

Impact of emerging technologies on the future of SSBNs*

Report on the Conference on 13th September 2016
at the National Liberal Club, Whitehall, London

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and **Sebastian Brixey-Williams**, Project Leader, BASIC

The conference, hosted by British Pugwash, BASIC and Leicester University, brought together experts from the science, technology, academic, defence and security communities, civil society and industry to explore the nature and potency of evolving new technologies, how they may shape future warfare, particularly for the undersea battle space, what strategic challenges they will present and how might they be countered.

The conference built on the British Pugwash Workshop held in May 2016. The workshop included seventeen scientists, technical experts and academics from the US and UK who assessed current and emerging undersea technologies, their likely future direction of travel, and the implications of developments in sensing, computing and communications for the undersea battle space.

The workshop concluded that: 'It is clear that the trend is towards increasing transparency in the undersea environment. The goal of those developing marine robotics, sensing and communications techniques is to be able to map and to be able to sense the entire ocean in the next five to ten years. This ability will impact very significantly on the ability of submarines to maintain the advantage of stealth. However, we do not know how long it will be before this advantage is fully compromised, who will get there first and whether effective and deployable countermeasures can be developed.'

The conference looked at this in further detail and at the wider impact on the international security environment.

* SSBNs (Sub-Surface Ballistic Nuclear) are commonly known as ballistic missile submarines or 'boomers'.



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Summary

The conference marked the two-year milestone of collaboration between British Pugwash and BASIC on emerging undersea technologies, and defined multiple avenues for the project's future work. Beginning with a relatively narrow focus on the potential vulnerabilities of the UK *Successor* programme and Trident to adversaries' undersea technical capabilities, the project has expanded to consider how the rapid development and deployment of new technologies could affect strategic stability: for example by breeding suspicion and catalysing arms races, by undermining weapons reductions, and by providing a temptation for the attainment of strategic dominance for those states that feel it is in reach.

The term 'emerging undersea technologies' is used deliberately as a catch-all to describe a wide variety of developments. The technologies presented herein describe only a narrow segment of current developments, and should be viewed as significant examples of trends rather than definitive shifts in themselves. These trends include large increases in range and resolution, such as for sonar and magnetic anomaly detection; increasing autonomy within ever-more-integrated systems of systems; and the fielding of new types of detection system not previously used widely in ASW, the data from which can be fused and analysed in real-time using big data techniques. Crucially, while a submarine can only be built once, with only a handful of major modifications possible over its lifetime, ASW technologies are progressing in a plurality of ways and will likely go through dozens or even hundreds of development iterations in a new SSBN's lifetime.

On a national level, participants expressed widespread agreement that new technologies do not pose an immediate threat to the UK's SSBN fleet, and some were of the opinion that they would not be a 'make or break' threat to the *Successor* programme. However, many argued that SSBN 'invulnerability' should not be taken for granted, and that discourse should reflect this by speaking rather of 'potential vulnerability'. BASIC and British Pugwash plan to continue to monitor technologies in this arena, and to communicate the effects of technological developments simply and objectively to strategic thinkers.

Democratising understanding of the technical issues involved will improve public oversight and accountability of the UK's nuclear weapons project.

On a regional level, emerging undersea technologies will have heterogeneous impacts depending on the states by which they are deployed, the precise areas of deployments, and the reactions of other states. Present areas of interest include the South and East China Seas, the Indian Ocean, and the Arctic Ocean. Understanding these complex technologies and relationships will likely depend upon a mixture of state and civil society vigilance; strategic thinkers must remain mindful that any deployments at a regional level might eventually be developed for use in the open oceans.

At the international level, the conference demonstrated the need for strategic thinkers to incorporate into their calculations the potential impact of undersea systems of systems on strategic stability and strategic dominance. Any deployment of new technologies by major powers, whether by NATO or other nuclear-armed states, shifts the balance of power and causes knock on effects. Moreover, even the perception that such technologies are being deployed to undermine strategic potential can drive dangerous reactions in adversary states, whether or not those perceptions are well founded. Dr Williams' apposite assertion in her talk that states facing new technological challenges can choose to enter into an arms race, seek arms control negotiations, or find ways to adapt, is a useful general framework.

