Simulation-Assisted Design of the Security System for the Offshore Nuclear Plant

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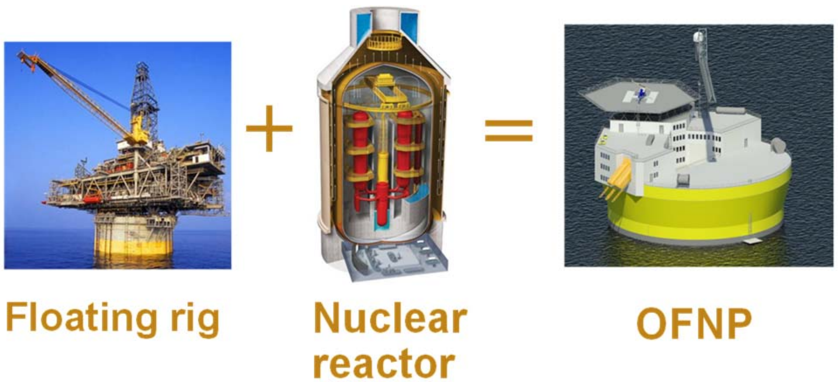
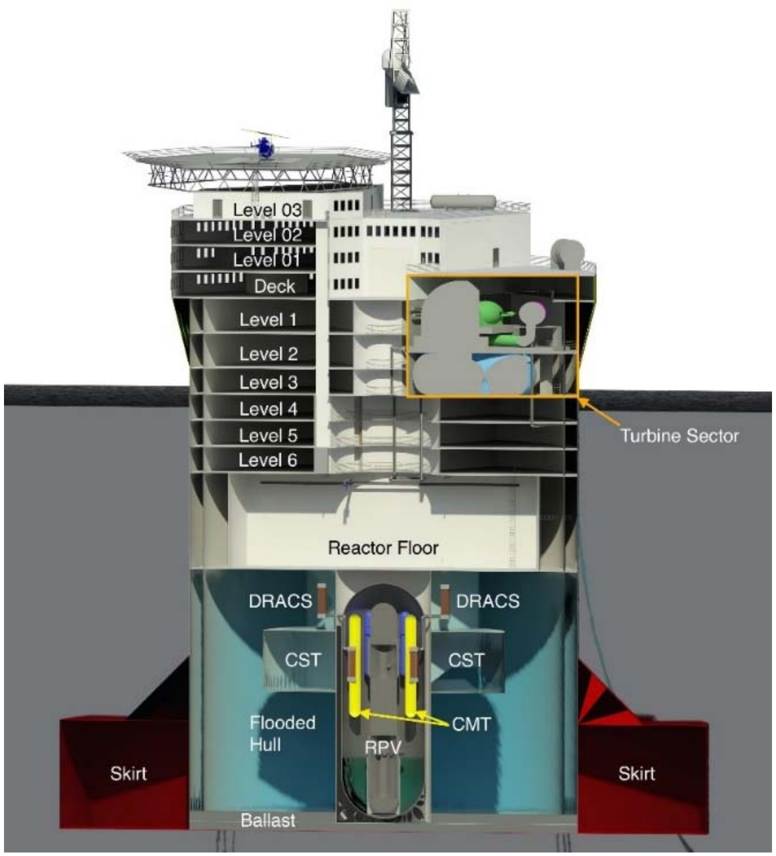
The Offshore Nuclear Power plant (ONP)





- Entirely built and decommissioned in a shipyard: faster and cost-effective plant construction (<36 months)
- Reduced capital cost (>90% cut in reinforced concrete)
- Transported to the site, moored 5-12 miles offshore, in relatively deep water (~100 m): insensitive to earthquakes and tsunamis
- Submarine AC cable connects to grid
- Reactor could be large LWR (1100 MWe), SMR (300 MWe) or other design
- Nuclear island underwater: ocean heat sink ensures indefinite passive decay heat removal (no Fukushima scenario)

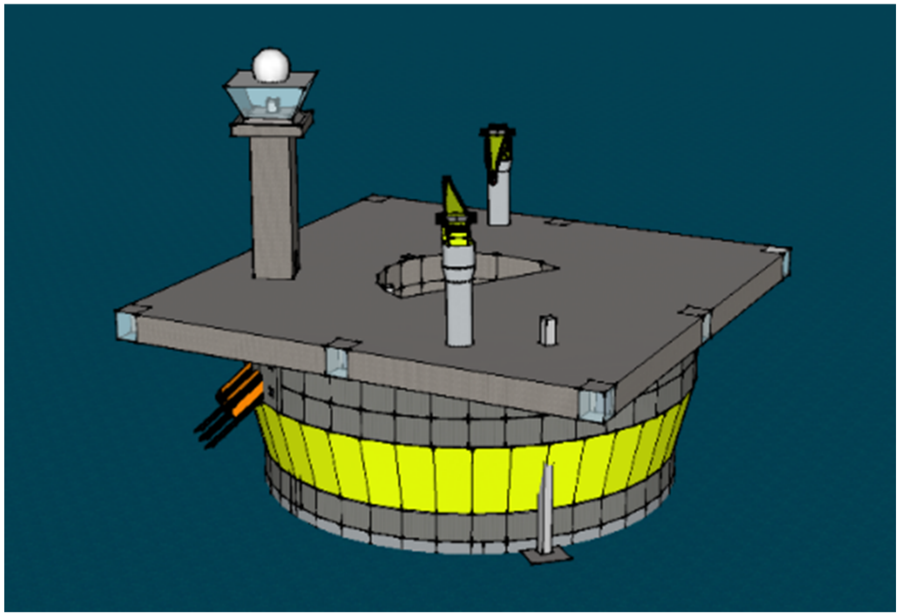
The Offshore Nuclear Plant (2)

Potential advantages:

- More affordable
- Easier to deploy
- More socially acceptable

Potential disadvantages:

- Isolated security
- Regulatory uncertainty



ONP-300

Violent Threats

Nature of the Threat	Response authority	
	Host Nation Military	ONP Security Team
Air	• Military aircraft • Commercial aircraft • Missile	• Drones • Light planes and helicopters
Surface	• Large tankers	• Non-military boats
Subsurface	• Large submarines	• Mini-subs (torpedoes) • Divers (explosives)




- Several Design Basis Threat (DBT) adversary groups were considered during simulations based on industry professional advice

Design Basis Threat

Problem: NRC Design Basis Threat (DBT) is classified

- How to accurately depict potential threats?

