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WATCHMAN Analysis

Using antineutrino detectors for nonproliferation

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DNN Review of WATCHMAN Project Status – May 27, 2014

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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Analysis of use cases for antineutrino detectors

This analysis seeks to understand the feasibility of using antineutrino detectors for nonproliferation monitoring.

- Collaborative effort
  - WATCHMAN project team and Sandia Systems Analysis group
  - High-level, objective analysis comparing technical capabilities of antineutrino detectors to needs of nonproliferation mission
- Analysis approach
  - "Can antineutrino detectors fulfill core requirements of different nonproliferation applications?"
  - Supported by feedback from nonproliferation experts (SNL / LLNL)
  - For completeness, evaluated all plausible use cases
    - New technologies generate options that may drive usage

Applications of large antineutrino detectors

"By 2016, demonstrate remote monitoring capabilities for reactor operations."

-NNSA Strategic Plan (May 2011)

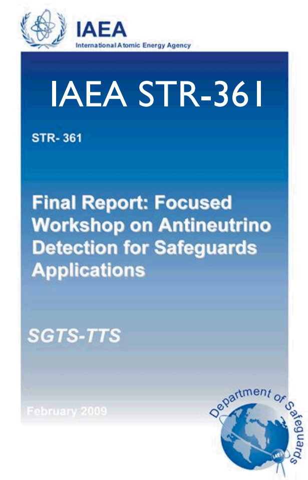
- Key features of antineutrino signal
  - Produced after fission events
  - Highly penetrating - detectable at long ranges
  - Effectively impossible to falsify, disguise, or shield
- Antineutrinos can be used to determine…
  - Existence of reactor
  - Operational status of reactor (i.e., on/off)
  - Power level of reactor
  - Burnup of reactor fuel
- Identified several reactor monitoring and discovery scenarios
  - Verifying reactor exclusion zone
  - Ensuring only declared reactors are operating
  - Characterizing reactor operations
  - Investigating potential reactor sites
- Examined other applications that would benefit from these properties
  - Monitoring for nuclear detonations
  - Monitoring spent-fuel repositories

Highlights from SME interviews

Spoke with 8 nonproliferation SMEs from SNL and LLNL

- Reactor characteristics available from antineutrinos are the right ones for nonproliferation
- Potential applications have value for nonproliferation community
  - No consensus on "best" application
  - Significant interest in better assurances regarding undeclared reactors
- Capabilities of antineutrinos are unique and very interesting
  - Selectivity to fission, high standoff, persistence, non-intrusiveness, tamper resistance
- Antineutrino detectors may create diplomatic options
  - Dual science/nonproliferation missions
  - Limited transparency (only reveal fission)
- Important operational features
  - Ease of operation; timeliness of information; ease of interpreting data
- Size/installation might be an issue
  - Unlikely that a country would allow installation of large, permanent detector
- Generally excited by antineutrino detectors, but questioned whether they are necessary
  - Other options are not as capable, but might be "good enough"

IAEA – Focused Workshop on Antineutrino Detection for Safeguards Applications


IAEA
International Atomic Energy Agency
IAEA STR-361
STR- 361
Final Report: Focused Workshop on Antineutrino Detection for Safeguards Applications
SGTS-TTS
February 2009
Department of Safeguards

- IAEA internal workshop identified following inspector needs:
  - "…improved capability to determine the power levels of a research reactor;"
  - "…improved capability to quantify & identify fuel/material in core of research reactor;"
  - "…improved capability to evaluate research reactor power cycle time;"
  - "…improved method to determine reactor status;"
  - "Power monitors not currently used in power reactors;"
  - "Research reactor activities can change between visits."
- "In all cases the AEG [Antineutrino Experts Group] deemed that all needs could be fully or partially fulfilled by an antineutrino detection system…"
- "It is recommended that the IAEA consider antineutrino detection and monitoring in its current R&D program for safeguarding bulk-process reactors."
- "…[antineutrino detection] differs significantly from, and is complementary to, the item accountancy, containment and surveillance measures …"
- "Several [antineutrino] detectors, built specifically for safeguards applications, have demonstrated robust, long-term measurements of these metrics in actual installations at operating power reactors…"