British Pugwash and BASIC hope that this discussion will encourage participants that travelled from abroad, particularly from nuclear-armed or hosting states, to initiate similar conversations at home to improve transparency and exchange on these issues, and that domestic participants will endeavour to explore some of the many new research avenues this project has revealed. It remains only to thank all participants for the high quality of the preparations and engagement on the day, and invite readers to contact our organisations if they are engaged or interested in related research in this area.

Introduction and contextual overview



Sebastian Brixey-Williams Project Leader, BASIC

This is taken from the paper presented to the conference entitled 'Will the Atlantic become transparent.' The paper is included in the appendices.

Mr Brixey-Williams gave a brief history of the 'transparent oceans' discourse, which emerged in the early 1970s at an International Pugwash Conference on emerging technologies, in which one scientist reported that new technology 'virtually removes all the technical barriers to ocean-wide ASW surveillance.'

The issue was taken up by the strategic community over the next twenty years, which typically concluded that it was unlikely that either the US or the Soviet Union would be able to destroy all of each others SSBNs simultaneously, and that therefore a second-strike capability remained. This was credited with creating the strategic stability which is assumed today.

This discourse has re-emerged, over the last couple of years, following developments in ocean sensing, increased sonar ranges and developments in unmanned undersea vehicles and unmanned surface vehicles.

Mr Brixey-Williams felt that the idea that the oceans could become 'transparent' is too simplistic, as transparency is always relative, and that using categories such as 'trailing', 'tracking', and 'open ocean search' are more appropriate to describe degrees of submarine detection. Submarines can move between these categories, for example, by giving away their position or through intelligent manoeuvring.

He pointed out, however, that it is not necessary to try to continuously sense and re-sense a submarine in the open sea; rather it is much more efficient to detect a submarine in ocean 'gateways' or 'choke points' and then to maintain contact with it. Analysis suggests that, within the next decade or so, it may be technically possible to trail submarines with a high level of reliability, a likelihood which is likely to increase with time. However, as Mr Brixey-Williams said, there is a great difference between capability and intention, and whether such systems are fielded at sufficient levels to significantly affect confidence in stealth will depend on whether there is the political will to resource and deploy these systems for this purpose.



Session 1:

Impact of emerging technologies on the direction of strategic warfare

Andrew Futter

Senior Lecturer in International Politics
University of Leicester



Dr Futter spoke on potential challenges to confidence in the UK nuclear weapon system from cyber, and noted that although this issue had gained more attention in recent months, understanding of its implications remains in its infancy.

Dr Futter thought it clear, however, that cyber challenges could affect the whole UK nuclear enterprise, although cyber attacks vary enormously in reach and implications, from hacking and espionage to sabotage and attacks causing physical destruction. Moreover, attacks can be direct or indirect, in person and in situ or remote, and disabling or enabling, depending on whether the aim is prevent function or cause an event: in the worst case scenario, a missile launch. While most UK nuclear systems are not connected to the Internet in any meaningful way, these systems do rely on networks, with complex software which requires regular updating and patching.

The biggest risk for submarines, said Dr Futter, is that hackers might sabotage weapons systems either to cause accidental or unauthorized explosion or launch, or more likely to prevent the system working as planned. The most likely scenario is that malware would be introduced during the procurement phase or during software updates, possibly to be activated remotely, but more likely to be built in to activate under certain conditions.

Dr Futter added that cyber attacks might target other systems that could cause the submarine to have to return to port. State adversaries would be most likely to target key systems to compromise the submarine's stealth, reactor or fire

control systems. Non-state actors might seek to cause a launch or explosion to exacerbate a crisis, or to target the reactor.

The second concern is interference with communications, such as jamming or spoofing with misleading information, which can increase crisis instability. There is evidence that hackers have attempted to compromise systems used by the US Navy, and one can assume attempts have been made against UK systems too.

