leq 50$ Hz</td>
<td>Limit accidental background to less than other backgrounds and keep data rate manageable</td>
</tr>
</tbody>
</table>

key feature of experiment: > “identical detectors” at near and far sites

detectors will never be identical but we can control

relative target mass & composition to $< 0.30\%$
relative antineutrino detection efficiency to $< 0.25\%$ between pairs of detectors
## Antineutrino Detector Requirements

### Physics Design Criteria

<table>
<thead>
<tr>
<th>Item</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target mass at far site</td>
<td>&gt; <strong>vessel size</strong> to achieve sensitivity goal in three years over all tests.</td>
</tr>
<tr>
<td>Precision on target mass</td>
<td>&gt; <strong>filling and target mass system</strong> to ensure baseline per module.</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>&gt; <strong>reflector</strong> to assure accurate calibration to achieve required uncertainty in energy-threshold cuts.</td>
</tr>
<tr>
<td>Detector efficiency error</td>
<td>&gt; <strong>identical vessels</strong> to ensure consistency.</td>
</tr>
<tr>
<td>Positron energy threshold</td>
<td>&gt; <strong>minimum use of acrylic and other structures</strong> to minimize background.</td>
</tr>
<tr>
<td>Radioactivity singles rate</td>
<td>≤1 MeV</td>
</tr>
</tbody>
</table>

**key feature of experiment:** > “identical detectors” at near and far sites

**detectors will never be identical but we can control**

- relative target mass & composition to < 0.30%
- relative antineutrino detection efficiency to < 0.25% between pairs of detectors
Antineutrino Detector - Simulations

Detector Design and Geant4 Simulations

Dimensions of 3-Zone Detector

- for details see the TDR

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A Short Guide to the AD

- PMT cable feedthroughs and dry boxes
- calibration boxes
- gas and electrical distribution boxes
- overflow tanks
- calibration pipes
- auxiliary ports for monitoring and filling
- PMTs
- PMT ladders and mounts
- inner 3-m acrylic vessel
- acrylic support ribs
- outer 4-m acrylic vessel
- stainless steel vessel
Antineutrino Detector - Scope & Responsibilities

A Broad Overview (details in MOU list of deliverables)

Taiwan - blue
- 3m acrylic vessel with bonded lid

US - orange
- 4m acrylic vessel with removable lid
- acrylic overflow tanks for Gd-LS and LS
- calibration pipes + bellows
- overflow tank instrumentation
- PMT mounts and ladders
- PMTs, bases, and testing
- PMT cables and feedthroughs
- Gd-LS and LS

PRC - grey
- stainless steel vessel (SSV)
- SSV lid
- reflector
- mineral oil (MO) overflow tank
- overflow tank instrumentation
- Gd-LS, LS, and MO
Organization, Management, WBS

Antineutrino Detector Co-Managers

Jun Cao, IHEP - China
Karsten Heeger, UW - USA

L3 Management

1.1 Detector Tank *(Zhuang, IHEP)*
1.2 Acrylic Vessels *(Heeger, UW / Hsiung, NTU)*
1.3 Liquid Scintillator *(Yeh, BNL / Zhang, IHEP)*
1.4 PMT AD Mechanical Systems *(Virostek, LBNL / Cherwinka, UW)*
1.5 System for Measuring Physical Detector Properties *(Wise, UW)*
1.6 Lifting *(Zhuang, IHEP)*
1.7 Materials & Compatibility Testing *(Yeh, BNL / Chen, IHEP)*
1.8 Other AD Systems *(Wise, UW)*
1.9 AD Integration *(Heeger, UW / Cao, IHEP)*
1.10 AD Assembly & Installation *(Cherwinka, UW / Cao, IHEP)*
1.11 Subsystem Management *(Heeger, UW / Cao, IHEP)*

*L3s combination of scientists and engineers as appropriate for subsystems*
Acrylic Vessel System (WBS 1.1.2)

Pair of Nested Vessels
- calibration pipe connections
- lids

3m vessel
4m vessel

ribs and support structure

FEA analysis of worst case scenario:
uneven filling

independent FEA by
UW-PSL and Reynolds
Polymer Technology

→ stress still below long-term limit
AV Prototype - 4m Vessel at Reynolds (WBS 1.1.2)