Solution:

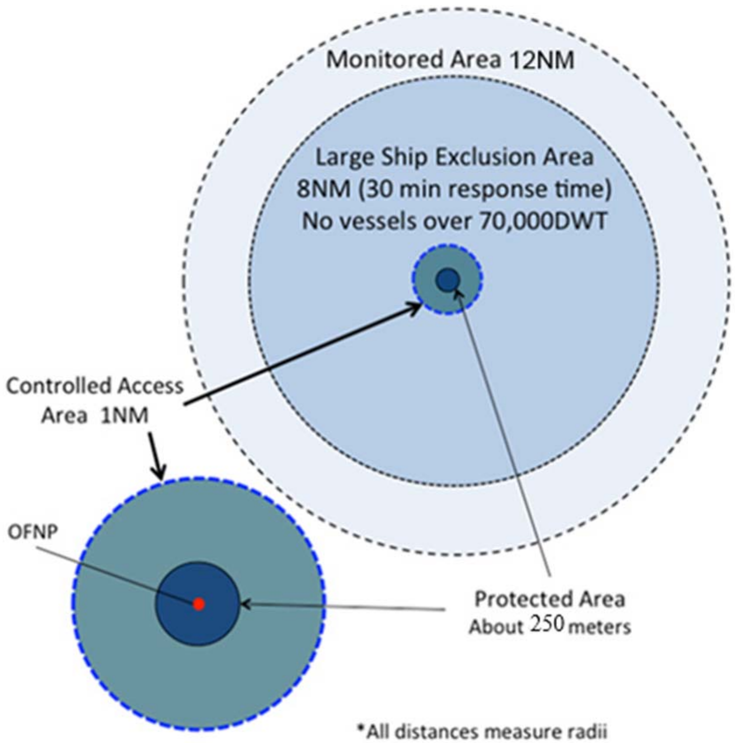
- Create four varying DBTs
- Full list of each DBT in backup slides

	Low Armament	High Armament
Low Skill	Pirates	Extremist Cult
High Skill	Experienced Terrorists	State-Sponsored Attack (Special Forces)*

*At the time of simulation, AVERT's underwater simulation abilities were very limited so there are no results for the State-Sponsored Attack

Security Plan

Multi-layered protection



Monitored Area:

- Electronic detection measures

Large Ship Exclusion Area

- 30 minutes to alter course of incoming ship

Controlled Access Area

- No unscreened access
- Sonar

Protected Area

- Physical barriers (booms, underwater netting)
- Blast radius (250 m)

Reactor platform and plant

- Restricted access

Security Officer Composition

Security Force		Security Positions	Officers Total
Platform Security Force	Platform Guards	**5**	26.5
	Platform Alarm Monitors	2	10.6
Shore Security Force	Shore Roving/ Monitors	4	21.2
	Shore Alarm Monitors	2	10.6
	Entry Control	3	15.9
	Response Team	2	10.6
Total		18	95.4

*Each Position: 5.3 personnel needed to maintain 24/7, 365 days a year

Platform Security Force

- 2 shifts on board at all times, working 12 hour shifts
- Monitor and maintain security

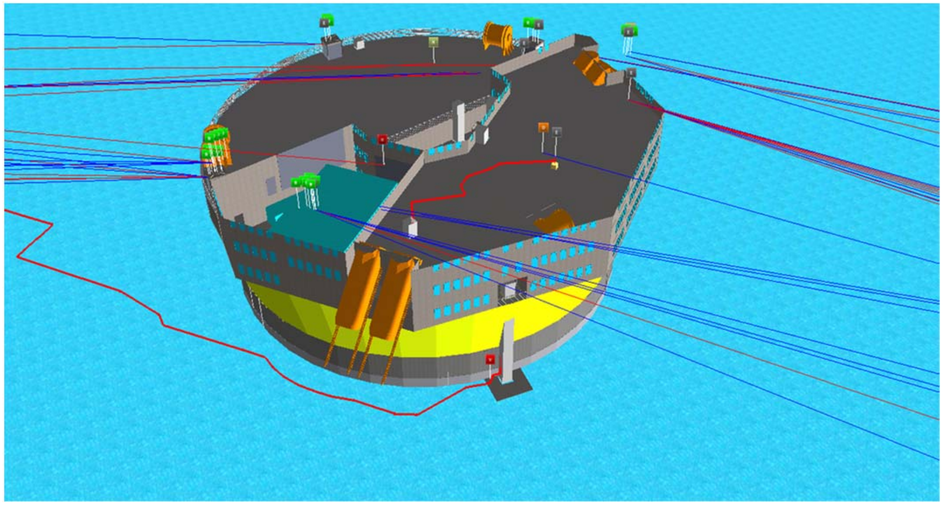
Shore Security Force

- Processes personnel
- Monitor shore alarm station

AVERT – Simulating Software

Overview:

- 3D-modeling, Monte-Carlo simulation software
- Lets the user input security cameras, guards, adversaries, and more.
- Over thousands of trials, determines probability of security system success
- In the backup slides:
  - Simulation settings
  - Modeling assumptions



Example AVERT Interface – ONP 1100 pictured with two incoming attack teams. Light blue lines indicate shot traces during this trial.