A further concern is cyber espionage: the theft of operational secrets. The past is littered with allegations of this nature, including against contractors building the new *Successor* submarines and defence contractors in the US.

In summary, Dr Futter proposed that we are moving towards a much more complex and challenging nuclear environment, of which cyber is only one of several complicating components; developments in other fields, such as missile defence, precision targeting and space, will further compound future deterrence challenges. While he concluded that this does not necessitate scrapping Trident imminently, it poses important questions about the future security environment in over a decade's time, when the first boat will be deployed.

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Dr Heather Williams

Lecturer, Centre for Science and Security Studies

King's College London



Dr Williams began her presentation by posing what she felt was the fundamental strategic question of the conference: whether emergence of these new technologies would undermine capabilities and jeopardize strategic stability and whether there is a framework that we can use to approach this.

In the 1960s new technology was the impetus for developing the SALT and the ABM treaty, namely MIRV and missile defences. Another impetus for developing the treaties was the Cuban Missile Crisis and the need to improve stability. The third driver was cost. However the biggest issue in negotiating SALT and the ABM treaty was accepting parity and defining and accepting sufficiency on both sides, with the need to satisfy domestic audiences also a key consideration.

Applying this framework for developing past treaties, and how that might inform how we deal with new technologies, she said that there were three routes that could be taken: an arms race; arms control; adapt; or a combination of all three of these. Dr Williams' conclusion was that adaptation was often the best route.

An arms race would mean engaging with an adversary in a 'like for like' race in the pursuit of superiority and so rejecting parity.

Dr Williams stressed that arms control does not equate to disarmament. While it can include a roll back of capabilities and reductions it is essentially about the management of weapons.

The third option is to adapt but, of course, all three can work in conjunction with each other.

When considering the 'adapt' route Dr Williams said we needed to consider what we mean by a stable environment and for her it is one where there is a low risk of escalation and, within that system, self regulation. Measures such as transparency can be included or developing countermeasures in response to an adversary's defence mechanism. However the key question is what is sufficiency and whether we are willing to accept it.

Dr Williams posed the question of what these routes would mean in relation to Trident and SSBNs. An arms race route would mean, for example, developing similar undersea robotic vehicles capabilities to go after an adversary in pursuit of superiority. This is costly however. The arms control route is complex and it is not clear which countries we are talking about, which are active in engaging in these new technologies relating to SSBNs and what the bilateral relationships are.

Dr Williams felt that the adapt route is the one that needs further consideration. What would adaption to these emerging technologies look like? She gave an example of how creativity can be pertinent, a low tech answer to a high tech problem in the Netherlands where the Dutch police have trained eagles to pluck illegal drones out of the air!

She also questioned what this would mean for the US / UK nuclear relationship and whether there was a possible collaboration on countermeasures.

Paul Schulte

Honorary Professor Birmingham University
Institute of Conflict Cooperation and Security
Senior Visiting Fellow, Centre for Defence
Studies, King's College London



Mr Schulte presented a sceptical unclassified strategic analysis of the potential for future Underwater Unmanned Vehicles (UUVs) to compromise SSBNs. He reminded the audience that anti-SSBN technologies had been intensively studied for the last 40 – 50 years.

The physical parameters of the sea, the vast area, its opaque and absorptive qualities, would continue to hinder the ability to detect SSBNs, unless there was an extraordinary breakthrough in technologies: frequently postulated but never proven. He pointed out that technological developments would also include countermeasures such as spoofing, jamming, launchable decoys and enhanced detection and destruction of UUVs. Future countermeasures-counter countermeasures races are inherently uncertain.

Geography and law would also play a their part. Any hostile UUV caught in territorial waters, within the 12-mile limit, waiting to track an SSBN's exit would create a huge stir in peacetime, and be liable to quick destruction in times of crisis.

It is widely believed that no British SSBN has ever been detected, and the Cold War practice of 'delousing', ridding the submarine of tracking mechanisms or followers, could be continued. Also during the Cold War, the Soviet Union had been interested in Anti Submarine Warfare (ASW) "keep out zones", or 'bastions', areas with a higher confidence of preventing effective ASW. This, if necessary, could be one stabilising option to support maintaining nuclear deterrence. Mr Schulte felt that Russia today was probably more concerned than anyone else about the survivability of its SSBNs at sea.