Status
- Reynolds built 4m vessel prototype vessel
- design of 4m prototype essentially same as fabrication vessel
- UW team surveyed vessel, meets specifications.
- AV FDR in Dec 07.
- will finalize fabrication drawings in Jan 2008, almost ready for procurement -> long lead item
Other Acrylic Vessel Work (WBS 1.1.2)

3m Vessel Prototype at Nakano, Taiwan

Geant4 Simulations of AV
- optical impact of support structure
- vessel shifts and variations

example:
- impact of vessel support pads

example:
- impact of vessel shifts

Status of AV Simulations
- verified all design features in simulations
  > vessel thickness
  > ribs and support structure
  > variations between vessels and detectors

-> see TDR appendix for details
Gd Liquid Scintillator Production (WBS 1.1.3)

Requirements

<table>
<thead>
<tr>
<th>Item</th>
<th>Requirement &amp; Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>long-term chemical stability of Gd-LS</td>
<td>&gt; 3-5 years</td>
</tr>
<tr>
<td>high optical transparency for oil, LS and Gd-LS</td>
<td>&gt; 10 m</td>
</tr>
<tr>
<td>high-light yield</td>
<td></td>
</tr>
<tr>
<td>ultra-low impurity content</td>
<td>&lt; $10^{-12}$ g/g</td>
</tr>
</tbody>
</table>

3-Phase Process and Production plan

1. Procurement of chemical and purification equipment -> long lead item
2. Mass production of Gd-solid (~1 ton): organo-gadolinium solid will be synthesized at IHEP, transported to Daya Bay and dissolved in LS Hall underground
3. Dissolution and mixing of 0.1% Gd-LS (~200 tons): 200 tons of LS (LAB + fluors) will be prepared first, followed by 200 tons of Gd-LS (Gd-LAB + fluors) production

Progress Since CD-1

- In-lab R&D for Gd-LS synthesis finished in 04/2007.
- Aging test (40 C) has been running since 07/2007.
- Baseline plan of final Gd-LS production selected in 08/2007.

Stability Tests of Gd-LS

(UV absorption values at 430 nm)
Gd Liquid Scintillator Production (WBS 1.1.3)

Solid Production Process

Status
• PDR of Gd-LS synthesis and handling in Oct 07
• FDR of Gd-LS production in Mar 08

LS Mixing and Preparation Underground in LS Filling Hall (Hall 5)

A. NH₄TMHA reaction tank (180 L)
B. GdCl₃ dissolution tank (180 L)
C. Gd(TMHA)₃ reaction tank (400 L)
1,2 Reciprocal metering pump
3,4 On-line pH meter
5 Diaphragm Pump
6 Pressure meter
7 Centrifuge
PMT Mounts and Ladders (WBS 1.1.4)

**PMT Mounts**
- A pair of prototype mounts is currently being fabricated
- Cost estimate close to that of MiniBoone
- Material for interface pads between mounts and PMT’s still must be identified and tested for MO compatibility

**PMT Ladders**
- Ladder has been integrated with the SSV final design and other internal AD components
- Ladder is installed at a slight angle to clear SSV flange and to allow adequate clearance from outer AV after installation
- Ladder design allows for placement of an optical shield
PMT Cable Feedthroughs and Drybox (WBS 1.1.4)

Objective
- PMT cables carrying the signals from the PMTs must pass through the walls of tank
- convenient to have electrical break in the cable to allow for easier transportation and testing of the ladder as well as movement of the ADs.
- dry box houses this electrical junction.

Design Features
- design also facilitates testing and provides possibility for corrective action if a leak develops.
- allows good leak checking of all seals
- cables paths adjusted to same length
- electrical cables connected with flange held open

Status
- design essentially final
- prototype under construction
- PDR in Dec 07
- FDR in March 2008
Overflow Tanks & Calibration Tubes (WBS 1.1.5)

- GDLS overflow
- LS overflow
- Calibration boxes (see calibration talk)
- Gate valves
- Expected liquid level
- Concentric Teflon bellows
- Central calibration tube
- Off-center calibration tubes
AD Target Monitoring and Instrumentation (WBS 1.1.5)

LS visual level monitor (CCD)
LS level sensors, 2 types (pressure, ultrasound)
Gd-LS level sensors, 2 types (pressure, ultrasound)
MO level sensors, 2 types (pressure, ultrasound)
Gd-LS visual level monitor (CCD)