Design Basis Threat Results

- High security system success rate
- 1000 trials per simulation
  - 99.5% = 995/1000 times security stopped adversaries
- Adversaries “win” if they board the platform and stand at the center for 1 second – highly conservative

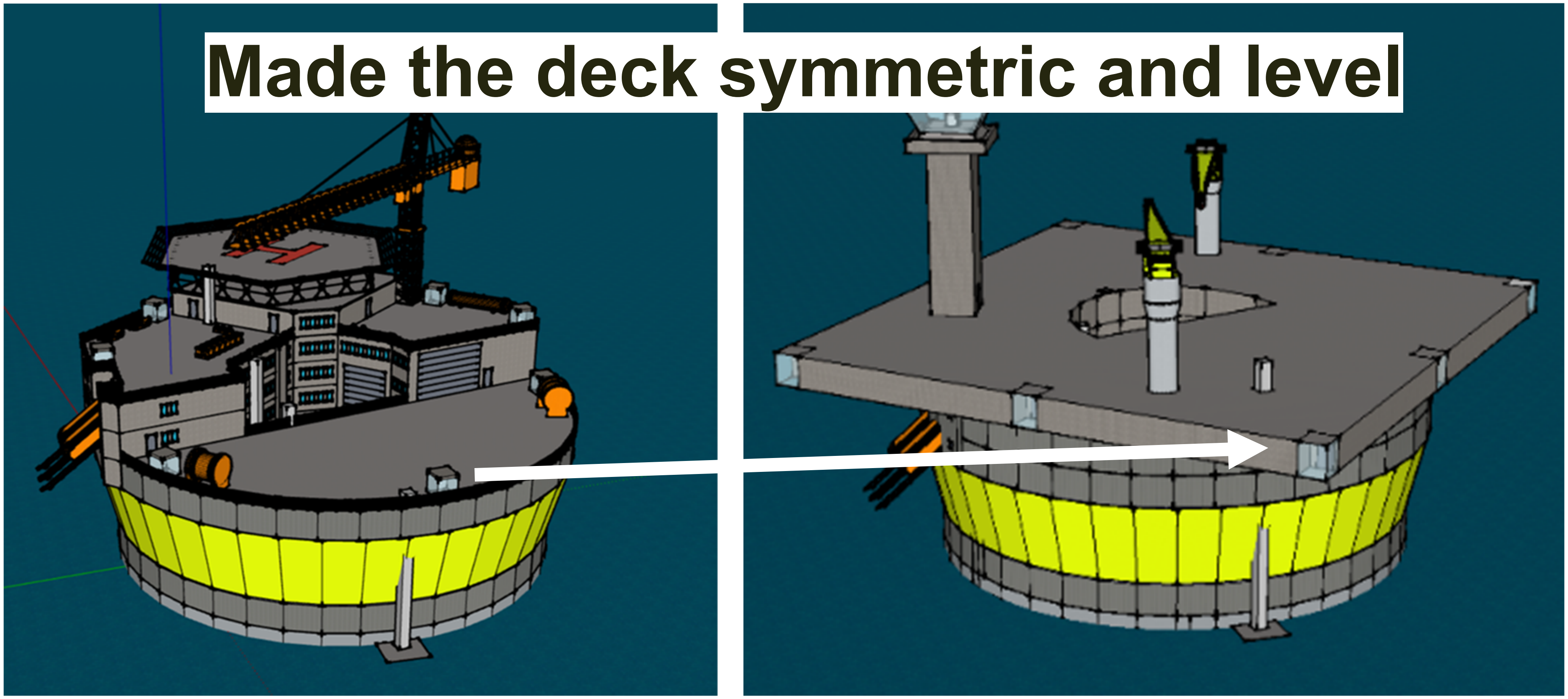
Success Rate	Day	Night	Stormy
Pirate	100.0%	100.0%	99.5%
Cult	100.0%	100.0%	100.0%
Terrorist	100.0%	100.0%	99.6%

Environmental Conditions (Day, Night, Stormy)

- Affects detection, accuracy, and more
- AVERT has default values for Day and Night
- Created Stormy environment
  - Same as night except lower chance of radar detection

Design Evolved Based on Simulation Results

Initial Design **Final Design**



Embedded Defensive Positions in the deck

Sensitivity Analysis – Decreasing Guard Force

Success Rate	DAY	NIGHT	STORMY
2 S 8 MG	100.0%	100.0%	99.0%
2 S 7 MG	99.9%	100.0%	99.0%
2 S 6 MG	99.9%	99.9%	100.0%
2 S 4 MG	100.0%	100.0%	99.4%
1 S 8 MG	100.0%	100.0%	99.0%
1 S 7 MG	99.9%	99.9%	98.5%
1 S 6 MG	99.5%	99.8%	98.9%
1 S 4 MG	99.4%	99.8%	98.2%
0 S 8 MG	100.0%	99.9%	99.4%
0 S 7 MG	99.7%	99.8%	96.3%
0 S 6 MG	98.9%	99.6%	98.1%
0 S 4 MG	99.3%	99.1%	97.9%

S: Snipers, MG: Machine Gunners

- All simulations except these were done with 10 guards on the platform
  - NRC requires 10 guards minimum at terrestrial plants
- Because of these results, the number of on-duty guards was lowered to 5
  - There will be 10 onboard, but five will be sleeping/training/resting
  - They are expected to respond quickly during alarm

*Results against Pirate DBT with 1000 trails per simulation

Sensitivity Analysis – Increasing Adversary Force

Question: Are there cliff-edge effects in adversary size?