Reactor exclusion zone

Ensure that there are no reactors operating in an area

- Search for excess antineutrino signal above natural background
- Best suited to finding reactors built after detector installation
  - Can work for existing reactors, but higher count rate required
- Potentially subject to countermeasures
  - Declared reactor that masks signal from smaller, undeclared reactor
- Range is highly dependent on background count rates
  - Substantial uncertainty due to lack of experience with Gd-doped water Cherenkov detectors
  - Scaling laws for kT $\rightarrow$ MT also uncertain
  - Additional modeling can provide some insights, but ultimately experimental data is needed
  - WATCHMAN will provide important information on backgrounds

Ensuring only declared reactors

Ensure that only declared reactors are operating (no undeclared reactors)

- Search for excess antineutrino signal above background
  - Background includes both natural sources and declared reactors
  - Background from other reactors depends on operating conditions
  - Higher background decreases sensitivity
- Similar to previous case except it requires real-time estimates of background from other reactors
  - Could build small detectors near each declared reactor and/or model expected background based on safeguards declarations
- Potentially subject to countermeasures
  - Declared reactor near detector to mask other signals
  - Manipulating operations of declared reactors to hide undeclared reactor

Characterize reactor operations

Understand how reactors are being operated

- Determine operational status (on/off), power level, and/or burnup of fuel in one or more reactors
  - Antineutrino data is complementary to other safeguards
    - Remote, persistent, nonintrusive monitoring
    - Direct information about conditions in the core and bulk quantities of mat'l
  - Opportunity to independently assess reactor operations and/or verify declarations
- Higher antineutrino count rates needed
  - Some measurements use antineutrino energy spectrum (~10x events)
- May be difficult to monitor many reactors with one detector
  - Challenging to deconvolve signals
- Medium- or high-standoff detectors unlikely to be useful due to higher cost and potential for including multiple reactors within range

Monitor for nuclear detonations

Verify that there are no unauthorized nuclear detonations (e.g., nuclear tests)

- Search for bursts of antineutrinos
- Subject of prior study
  - Bernstein, West, and Gupta, 2001
  - 1 kT test within 10 km with 10 kT detector (>2 events)
  - 1 kT test within 100 km with 1 MT detector (>2 events)
- Largest feasible detector has relatively limited range
  - Could be useful for treaty verification of former test site

Rejected applications

- Monitoring spent-fuel repositories
  - *Use antineutrino detectors to detect changes in the amount or configuration of spent fuel in a repository*
  - Signal from spent fuel is ~ 1% that of operating reactor
  - Repository might have enough fuel to yield statistically significant signal overall, but detector would not be sensitive to changes in spent fuel
- Rapid follow-up to investigate potential reactor sites
  - *Use antineutrino detectors to investigate signs that a site might be hosting a clandestine nuclear reactor*
  - Lengthy timescale for installing WATCHMAN-type detectors makes them poorly suited for responsive deployment

Performance estimation – Scaling of existing detectors

- Backgrounds in a large Gd-doped water detector are not well known, but likely to be lower than liquid scintillator (LS).
- Borexino will be used to estimate WATCHMAN backgrounds [1]
  - Radionuclides = ~0.11/year/kton
  - Fast Neutron = ~0.18/year/kton
- Recent simulation studies suggest production on C and O target are similar [2,3]
- Radionuclides can be rejected more efficiently in larger volumes
- Muogenic backgrounds scale as power law with average muon energy (depth to the power 0.73) [4]
- Di-neutron background scales as detector surface area

1. Jocher, et al., 2013. (http://arxiv.org/pdf/1307.2832v2.pdf)
2. Li and Beacom, 2014. (http://arxiv.org/pdf/1402.4687.pdf)
3. Abe, et al., 2010. (http://arxiv.org/pdf/0907.0066.pdf)
4. Abe, et al., 2012. (http://arxiv.org/pdf/1210.3748.pdf)