Karsten Heeger, Univ. Wisconsin
December 12, 2007

Ultrasonic Thickness Gauge
- started some R&D on measuring liquid heights with ultrasonic
> need to immerse transducer in liquid. cannot measure through air or acrylic.
> watertight transducers are available or can be obtained through potting electrical
> connections
> mm accuracy seems attainable. some systematic issues to be studied (reflections from wall etc.)
Assembly of Antineutrino Detector (WBS 1.1.10)

Surface Assembly Building

- assembly line for pairs of detectors (one near + one far)

- pits for vessel+tank assembly in SAB

- modular PMT structure, prefabricated, tested
AD Assembly Sequence in SAB (WBS 1.1.10)

- Bottom reflector
- 4m AV
- Work platform
- Lifting fixture
- 3m AV
- 4m AV lid
- PMT installation
- Top reflector
- SSV lid
AD Assembly Sequence in SAB (WBS 1.1.10)

Nov 10, 2008
bottom reflector

Dec 17, 2008
work platform

Jan 23, 2009
3m AV

4m AV lid

lifting fixture

Feb 27, 2009
top reflector

SSV lid

Apr 25, 2009 - AD fully assembled but not filled
dates for AD #1,2 assembly
Moving the Detector Underground

Note: transporter part of WBS 1.7

1. Installation and Deployment
   - moving down <10% grade when empty (20 t)
   - moving on 0.5% tunnel grade when full (100 t)
   - lifting full AD into water pool (100 t)

2. Detector Swapping (optional)
Filling the Detector & Measuring the Target Mass (WBS 1.1.5)

Three Detector Liquids:

I. Target: 0.1% Gd-loaded liquid scintillator (Gd-LS)
II. $\gamma$-catcher: liquid scintillator (LS)
III. Buffer shielding: mineral oil (MO)

Filling Requirements
- all detector volumes have to be filled simultaneously to minimize stress on AVs
- detectors are filled “in pairs” from common storage tanks, i.e. in sequence within a short period of time (~ 1-2 weeks)
- filling system must be compatible with Gd-LS, LS, and MO

Target Mass Measurement Requirements
- Gd-LS target mass measured to < 0.1%
- LS and MO mass measured to < 0.5%
- redundant measurement methods:
  > load cells,
  > Coriolis mass flow meters,
  > electromagnetic flow meters
AD Filling System & Target Mass Measurement (WBS 1.1.5)

load cell equipped Gd-LS ISO weighing tank with < 20 t capacity

Sartorius load cell accuracy < 0.015%

calibration boxes removed during AD filling
load cell equipped Gd-LS
ISO weighing tank
Sartorius load cell
accuracy < 0.015%
calibration boxes removed
during AD filling
flow meters
diaphragm pump
pulse damper
purge/waste container
load cell equipped Gd-LS
ISO weighing tank
Sartorius load cell
accuracy < 0.015%

Status
- load cells tested, accuracy verified
- ISO tank specifications drafted, ready for procurement, -> long lead item
- PDR of system in Oct 07
- FDR of system in March 08
Antineutrino Detector Design Status & Reviews

- Jul/Aug 2007
  - AD PDR
- Oct 2007
  - Steel Vessel FDR
  - LS Hall and Gd-LS Synthesis PDR
- Dec 2007
  - PMT FDR
  - AV and SSV Lid FDR
  - PMT AD Mechanical Systems PDR
- Mar/Apr 2008
  - Gd-LS production and LS Hall FDR
  - PMT AD Mechanical Systems FDR

PDR = prelim design review
FDR = final design review
> completed FDRs in green
Antineutrino Detector Design Status & Reviews

- Jul/Aug 2007
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\[> \text{completed FDRs in green} \]

- long-lead item: PMTs
- long-lead item: 4m AVs
- long-lead item: Gd-LS chemicals
- long-lead item: ISO tank
## AD Baseline Cost and Contingency