- NO!

Question: Is security heavily dependent on radar/early detection?

- Yes, very

Increasing Adversary Force

# of Adversaries	Day	Night	Stormy
10 - DBT	100.0%	100.0%	99.4%
15	100.0%	100.0%	99.3%
20	99.9%	100.0%	98.2%
25	100.0%	100.0%	98.2%
30	100.0%	100.0%	97.6%
35	100.0%	100.0%	97.9%

Increasing Adversary Force without Radar

# of Adversaries	Day	Night	Stormy
10 - DBT	79.1%	55.2%	63.5%
15	56.1%	56.8%	43.4%
20	28.4%	18.3%	25.9%
25	32.7%	16.5%	8.5%
30	14.2%	7.5%	2.6%
35	9.0%	4.8%	3.4%

5 adv. per attack boat: 35 adv. = 7 boats attacking from 7 directions

Sensitivity Analysis – Semi-Automatic Weapons

Platform Security Force

- Initially given 50 caliber machine guns (**Control**)

- Test **effect of changing weaponry** to 5.56mm Assault Rifle
  - No major change in performance
    - Tested with 10 person guard force however
  - Still recommend high-caliber machine guns

	Cult Attack		Pirate Attack		Terrorist Attack	
	50 Cal. MG	Assault Rifles	50 Cal. MG	Assault Rifles	50 Cal. MG	Assault Rifles
Day	100.0%	100.0%	100.0%	100.0%	100.0%	99.9%
Night	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Stormy	100.0%	99.7%	99.5%	99.6%	99.6%	99.9%

Sensitivity Analysis – Insider Threats

Two types of insider threat

Lone Attacker

- One person sabotaging equipment
- Impossible to simulate in AVERT
- Solutions include:
  - Background checks
  - Hiring trustworthy individuals
  - Extensive access control
  - Defensive equipment such as bulletproof doors

Coordinated Strike

- Seaborn attack plus single insider
- Simulated a guard turning on others
  - **No significant drop in system performance**
- Solutions include:
  - Bulletproof defensive positions for guards prevent easy access to other guards

Conclusions

- The ONP 300 can be adequately defended with a five-officer guard force
- **Simulation and redesign early = reduced back fitting after building**
- A proven history of US naval ship security suggests effective security is possible

Recommendations

- **Redundant early detection and radar systems**
- Embedded bulletproof defensive positions in the deck

Future Work

- ONP-1100 simulations
- Simulations of underwater attacks
- Simulation of shore station security
- Investigation into drone deterrents
- Cyber security program


OFFSHORE FLOATING NUCLEAR PLANT
OFNP
AFFORDABLE - SAFE - FLEXIBLE NUCLEAR ENERGY

BACKUP SLIDES

Background

ONP-300

- 300 MWe reactor
- Based on Westinghouse SMR
- All simulations done with this reactor