He questioned the risk to UK Successor, given its very low sound levels and the legendary ability of SSBN captains to manoeuvre. UK SSBNs operate in the Atlantic which has much more background noise than the Pacific where the US, China and others patrol.

The US can be expected to develop technology to improve sonar stealth in that more challenging Pacific environment which the UK could acquire or share. Moreover SSBNs are fast and have near limitless range and the only way a UUV could match these characteristics would be by nuclear power. This would be exceptionally expensive and create a set of vulnerabilities.

Mr Schulte questioned what difference plausible future UUV or other detection or tracking technologies would make in a significant nuclear crisis:

- Could enemy UUVs really consistently shadow SSBNs, which have much greater hull length and therefore theoretical speed?
- Could they be reliably controlled, given the difficulties of underwater communications?
- Could they be ordered to timely pre-empt an SSBN missile launch?
- Could it be assumed that all the US, UK and French SSBNs would be preempted in that same moment?

This strategy would carry high risk because it would precipitate precisely the nuclear retaliation it was intended to preempt. By virtue of the way that these postulated nuclear UUVs would have to operate, their close presence would, in itself, indicate that a missile launch was in prospect.

These were daunting objections for anyone thinking to activate and continuously maintain a fleet of expensive autonomous nuclear UUVs.

He remarked that scepticism about the continuing utility of the British SSBN program had been widely reported in UK antinuclear publications (and in Russian media seen as instruments of transnational Information Warfare.) He suspected that many would like to believe in the inevitable doom of UK Trident, despite the lack of conclusive evidence, and that this might complicate conscientious assessment of the technical risks and vulnerabilities of national security arrangements.

Dr Nick Ritchie

Senior Lecturer in International Security University of York



Dr Ritchie observed that the practice of nuclear deterrence remains an abstract conceptual system, with only a slim empirical base, and that our approach to emerging technologies relies upon populating the future by imagining the impacts of existing or 'plausible' technology. In other words, there is inevitably a great deal of speculation.

Dr Ritchie encouraged us also to consider the political role of Britain's nuclear weapons deployed at sea on submarines. The government narrative has narrowed the role of UK nuclear weapons, and their political utility, to the idea of last resort. However, he argued that they are currently used for other purposes, including coercion and political signalling, intimidation and so on, without necessarily an existential dimension.

Dr Ritchie considered the possibility of Russia attempting to hold at risk a UK ballistic nuclear submarine, and thought that these emerging technologies would not affect the capacity of the UK government to issue a credible nuclear threat in times of crisis. The Russians would need to consider an uncertain pre-emptive strike that would escalate a crisis, particularly if the UK submarine was on alert on 15 minutes to fire (as it would be in a crisis). He thought this would be beyond acceptable levels of risk and uncertainty for Russia.

The logic of nuclear deterrence, as deployed by the UK government to justify our continued retention of nuclear weapons, is very much under threat, however. The government narrative routinely frames the case for Trident in terms of certainties, as the 'ultimate insurance' and 'guarantor' of protection from all 'nuclear nasties'. This rests on the idea of an assured second-strike capability. However, he argued that this is a false narrative, deployed for marketing purposes. Numerous studies have shown that there are fundamental uncertainties associated with the theory and practice of nuclear deterrence.

What these emerging technologies do is to add to these uncertainties and create new operational uncertainties on top of existing political ones. This gives further weight to existing questions about the deterrence value of UK nuclear weapons.

He added there are compound uncertainties created by cyber capacity to disrupt submarine command and control operations and advances in ballistic missile interception over the coming 20-40 years. We must be prepared, he said, to

consider the possibility that the technical feasibility to confidently secure a

second strike from nuclear weapons is going to diminish and, on the basis of that understanding of nuclear deterrence, the practice of nuclear deterrence could be rendered intrinsically unstable.