Global reactor antineutrino background

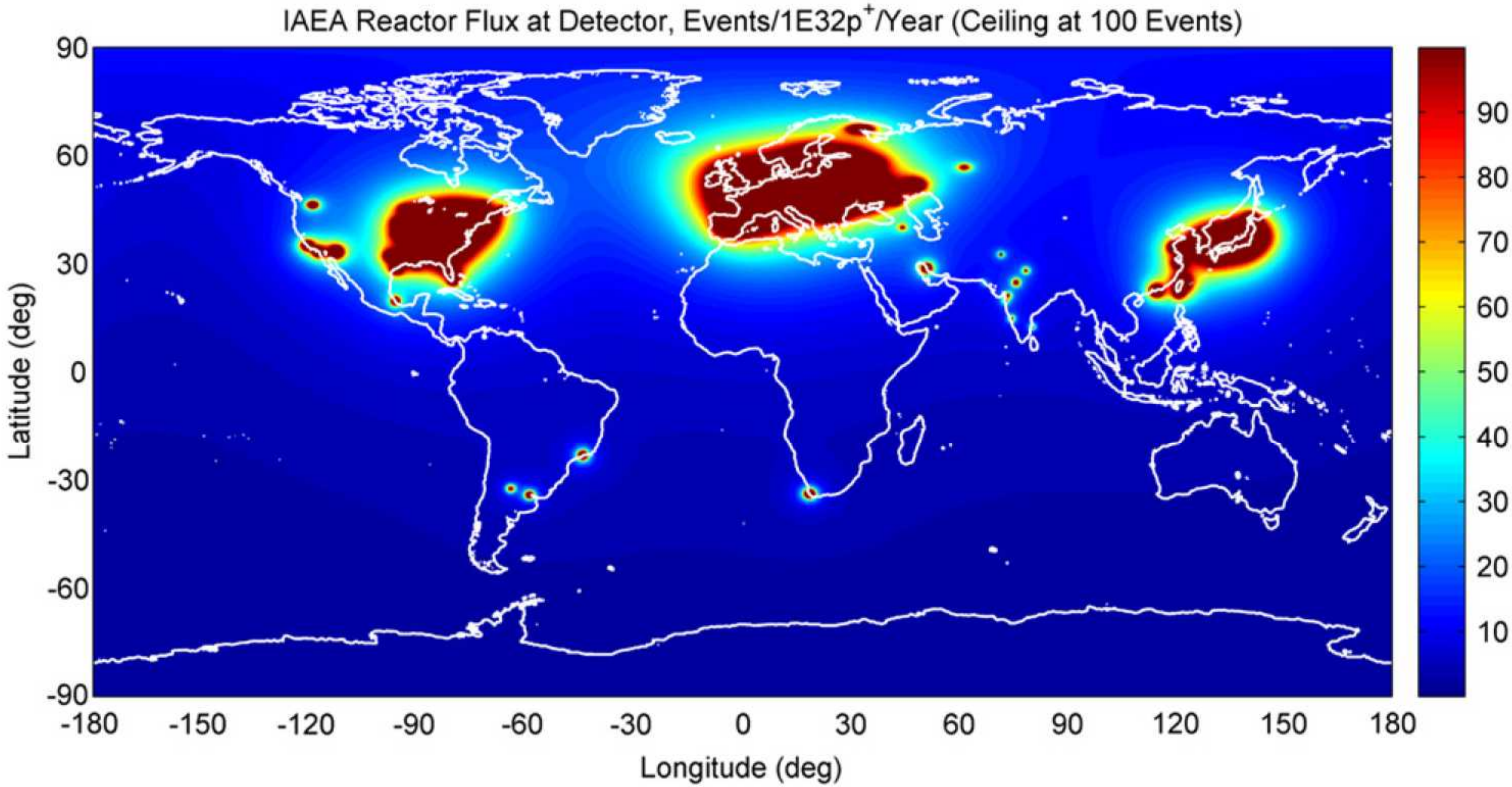


Fig. 11. IAEA known reactor background for a $10^{32}p^+$ detector, saturated at 100 events per year.

From Jocher, et al., 2013.