ONP-1100

- 1100 MWe reactor
- Based on AP1000

DBT Matrix

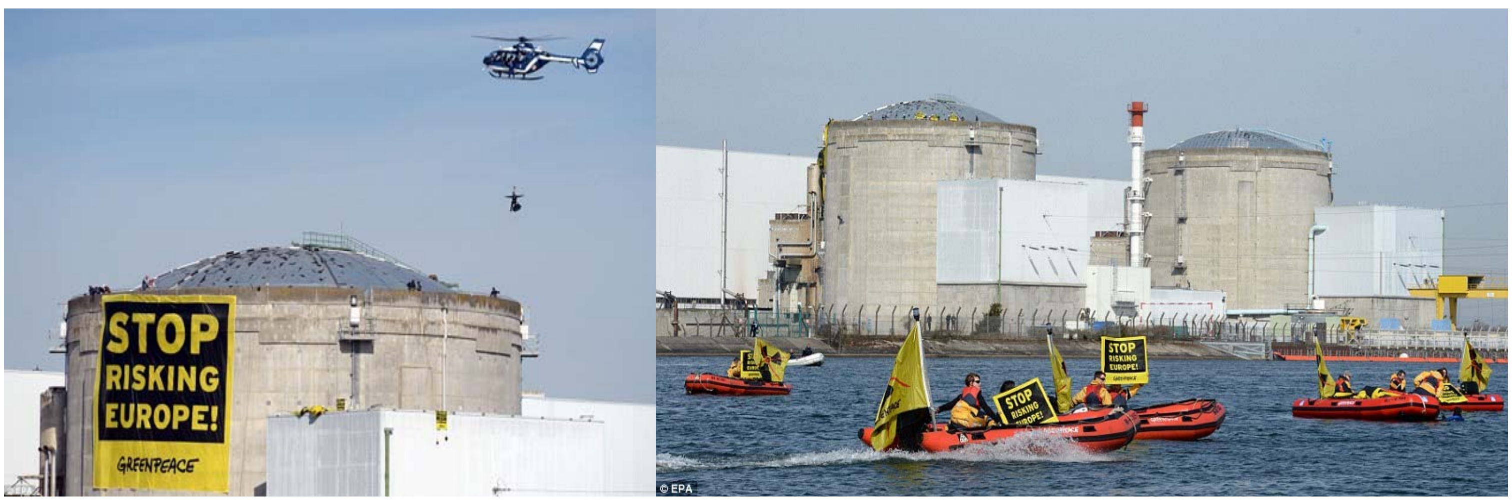
Return

Adversary Armament and Skill Level	Low Armament	High Armament
Low Skill Level	Pirate Attack (0.9x Skill) 2 Speedboats w/ 50 cal. Mounted MG (5 men each) • 4 Riflemen (7.62mm AR) • 1 Rocketeer (66mm RPG-7 with 5 rounds, 7.62mm AR)	Cult Attack (0.9x Skill) 2 Speedboats w/ 50 cal. Mounted MG (5 men each) • 3 Riflemen (7.62mm AR) • 1 Sniper (12.70mm SR) • 1 Machine Gunner (7.62mm MG)
High Skill Level	Terrorist Attack (1x Skill) 2 Speedboats w/ 50 cal. Mounted MG (5 men each) • 2 Riflemen (7.62mm AR) • 1 Rocketeer (66mm RPG-7 with 5 rounds, 7.62mm AR) • 1 Sniper (10.4mm SR and 7.62mm AR) • 1 Machine Gunner (7.62mm MG)	State-Sponsored Attack (1.3x Skill) 1 Speedboats w/ 50 cal. Mounted MG (5 men) • 3 Riflemen (5.56mm AR) • 1 Sniper (12.70mm SR, 66mm RPG-7 with 5 rounds) • 1 Machine Gunner (7.62mm MG) 1 Underwater Delivery Vehicle (5 Men, Closed Circuit Breathers) • 4 Riflemen (5.56 AR) • 1 Machine Gunner (7.62mm MG)

The skill level noted is how AVERT simulates varying skills. Someone with 2x skill is twice as likely to hit a target at the same distance as someone with 1x skill.

Nonviolent Threats

- Most likely attack scenario for the platform
- Plan:
  - Articulate ONP role in sustainable, green future
  - Proactive outreach and active monitoring of groups
  - Minimize media sensationalism during protests



Greenpeace breaking into a French nuclear plant

Simulation Settings

- All Tests: 1000 trials per simulation

- DBT Tests: 10 guards against all DBTs
- Increasing Adversary: 10 guards against pirate DBT
- Decreasing Guards: Varying guards against pirate DBT
- Semiauto Tests: 10 guards against all DBTs
- Coordinated Strike: 10 guards against pirate DBT and insider

Return

AVERT Modeling Assumptions

Red - hurts security system, orange – helps/hurts both guards and adversaries

- No waves – boat motion unaffected
- No CCTV or sonar – detection came from radar or eyes/ears
- Guards cannot move – To give guards 50 cal. weapons in AVERT, it made them unable to move, thus preventing engagement with adversaries on the platform
- No Interior guards – off duty guards not simulated
- No protective barrier – would delay adversaries significantly
- Ladders not recessed – normally, adversaries could not simply climb the ladder to the platform
- No shore response – would help the onboard security team

Return

Insider Threat Results- General Turncoat

	Cult		Pirate		Terrorist	
	Control	Insider	Control	Insider	Control	Insider
Day	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Night	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Stormy	100.0%	100.0%	99.5%	100.0%	99.6%	100.0%

- Control: that DBT Results for that condition/DBT
- General Turncoat: not a guard
- Results: no significant lack of performance
- Guard Turncoat: Still no lack of performance

Return

Other marine nuclear power plants

Akademik Lomonosov (Russia): two icebreaker reactors (52 MW_e each) mounted on a barge and docked on the coast

Length: 144 m; Beam: 30 m; Draft: 5.6 m; Displacement: 21,500 tons; crew: 69

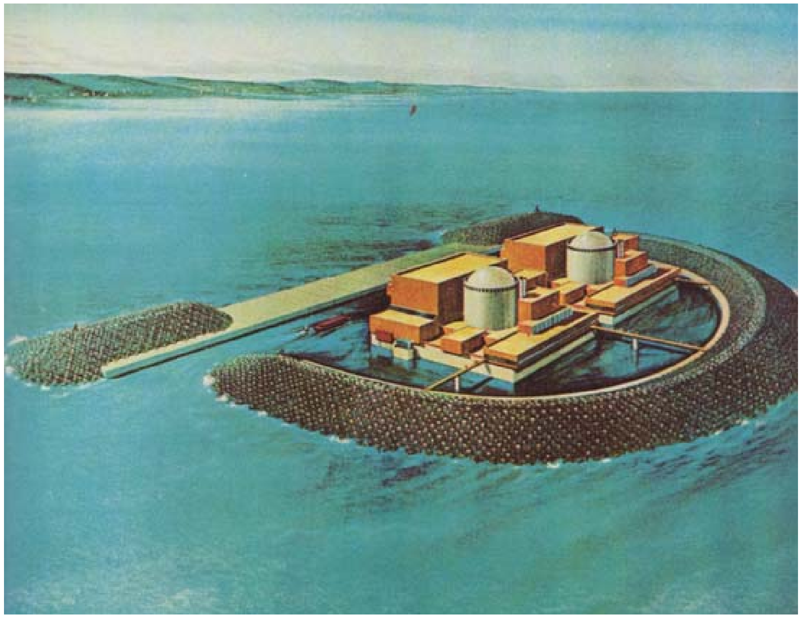
Other marine nuclear power plants (2)

Flexblue (France): small (160 MW_e) submarine-type reactor resting on the seabed, remotely operated

Moored down to 100 m depth;
Length: 140 m, Diameter: 14 m;
Displacement: 20,000 tons