This raises questions over the efficacy of nuclear-based conceptions of national security, and could prompt changes in nuclear practice and investment in alternative nuclear delivery systems.

Dr Ritchie felt that there was insufficient incentive for substantial investment in a mass system of detection, tracking and targeting, particularly of SSBNs, in order to hold them at risk and, more likely, we would see localised networked systems to target attack submarines. This could possibly be scaled up in future to an ocean-wide surveillance system. However, if nuclear adversaries could be brought to a shared understanding of deterrence, one that privileges submarine-based nuclear second-strike as inherently stabilizing, then we may not see the development of these technologies in politically meaningful ways.

More likely, the direction of travel would be for technologically-induced nuclear instability and therefore insecurity, of the type we see expressed by Russia with respect to the US missile defence and conventional global prompt strike, compounded by any future US capacity to negate Russian SSBNs.

What these emerging technologies do is to add to these uncertainties and create new operational uncertainties on top of existing political ones.



Audience and panel discussion

Audience members noted that there are UUVs already developed by the US and China that have the capacity to match the speed of SSBNs unless the submarines broke cover and travelled at higher speeds, thus compromising their abilities to maintain stealth. It was also noted that there may be no need for individual UUVs to 'chase' an SSBN, as instead many networked systems, including airborne assets, could be used to track an SSBN and relay information between assets. The reintroduction of the maritime patrol aircraft (MPA) was an example.

It was suggested that, in future, there could be challenges in processing and filtering the sheer quantity of data gathered to make it meaningful and useful.

Much of the discussion focused on the effect that this trend towards greater ocean transparency will have on strategic stability. This raised the connected question of how perceptions of strategic stability have changed, are interpreted differently by different nations, and now include areas other than military force, such as culture and economics.

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It was argued that the speed of development, proliferation and accessibility of this new technology will mean that traditional arms control models will also need to evolve, taking into account issues around verification, trust, confidence building measures, the possibilities for asymmetric arms control, and acceptable limits to arms control. It was felt by some

participants that this was a particularly unpropitious moment for arms control, and that the international environment will need to mellow before there could be further progress.

However it was noted that there is current intellectual engagement on this new arms control architecture that would be inclusive of perceptions of acceptability from China and France also.

The supremacy of US advanced conventional weapons was also raised as a complicating factor in engaging Russia and China in nuclear weapons reductions.

The complications arising from cyber warfare were discussed and particularly how it might drastically impact the perceptions, understanding and escalation of a crisis situation. The need for investment in people and cyber hygiene was felt to be the key to combating this.

Session 2:

Developments in sensing technologies

Professor Nicholas Makris Massachusetts Institute of Technology and Director of the Laboratory for Undersea Remote Sensing



Professor Makris spoke on developments in instantaneous acoustic sensing of the undersea environment over areas spanning tens of thousands of square kilometres using active and passive Ocean Acoustic Waveguide Remote Sensing (OAWRS/POAWRS). These systems rely on the capacity of the ocean environment to behave as an acoustic waveguide, in which sound propagates over long ranges via trapped modes. Therefore, generated sound waves suffer only cylindrical spreading loss rather than the much greater spherical loss suffered in conventional fish finding technologies.

Professor Makris stated that his goal as a scientist is to make the oceans as transparent as possible, in order to understand it better, focussing on acoustic techniques. As sound travels at 1.5km/s in water, Professor Makris noted that using OAWRS techniques, his team is able to view a 100km diameter area in about 90 seconds and update the image every 90 seconds to make a 'movie'.

They are able to detect different objects in the water, from herring shoals containing many hundreds of thousands of fish, to a small man made object (a long cylindrical inflated fire hose around 10m long), using different acoustic frequencies that excite different resonances.

...using a Passive Acoustic Array his team can detect and localize many species of whales over areas spanning 400 km in diameter, from hundreds of thousands of whale calls each day.

While lower frequencies of around 200Hz are typically dominated by shipping noise, using a Passive Acoustic Array his team can detect and localize many species of whales over areas spanning 400 km in diameter, from hundreds of thousands of whale calls each day. His findings have been published in journals including *Nature*¹ (passive sensing/whales) and *Science*² (active sensing). Sensors can be either bistatic (sender and receiver separate) or monostatic (sender and receiver at roughly the same location).