Sensitivity ranges for reactor discovery – Exclusion zone

Maximum detection range (km) for 20 MW_{th} reactor *3σ with lowest global reactor background (650 events/MT/year)*					
Detector size →	**1 kT**		**1 MT***		**Detection timescale**
Overburden (mwe) →	**400**	**1500**	**1500**	**5000**	
Exclusion zone (excess counts)	~20	~20	~200	~200	365 days (1 SQ of Pu)
Exclusion zone (on/off cycle)	~4	~4	~90	~90	14 days (refueling)

Maximum distance at which detector could discover an undeclared reactor at 3σ level against global background of reactor antineutrinos

- Minimum rate from all other reactors is ~650 events/MT/year (anywhere in the world)
- "Excess counts" – Reactor is discovered by measuring excess counts above background
  - Duration: Time required to produce 1 IAEA S.Q. of Pu (365 days)
- "On/Off Cycle" – Reactor is discovered by detecting the change from reactor on/off cycle
  - Duration: Time required for refueling (~14 days for research reactor)

* Radionuclide background assumed to be removable in MT detector

Sensitivity ranges for reactor discovery – Only declared reactors

Maximum detection range (km) for 20 MW_{th} reactor *3σ with ~10^5 events/MT/year background from declared reactors*					
Detector size →	**1 kT**		**1 MT***		**Detection timescale**
Overburden (mwe) →	**400**	**1500**	**1500**	**5000**	
Only declared (excess counts)	~10	~10	~60	~60	365 days (1 SQ of Pu)
Only declared (on/off cycle)	~4	~4	~30	~30	14 days (refueling)

Maximum distance at which detector could determine the presence of undeclared reactor at 3σ level in the presence of other reactors

- Declared reactor contribution is assumed to be 10^5 events/MT/year (relatively high) @ 50% efficiency
- "Excess counts" – Reactor is discovered by measuring excess counts above background
  - Duration: Time required to produce 1 IAEA S.Q. of Pu (365 days)
- "On/Off Cycle" – Reactor is discovered by detecting the change from reactor on/off cycle
  - Duration: Time required for refueling (~14 days for research reactor)

* Radionuclide background assumed to be removable in MT detector

Analysis focused on technical suitability

- Studied ability of antineutrinos to meet core requirements of each application
  - Determined critical detector characteristics for each use case
    - Type of signal to be detected
    - Ability to achieve desired standoff
    - Ability to provide high assurance (not susceptible to countermeasures)
    - Also identified other useful ("nice to have") features
  - Evaluated performance of antineutrino detectors against these characteristics
- Antineutrino detectors have many other features that might be relevant to individual deployments *(next slide)*
  - Importance depends heavily on particulars of situation
- When comparing to other technologies, additional factors would be relevant
  - Cost, technical risk, sustainability, ruggedness, …
  - This analysis serves as initial screen for technical feasibility
- High-level gap analysis (closed session)
  - Not a detailed comparison of options

Features of antineutrino detectors that may affect particular deployments

- ✓ Remote, semi-autonomous, continuous monitoring is possible
  - Less invasive for state being monitored
  - Reduced inspection burden for monitoring agency/state
- ✓ Signal is directly related to fission process (and only reveals fission)
  - Many other measurements are only indirectly related to fission
  - Limited (granular) transparency may be more acceptable to state being monitored and/or host nation
- ✓ Supports dual missions of nonproliferation and science *(next slide)*
- ✘ WATCHMAN technology requires large, underground detectors
  - Unilateral and/or mobile deployments are not feasible
  - May not be welcomed by host country
- ✘ Observations typically have low signal-to-noise ratio
  - Multiple streams of evidence may be needed to corroborate findings
  - Many valuable detection technologies face similar challenges

Potential for dual missions

Antineutrino detectors can support nonproliferation monitoring and fundamental science research.

Potential for dual missions may enhance nonproliferation usage by …

- Providing advantages to host country
  - Access to world-class research facility and possible influx of foreign investment
  - Incentive for a state to permit monitoring or for a third-party state to allow cross-border monitoring
- Allowing cost sharing with scientific organizations
  - Host nation may pay for detectors to enhance scientific capabilities
  - Foreign states may contribute to join collaboration
- Supporting multinational scientific collaboration
  - Interpersonal and organizational relationships might ease diplomatic tensions
  - Sharing data may enhance transparency