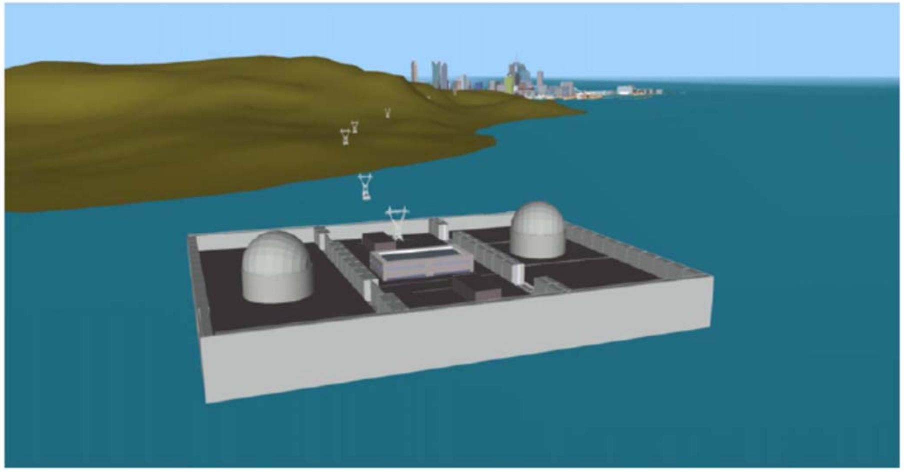
Other marine nuclear power plants (3)

Atlantic Generating Station (US, 1970s)



Large (>1000 MW_e) terrestrial PWRs built on a barge and moored in shallow waters with a huge (uneconomical) breakwater

Offshore Nuclear Power Plant (South Korea)

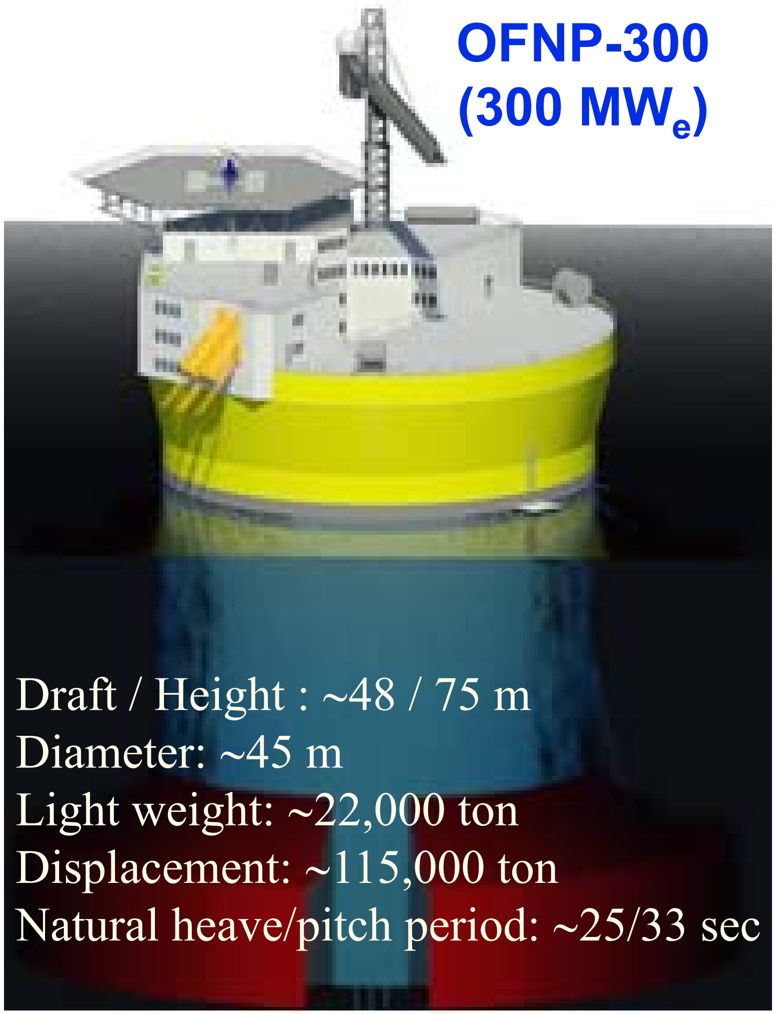


Large terrestrial plant with two APR1400 reactors housed in concrete/steel structure resting on seabed (gravity platform), suitable only for shallow waters

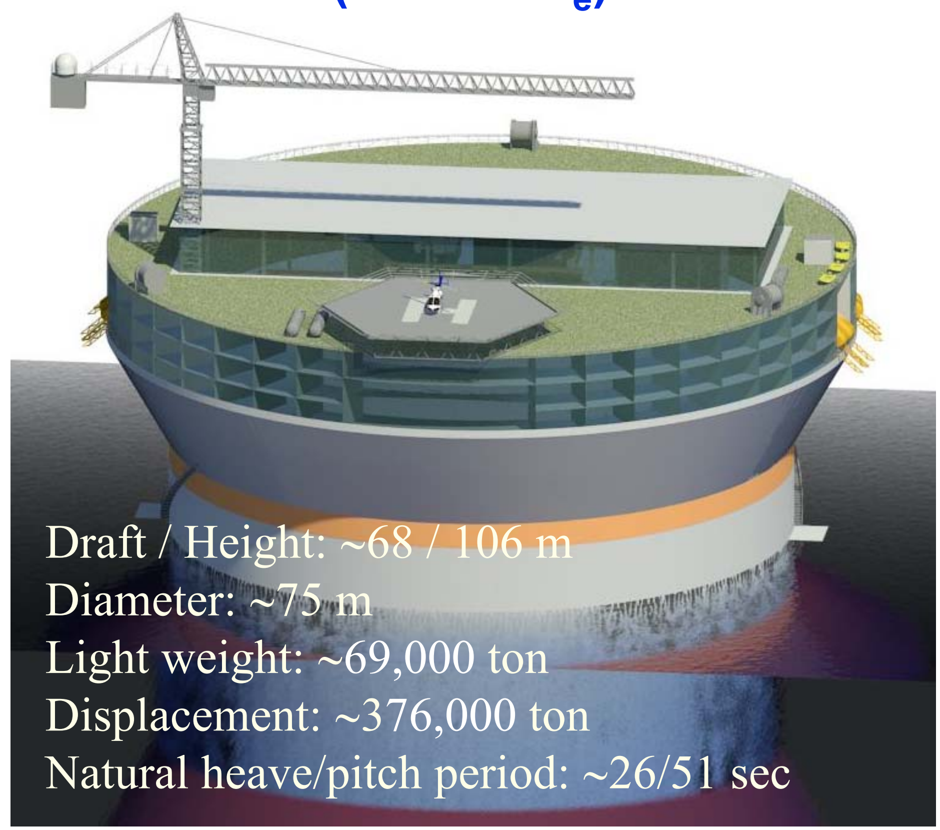
Design – Platform

Cylindrical, double-hull floating platform: simple, stable and cost-effective design