2 "Here we use passive ocean acoustic waveguide remote sensing (POAWRS) in an important North Atlantic feeding ground to instantaneously detect, localize and classify MM vocalizations from diverse species over an approximately 100,000km square region." *Nature*, Volume 531, 366–370 (March 17, 2006)
www.nature.com/nature/journal/v531/n7594/abs/nature16960.html

3 N.C. Makris, P. Ratilal, D. Symonds, S. Jagannathan, S. Lee, R. Nero, "Fish population and behavior revealed by instantaneous continental-shelf-scale imaging," *Science*, Volume 311, 660-663 (February 3, 2006)

Professor David Lane

Ocean Systems Laboratory

Edinburgh Centre for Robotics

Heriot-Watt University



Professor Lane presented on three types of biomimetically inspired sensing.

Fish lateral line analogues

At present, hydrodynamic imaging uses Acoustic Current Doppler Profiles (ACDP) to measure motion. However, fish have a sensor down the sides of their bodies called a fish lateral line which measures fluid flow, and allows fish to build hydrodynamic images of the animals, objects, and water around them.

Through a company called Lakshmi, Professor Lane's lab and European partners have been developing a fibre optic cable analogue of the fish lateral line, laid on the sea floor to look at the water above. Professor Lane gave two examples of potential applications: measuring the efficiency of marine renewable energy turbines, and cueing vessels in maritime surveillance including submarines. The fish lateral line analogue could also be mounted on the side of surface or underwater vessels.

Its potential ranges and other practical issues are unknown. However, using these technologies, the team expects to be able to 'build images that give us good visibility of what's happening in the water.'

In a side note, showing a video of a dead trout seeming to swim upstream, Professor Lane also observed that fish bodies could inspire new types of self-propulsion for underwater vehicles.

Bioinspired sonar

Dolphin sonar is able to distinguish an object as small as a ping pong ball at the length of a football pitch, and also distinguish the density of what it contains. It also works at low frequencies (10-100 Hz), and can therefore propagate over long distances. By analysing dolphin 'clicks,' Professor Lane and his team discovered that dolphins use a 'double down chirp' structure: this allows them to use the slope of the down chirp, the time difference between chirps, and their respective power levels to build up a complex picture of the water space. Moreover, dolphins choose signals that will provide the greatest signal resolution each time they click. Professor Lane and his team, through a company called Hydrason, have been creating a bioinspired sonar platform in order to see inside objects.

This is useful for viewing blockages in pipelines, or for sensing mines camouflaged as rocks and other objects that have been designed to blend into the ocean environment.

Electric sensing

An EU Project called ANGELS (ANGulliform robot with ELectric Sense), which Professor Lane helped review, tried to recreate the electric sense that some fish use to understand their environment. This sense is limited to a few centimetres, but it is unaffected by visibility, can distinguish between friends, foe and food, and allow fish to see around corners (due to the nature of electromagnetic field patterns). Fish can also bend their bodies to improve their sensor processing. ANGELS demonstrated that a small, eel-like AUV equipped with an electric sense could navigate around an electric dipole in a tank, and while in the early stages, this type of technology could be applied widely to unmanned platforms in future.

David Hambling

Freelance Science Journalist and author of *Swarm Troopers*



Mr Hambling presented on what he called 'weird science': scientific discoveries that are not fully understood and the future ramifications of which are unclear, but that could be influential in future.

First, he discussed wake detection, as it is well known that submarines leave wakes astern. The most obvious are the 'V' shaped wakes behind the vessel, and marine commanders are trained to stay deep in order to ensure that these wakes are not easily picked up by radar or satellite. However, Mr Hambling told the audience, there are other ways to detect wakes, even at depth. He gave the example of technology modelled on the ability of harbour seals to pursue a fish from tens of meters away using only their whiskers; artificial 'whiskers' of this nature could theoretically be fitted to unmanned underwater vehicles for submarine tracking.