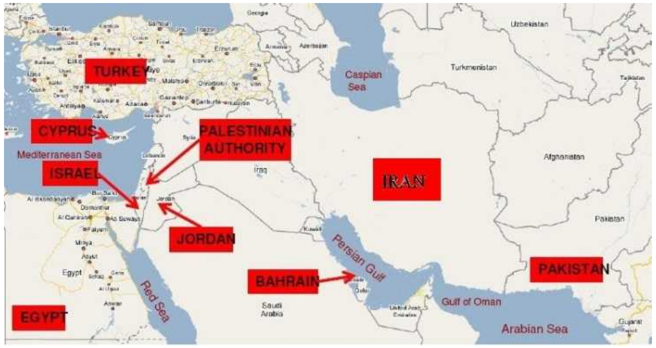
Example: SESAME project in Jordan (next slide)

SESAME Project

- International, multi-user synchrotron facility in Jordan, modeled after CERN
- Mission:
  - Foster scientific and technological excellence in the Middle East and neighboring countries by enabling world-class scientific research
  - Build scientific and cultural bridges between diverse societies
- Formed under auspices of UNESCO
  - German government donated decommissioned synchrotron
  - UNESCO and international community funded creation (Including US Dept. of State)
  - Ongoing costs borne by members
- Members (2013)
  - Bahrain, Cyprus, Egypt, Iran, Israel, Jordan, Pakistan, the Palestinian Authority, and Turkey

SESAME

Synchrotron-light for **E**xperimental **S**cience and **A**pplications in the **M**iddle **E**ast



Analysis overview

- Several deployment regimes
  - Non-cooperative - presumed to require cross-border installation at "far" range
  - Non-cooperative niche applications may exist at shorter ranges
- Not targeting any particular agency, treaty, etc.
- Primarily considered WATCH-MAN-type detectors, but many results are applicable to anti-neutrino detectors in general

Standoff distance	Range
Near	< 1 km
Medium	1 – 25 km
Far	25 – 250 km

Engagement with state being monitored	
Cooperative	Allows installation of detector, but may limit further access to detectors and/or data
Non-cooperative	Does not permit installation of detectors; presumed to require cross-border ("far") deployment

Reactor exclusion zone - Analysis

	Cooperative			Non-Cooperative		
Standoff distance →	Near	Med	Far	Near	Med	Far
				Range too short for cross-border non-coop use		

- Consider all employment options
  - Cooperative: Near, medium, and far
  - Non-cooperative: Far only

Reactor exclusion zone - Analysis

		Cooperative			Non-Cooperative
	Standoff distance →	Near	Med	Far	Far
Characteristic	Reveals existence of operating reactor within range				
	Can achieve desired standoff				
	Difficult to shield signal				
	High selectivity towards undeclared reactors				
	Reveals location of reactor(s) generating signal				

- Identify core characteristics associated with each use case

Reactor exclusion zone - Analysis

		Cooperative			Non-Cooperative
	Standoff distance →	**Near**	**Med**	**Far**	**Far**
Characteristic	Reveals existence of operating reactor within range	X	X	X	X
	Can achieve desired standoff	X	X	X	X
	Difficult to shield signal	X	X	X	X
	High selectivity towards undeclared reactors	/	/	/	/
	Reveals location of reactor(s) generating signal	-	O	/	/
Overall Rating					

- Evaluate importance of each characteristic for each option
  - *(Italicized if not required)*

X	Required for core mission
/	Offers substantial improvement in capability
O	Optional, but helpful - "nice to have"
-	Low importance

Reactor exclusion zone - Analysis

		Cooperative			Non-Cooperative
	Standoff distance →	Near	Med	Far	Far
Characteristic	Reveals existence of operating reactor within range	X	X	X	X
	Can achieve desired standoff	X	X	X*	X*
	Difficult to shield signal	X	X	X	X
	High selectivity towards undeclared reactors	/	/	/	/
	Reveals location of reactor(s) generating signal	-	O	/	/

- Evaluate performance of antineutrino detectors against each characteristic

Performance of antineutrino detectors		
Good	Moderate	Poor

* Assumes current background estimates are correct. Can achieve full range at some locations.