OFNP-300
(300 MW_e)



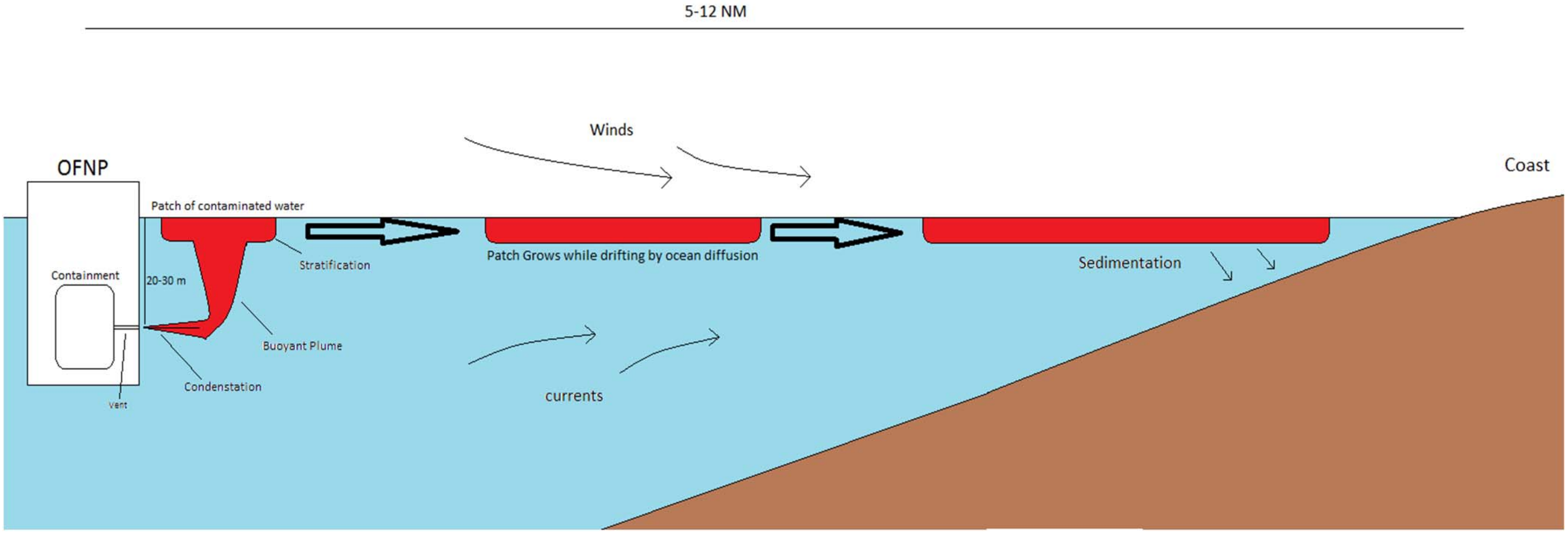
OFNP-1100
(1100 MW_e)



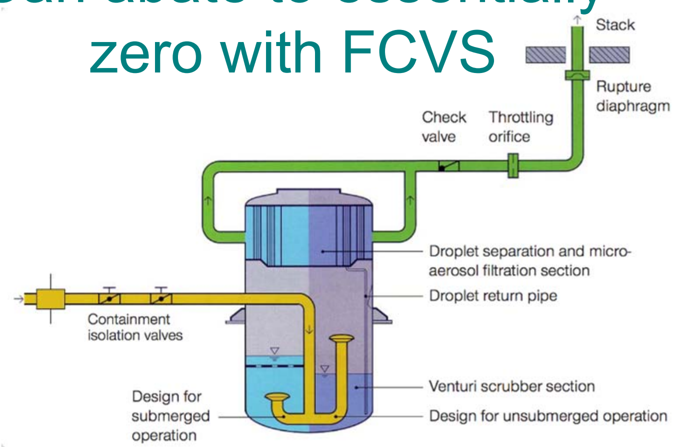
Natural period must be < tsunami wave period (plant rides tsunami) and > peak storm wave period (minimized oscillations in storms)

No Land Contamination following Hypothetical Containment Vent

Transport of radioactive Cs and I following an unfiltered release



Can abate to essentially zero with FCVS



Radionuclide (unfiltered event)	Dose rates to near-coast swimmers (NRC limit is 2 mrem/hr)
Cs-137	5E-07 mrem/hr
I-131	1E-02 mrem/hr
I-131 after 1 week	7E-3 mrem/hr
I-131 after 1 month	9E-4 mrem/hr

Publications

Journal Articles

1. J. Buongiorno, J. Jurewicz, M. Golay, N. Todreas, "The Offshore Floating Nuclear Plant (OFNP) Concept", *Nuclear Technology*, Vol. 194, pp. 1–14, April 2016.
2. J. Conway, N. Todreas, J. Halsema, C. Guryan, A. Birch, T. Isdanavich, J. Florek, J. Buongiorno, M. Golay, "Physical Security Analysis and Simulation of the Multi-layer Security System for the Offshore Nuclear Plant (ONP)", *Nuclear Engineering and Design* 352, 2019.