### Antineutrino Detector WBS & Cost (US scope)

<table>
<thead>
<tr>
<th>WBS</th>
<th>Task Description</th>
<th>Base</th>
<th>Cont.</th>
<th>Cont.</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Antineutrino Detector (TEC + OPC)</td>
<td>$8,285,277</td>
<td>31.3%</td>
<td>$2,596,562</td>
<td>$10,881,839</td>
</tr>
<tr>
<td>1.1.1</td>
<td>Detector Tank</td>
<td>$0</td>
<td>0%</td>
<td>$0</td>
<td>$0</td>
</tr>
<tr>
<td>1.1.2</td>
<td>Acrylic Vessels</td>
<td>$522,863</td>
<td>16%</td>
<td>$83,658</td>
<td>$606,521</td>
</tr>
<tr>
<td>1.1.3</td>
<td>Gd-LS Production</td>
<td>$1,106,241</td>
<td>32%</td>
<td>$349,423</td>
<td>$1,455,664</td>
</tr>
<tr>
<td>1.1.4</td>
<td>PMT AD Mechanical Systems</td>
<td>$1,535,322</td>
<td>31%</td>
<td>$479,764</td>
<td>$2,015,086</td>
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<tr>
<td>1.1.5</td>
<td>System for Measuring Physical Detector Properties</td>
<td>$386,342</td>
<td>16%</td>
<td>$61,815</td>
<td>$448,157</td>
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<tr>
<td>1.1.6</td>
<td>Lifting</td>
<td>$0</td>
<td>0%</td>
<td>$0</td>
<td>$0</td>
</tr>
<tr>
<td>1.1.7</td>
<td>Materials Compatibility and Low BacCground counting</td>
<td>$157,532</td>
<td>36%</td>
<td>$56,712</td>
<td>$214,244</td>
</tr>
<tr>
<td>1.1.8</td>
<td>Other AD Systems</td>
<td>$424,153</td>
<td>40%</td>
<td>$168,937</td>
<td>$593,090</td>
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<tr>
<td>1.1.9</td>
<td>AD Integration</td>
<td>$120,050</td>
<td>34%</td>
<td>$40,817</td>
<td>$160,867</td>
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<tr>
<td>1.1.10</td>
<td>AD Assembly&amp;Installation</td>
<td>$594,770</td>
<td>34%</td>
<td>$202,222</td>
<td>$857,992</td>
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<tr>
<td>1.1.11</td>
<td>Subsystem Management</td>
<td>$416,311</td>
<td>16%</td>
<td>$65,405</td>
<td>$481,716</td>
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<tr>
<td>1.1.12</td>
<td>Univ of Wisconsin Milestone Payments</td>
<td>$3,021,693</td>
<td>36%</td>
<td>$1,087,809</td>
<td>$4,109,502</td>
</tr>
</tbody>
</table>

- 4-m acrylic vessels + lids + overflow tanks
- Target mass measurement and filling system
Antineutrino Detector Selected Risks & Further R&D

Risk, R&D, and Development Items

- **Gd-LS Production** (*risk*)
  - time for large-scale, batch production
  - long-term degradation of Gd-LS

- **Materials Compatibility** (*risk, R&D*)
  - Gd-LS, LS, MO degradation due materials incompatibility
  - materials compatibility study and archive of all detector materials

- **Fabrication QA** (*R&D*)
  - finalizing consistent QA plan for all AD subsystems between countries and continents

- **AD Assembly & Installation** (*R&D*)
  - develop and build special tooling for AD assembly and installation. Conceptual designs exist.
Schedule and Milestones

- CD-2 review
- Start fabrication of acrylic vessels #1,2
- Complete chemical procurement for Gd-LS and LS
- PMT mounts and ladders at Daya Bay
- Acrylic vessels #1, 2 delivered to Daya Bay
- Mixing of LS and Gd-LS begins in LS Hall
- Target mass system installed in LS Hall
- LS Hall ready for AD filling
- Complete assembly of AD #1,2
- Complete filling of AD #1,2
- Daya Bay near site ready for data taking
- Complete assembly of AD #3,4
- Complete assembly of AD #5,6
- Complete assembly of AD #7,8
- Ling Ao near site ready for data taking
- Daya Bay far site ready for data taking

Jan 08 | Apr 08 | Jul 08 | Dec 08 | May 09 | May 09 | May 09 | Jul 09 | Nov 09 | Sep 09 | Dec 09 | Jun 10 | Jul 10 | Dec 10
Summary

- Antineutrino Detector System is in an advanced design stage, PDRs for all subsystems and FDRs for major detector elements.
- Critical and novel detector elements have been prototyped or prototypes are being evaluated (AVs, PMT feedthroughs, precisions load cells, etc.)
- Simulation for all principal detector elements completed.
- Cost estimates for major subsystems based on full-size prototype work (e.g. AVs)
- Antineutrino Detector system expected to meet or exceed (e.g. target mass) design requirements.
- Construction of subsystem elements can begin in Spring 2008 and will meet international project schedule.