Reactor exclusion zone - Analysis

		Cooperative			Non-Cooperative
	Standoff distance →	**Near**	**Med**	**Far**	**Far**
Characteristic	Reveals existence of operating reactor within range	X	X	X	X
	Can achieve desired standoff	X	X	X*	X*
	Difficult to shield signal	X	X	X	X
	High selectivity towards undeclared reactors	/	/	/	/
	Reveals location of reactor(s) generating signal	-	O	/	/
Overall Rating				*	*

- Determine overall score based on performance against required characteristics

All required characteristics are "good"
Some req'd characteristics are "moderate"
Some req'd char "poor" - no clear use case

Reactor exclusion zone - Analysis

		Cooperative			Non-Cooperative
	Standoff distance →	Near	Med	Far	Far
Characteristic	Reveals existence of operating reactor within range	X	X	X	X
	Can achieve desired standoff	X	X	X*	X*
	Difficult to shield signal	X	X	X	X
	High selectivity towards undeclared reactors	/	/	/	/
	Reveals location of reactor(s) generating signal	-	O	/	/
Overall Rating				*	*

X	Required for core mission
/	Offers substantial improvement in capability
O	Optional, but helpful - "nice to have"
-	Low importance

* Assumes current background estimates are correct. Can achieve full range at some locations.

Performance of antineutrino detectors		
Good	Moderate	Poor

All required characteristics are "good"

Some req'd characteristics are "moderate"

Some req'd char "poor" - no clear use case

Ensuring only declared reactors - Analysis

Characteristic	Standoff distance →	Cooperative Near	Cooperative Med	Cooperative Far	Non-Cooperative Far
Characteristic	Reveals existence of operating reactor within range	X	X	X	X
	Offers selective sensitivity to undeclared reactors*	X***	X	X	X
	Can achieve desired standoff	X	X	X	X
	Difficult to shield signal	X	X	X	X
	Difficult to spoof signal**	X	X	X	X
	Difficult to mask signal**	X	X	X	X
	Reveals location of reactor(s) generating signal	-	O	/	/
Overall Rating					

* Assumes that calibration detectors or modelling is used to determine expected signal from declared reactors
** Assumes that increasing range raises likelihood of including other reactor signals
*** Higher performance corresponds to cases where location of undeclared reactor is known (e.g., a shutdown reactor)

Characterize reactor operations - Analysis

		Cooperative			Non-Cooperative
	Standoff distance →	Near	Med	Far	Far
Characteristic	Reveals operational status (on/off) of one or more known reactors	X	X	X	X
	Reveals power level of one or more known reactors	X	X	X	X
	Reveals burnup of fuel in one or more known reactors	X (LS)	X (LS)	X	X
	Can achieve desired standoff	X	X**	X**	X
	Difficult to shield signal	X	X	X	X
	Difficult to spoof signal*	X	X	X	X
	Difficult to mask signal*	X	X	X	X
	Can separate signals from different reactors	O	/	X	X
Overall Rating					

* Assumes that increasing range raises likelihood of including other reactor signals

** Although technically feasible, increased standoff would lower performance by raising background levels and complicating analysis. Scoring reflects the low likelihood of using these standoffs in cooperative case.

Monitor for nuclear detonations - Analysis

		Cooperative			Non-Cooperative
	Standoff distance →	**Near**	**Med**	**Far**	**Far**
Characteristic	Reveals nuclear detonation	X	X	X	X
	Can achieve desired standoff	X	X	X	X*
	Difficult to shield signal	X	X	X	X
	Difficult to mask signal	X	X	X	X
	Offers signal that is selective to nuclear detonation / fission	/	/	/	/
Overall Rating					

* Higher end of range is more important for non-cooperative case. Overall score for non-cooperative case is consequently lower.

Suitability of antineutrino detectors

Standoff distance →	Cooperative			Non-cooperative
	Near	Medium	Far	Far
Exclusion Zone			*	*
Only Declared Reactors				
Reactor Character-ization				
Nuclear detonations				

Poor suitability	Moderate suitability but with caveats	Good suitability

Suitability of Antineutrino Detectors

Standoff distance →	Cooperative			Non-cooperative
	Near	**Medium**	**Far**	**Far**
Exclusion Zone			*	*
Only Declared Reactors				
Reactor Characterization				
Nuclear detonations				

- Antineutrino signal offers unique opportunities for detection of undeclared reactors
- Long range supports non-cooperative (cross-border) installation
  - If global antineutrino flux is dominant background and detector is placed in location with lowest flux, MT has range ~200–300 km
  - Desired locations may have higher backgrounds (lower range)
- Non-cooperative installations may be subject to countermeasures

* = Backgrounds are poorly understood for very large, Gd-doped water detectors, creating uncertainty in maximum range. WATCHMAN (and possibly modeling) would provide insights.