Mr Hambling then discussed bioluminescence, the light emitted by marine micro-organisms when disturbed. This was recognised as an issue for submarines in World War I, and today it may be possible to detect submarines using other kinds of luminescence outside of the visible spectrum.

Mr Hambling went on to discuss the sono-magnetic effect: weak electromagnetic fields generated by mechanical/acoustic vibrations of a conducting medium in a magnetic field. Though, in theory, it would be possible to detect a moving object under water using this effect, calculations suggest that the sono-magnetic effect of a submarine is around 1,000 times weaker than the magnetic anomaly caused by the submarine's hull, so practical applications seem unlikely. However, in 1996 Dr James Peddle published three papers on unusual magnetic anomalies associated with underwater objects. While there were no further references to this work in the literature, Dr Peddle was soon appointed Technical Leader of Detections Systems at the US Defense Research Agency, and subsequently Head of Sensor Systems at DSTL and Defense Attaché in Washington. Mr Hambling felt it reasonable to assume that his ideas have not been entirely ignored.

Dr Peddle was looking at the 'Debye effect', discovered in 1933: the magnetic field generated by the difference in movements between sodium and chlorine ions in the sea. The US launched a programme to research the application of the 'Debye effect' to detect submarines (Phase One), and, if the research proved positive, to build a detector (Phase Two). The company Cortana has now been awarded a Phase Two contract, indicating that Phase One was successful. This work on the 'Debye effect' also references 'foreign work' carried out in this field.

In the 1990s, Russian publications suggested that wake anomaly detection was easier than magnetic anomaly detection; however, Russian claims that they could track submarines using their wakes have rarely been taken seriously in the West. Mr Hambling speculated that the Russians could have been using this capacity to detect submarines for the last twenty years, unknown to others. Reducing submarine wakes is very challenging, but it is expected that *Successor* will be much stealthier with respect to wake than any past submarine.

Finally, Mr Hambling discussed the Aqua-Quad, an amphibious quadcopter drone that can float on the water's surface and lower sensors into the water. It is highly adaptable and can re-charge using its solar powered cells, before flying elsewhere. While currently in prototype stage, tests have been successful to date and it seems likely that they will be operated by the US Navy in large numbers. The Aqua-Quad can also be fitted with other kinds of sensor, such as hyperspectral sensors, thermal sensors, lateral line sensors, or even future sensors as yet unknown as it has the advantage of being able to deploy in the water.

Mr Hambling concluded that hiding from innovative sensing techniques that emerge over the coming decades will be very difficult, because they will not have been anticipated at this stage in the submarine's design and construction.

Professor David Caplin

Emeritus Professor of Physics Blackett Laboratory Imperial College London



Professor David Caplin gave a presentation on developments in magnetic anomaly detection.

He began by stating that it has been long known that any iron or steel object gradually becomes magnetised by the Earth's magnetic field. Submarines are regularly demagnetised ('degaussed'). The effectiveness of degaussing is classified, but for the purposes of discussion Professor Caplin assumes that a submarine weighs about 10,000 tons and that a highly efficient degaussing would leave a residual magnetism of 0.1%.

He went on to speak in more detail about one type of magnetometer, the Superconducting Quantum Interference Device (SQUID), that typically can detect a small bar magnet at hundreds of metres. As it detects magnetic fields by measuring the magnetic flux passing through a 'loop', the larger the loop the more sensitive the device. Professor Caplin showed that SQUID detectors are being used to detect the tiny magnetic fields associated with electric currents in the brain in magnetoencephalography techniques.

The magnetic signal from a submarine drops away as an inverse cube law, becoming smaller than the Earth's field a hundred metres away. A submarine's signal may still be detectable by a SQUID from around 30km, but it would be difficult to discriminate against the Earth's field (requiring significant processing power). The standard geophysical approach to overcome this issue is to connect two anti-parallel loops to one SQUID that cancel the Earth's uniform background field, but pick up the magnetic field gradient of the submarine. Spatial and temporal variations in the complex ocean space would also be challenging to overcome.