Peer-reviewed Conference Papers

1. Y. Zhang, J. Buongiorno, M. Golay, N. Todreas, "Effect of Platform Motion on the Safety Performance of an Offshore Floating Nuclear Power Plant", *17th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-17)*, Xi'an, China, September 3-8, 2017.
2. *G. Genzman, K. Shirvan, N. Todreas*, J. Buongiorno, M. Golay, "Ship Collision Security for an Offshore Nuclear Platform", *Proceedings of ICAPP 2017*, April 24-28, 2017, Fukui and Kyoto, Japan.
3. *J. Jurewicz, J. Buongiorno, M. Golay, N. Todreas, F. Major, O. Skjastad, "Construction and Transportation of the Offshore Floating Nuclear Plant (OFNP)", *3rd Conference on Technological Innovations in Nuclear Civil Engineering (TINCE-2016)*, Paris (France), September 5-9, 2016 (ABSTRACT)
4. *V. Kindfuller, N. Todreas, H. Stevens, R. Thomas, A. Birch, T. Isdanovich, J. Buongiorno, M. Golay, "Overview of an Offshore Floating Nuclear Plant Security Plan", Paper 61029, *Proc. 2016 24th Int. Conf. Nuc. Eng. (ICONE-24)*, June 26-30, 2016, Charlotte, USA.
5. *J. Jurewicz, J. Buongiorno, M. Golay, N. Todreas, F. Major, O. Skjastad, "Construction and Transportation of the Offshore Floating Nuclear Plant (OFNP)", *ICAPP 2016*, San Francisco, April 17-20, 2016.
6. J. Buongiorno, M. Golay, N. Todreas, J. Zhang, "Safety of the Offshore Floating Nuclear Plant (OFNP)", *ICAPP 2016*, San Francisco, April 17-20, 2016.
7. P. Minelli, J. Buongiorno, M. Golay, N. Todreas, "Balance of Plant and Power Transmission for the Offshore Floating Nuclear Plant", *The 16th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-16)*, Chicago, IL, USA, August 30-September 4, 2015
8. J. Zhang, J. Buongiorno, M. Golay, N. Todreas, "Ocean-based Passive Decay Heat Removal in the Offshore Floating Nuclear Plant (OFNP)", *The 16th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-16)*, Chicago, IL, USA, August 30-September 4, 2015
9. J. Buongiorno, J. Jurewicz, M. Golay, N. Todreas, "Light-Water Reactors on Offshore Floating Platforms: Scalable and Economic Nuclear Energy", Paper 15366, *Proceedings of ICAPP '15,* Nice, France, May 3-6, 2015.
10. G. Srinivasan, M. Golay, J. Buongiorno, N. Todreas, "Refueling and Fuel Transportation using a Barge for the Offshore Floating Nuclear Power Plant", Paper 15077, *Proceedings of ICAPP '15,* Nice, France, May 3-6, 2015.
11. *J. Jurewicz, J. Buongiorno, N. Todreas, M. Golay "Conceptual Design of an Offshore Floating Nuclear Power Plant with Spar-Type Platform", Paper 1104, *The 10th International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety (NUTHOS-10)*, Dec. 14-18, 2014, Okinawa, Japan.
12. J. Buongiorno, M. Golay, N. Todreas, A. Briccetti, J. Jurewicz, V. Kindfuller, D. Fadel, G. Srinivasan, R. Hannink, A. Crowle, M. Corradini, "Offshore Small Modular Reactor (OSMR): An Innovative Plant Design for Societally Acceptable and Economically Attractive Nuclear Energy in a Post-Fukushima, Post-9/11 World", SMR2014-3306, *Proc. ASME 2014 Small Modular Reactors Symposium (SMR2014)*, Washington, DC, April 15-17, 2014.
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Publications (2)

Paper Summaries

1. *J. Jurewicz, J. Buongiorno, M. Golay, N. Todreas, "Offshore Floating Nuclear Plant (OFNP) with Spar-Type Platform Design", *Proc. 2014 ANS Winter Meeting*, Anaheim CA, Nov. 9-13, 2014.
2. *A. Briccetti, J. Buongiorno, M. Golay, N. Todreas, "Where to Site an Offshore Floating Nuclear Power Plant", Technical Presentation, *Proc. 22nd Int. Conf. Nuclear Eng. (ICONE-22)*, Prague, July 7-11, 2014.

Reports/Theses

1. J. Conway et al, "Security and the Offshore Nuclear Plant (ONP) Simulation Testing of the Multi-Layer Security System", CANES Report ANP-TR-176 and S.B.Thesis, Massachusetts Institute of Technology, 2018.
2. *G. Genzman, N. Todreas, J. Buongiorno, M. Golay, "Ship Collision and the Offshore Floating Nuclear Plant (OFNP): Analysis of Possible Threats and Security Measures", CANES Report ANP-TR-168, Massachusetts Institute of Technology (2016).
3. J. Zhang, J. Buongiorno, M. Golay, N. Todreas, "RELAP5 Analysis of OFNP-300 and OFNP-1100 design basis events", CANES Report ANP-TR-164, Massachusetts Institute of Technology (2015)
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5. *J. Jurewicz, J. Buongiorno, M. Golay, N. Todreas, "Design and Construction of an Offshore Floating Nuclear Power Plant", CANES Report ANP-TR-160, Massachusetts Institute of Technology (2015)
6. *M. Strother, J. Buongiorno, M. Golay, N. Todreas, *Hydrodynamic Analysis of the Offshore Floating Nuclear Power Plant*, CANES Report ANP-TR-159, Massachusetts Institute of Technology (2015).
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