Poor suitability	Moderate suitability but with caveats	Good suitability

Suitability of Antineutrino Detectors

Standoff distance →	Cooperative			Non-cooperative
	Near	Medium	Far	Far
Exclusion Zone	▸ Similar advantages to cooperative exclusion zone ▸ Antineutrinos from declared reactors limit sensitivity ▸ MT range ~55 km in presence of high reactor flux			
Only Declared Reactors				
Reactor Character-ization	▸ Need models and/or calibration detectors to separate signals from declared reactors (esp. for medium- and high-standoff) ▸ Potentially subject to countermeasures (esp. in non-coop case) ▸ Cooperative use may decrease likelihood of countermeasures			
Nuclear detonations				

Poor suitability	**Moderate suitability but with caveats**	**Good suitability**

Suitability of Antineutrino Detectors

<table>
<tr><th rowspan="2">Standoff distance →</th><th colspan="3">Cooperative</th><th>Non-cooperative</th></tr>
<tr><th>Near</th><th>Medium</th><th>Far</th><th>Far</th></tr>
<tr><td>Exclusion Zone</td><td colspan="4" rowspan="2">
- Small, close detector (e.g., outside containment dome or off-site) provides sufficient signal without intruding on reactor operations
- For cooperative case, larger detectors offer no advantage
  - Increased cost and complexity with no clear benefits
  - Increased likelihood of capturing signals from other reactors, which complicates signal analysis
</td></tr>
<tr><td>Only Declared Reactors</td></tr>
<tr><td>Reactor Character-ization</td><td>[green]</td><td>[yellow]</td><td>[red]</td><td>[yellow to red]</td></tr>
<tr><td>Nuclear detonations</td><td colspan="4">
- Maximum range has not been modeled in this study
  - Expect that some measurements will not be accessible at higher end of range, which may limit non-cooperative use
</td></tr>
</table>

Poor suitability	Moderate suitability but with caveats	Good suitability

Suitability of Antineutrino Detectors

Standoff distance →	Cooperative			Non-cooperative
	Near	**Medium**	**Far**	**Far**
Exclusion Zone	MT detector has range of ~100-km – For non-cooperative (cross-border) case, this range may not be sufficient to reach sites of interest			
Only Declared Reactors	Cooperative uses may exist – Treaty verification; international assurances			
Reactor Character-ization	Antineutrinos are selective to fission, indicating that a nuclear detonation took place			
Nuclear detonations				

Poor suitability	Moderate suitability but with caveats	Good suitability

Suitability of antineutrino detectors

Standoff distance →	Cooperative			Non-cooperative
	Near	Medium	Far	Far
Exclusion Zone			*	*
Only Declared Reactors				
Reactor Character-ization				
Nuclear detonations				

Poor suitability	Moderate suitability but with caveats	Good suitability

Summary

- When used for nonproliferation purposes, antineutrinos…
  - Offer a strongly penetrating signal that is highly tamper-resistant
  - Permit high-standoff, non-intrusive, persistent, remote monitoring
  - Are highly selective, representing a "smoking gun" of fission
- Nonproliferation SMEs seem intrigued by features and capabilities
  - Use cases and available data match community's needs
  - Some concern about whether host country would allow installation
- Detection of undeclared reactors is a promising application
  - Antineutrino detectors provide valuable capabilities and nonproliferation community interested in this capability
  - Up to ~200 – 300 km range for MT detector if no other reactors present
    - This range assumes optimal placement and low detector backgrounds (best case)
    - Uncertainty in expected backgrounds affects range estimates
    - Even maximum range may be insufficient for cross-border installation
  - Presence of other reactors significantly decreases sensitivity (~55 km for MT)
- Small detectors are a good match for cooperative monitoring of reactors
- Monitoring of nuclear test sites also promising for ranges < 100 km