The ability of a SQUID to sense a submarine is augmented if the submarine's magnetic signature is known, and Professor Caplin suggested that naval labs are able to produce bespoke magnetic anomaly detectors that are particularly responsive to the kinds of signals given off by submarines. In future, Professor Caplin expects that data from magnetic anomaly detection will be fused with other kinds of sensing data.

SQUIDs will become significantly more useful in ASW if air or ocean temperature superconductors are developed. Previously superconductors had to be cooled to near absolute zero temperatures with liquid helium, but in recent years, high-temperature superconductors have been developed that work at temperatures of 150K; however, this still requires liquid nitrogen cooling, which complicates their deployment in anti-submarine warfare. Yet, given the many surprises in the history of superconductivity, it is possible that materials may eventually be found that superconduct at room or ocean temperatures, which might allow the deployment of very much larger flux loops, and so increase sensitivity by orders of magnitude.

Audience and panel discussion

In the discussion with the audience, various countermeasures were discussed.

Two methods of degaussing were mentioned: passing the submarine through a coil of wire, and internal coil loops through which an electrical current can be run, which effectively reduce the magnetic signature of the submarine by about 99%. However, it was pointed out that as, for example, magnetic anomaly detection (MAD) becomes more advanced, improvements to counter detection will be developed. Yet, it is still very difficult and costly to retrofit a submarine to maintain the balance of detection and counter measures.

Countering both active and passive acoustic detection over large distances through noise reduction, jamming and spoofing was also discussed. While noise cancellation is possible for low frequency noise, such as is used in BOSE headphones, it is significantly more challenging to design and deploy a system that can cancel all the high and varied frequencies emitted along the length of a submarine hull. Acoustic displacements are tiny and it would be a major challenge to implement effective noise cancellation in the case of submarines. One would need to create complex active displacements over the entire hull, and, if these are not precisely correct, the submarine will transmit instead, with obvious opposite intention. Spoofing and jamming have their own problems; for instance, a sudden increase in noise would be noted by an opponent and alert them to the presence of a submarine in the locality. One would need to know exactly where the passive sensor is located and the optimum distance to begin transmitting, and be able to transmit through 360 degrees. Again, it was thought more likely that attempting jamming or spoofing would be counterproductive.

While noise cancellation is possible for low frequency noise, such as is used in BOSE headphones, it is significantly more challenging to design and deploy a system that can cancel all the high and varied frequencies emitted along the length of a submarine hull.

The practical range for submarine detection using the technology developments discussed in the conference was also discussed. It was suggested that the future emphasis would be on smaller distributed sensors with shorter ranges. For example, MAD has a range of only 500 meters if using one aircraft but if using 1,000 small drones a much greater area can be covered simultaneously. One participant reflected that the technologies used 25 years ago had been thought incredible at the time and inspired awe. In 25

years time one can only imagine the computational speed that will be routinely possible, and the knowledge and understanding of propagation through oceans that will be available; it can be confidently predicted that technology then will be very different from what we have now.

Another issue discussed was sensor fusion, and the difference that networked systems would make in future. For these to be effective, multiple sensors will have to have the capability to all work at compatible ranges and resolutions. This is a challenge as some sensors – optical sensors, for example – work over short range underwater while others – such as low frequency acoustic sensors – work over longer ranges. Finding the optimum overlap range and resolution is the key, and the potential resulting capability was said to be fantastic when used properly, and very likely to be crucial in future. There are commercial companies who are looking into this; in oceanography, sensor fusion is happening already.

'Big data' and machine learning is another area that is becoming increasingly important. As an example, the original Sound Surveillance System (SOSUS) network used to produce paper traces that the human staff had to read and analyse. Later, computer analysis became the norm, and today, analysis can be done on a smartphone.

Session 3:

Developments in marine robotic vehicles

Professor David Lane
Ocean Systems Laboratory
Edinburgh Centre for Robotics
Heriot-Watt University



Marine and Terrestrial Robotics and Autonomy

In his second presentation, Professor Lane discussed some of the emerging technologies that might influence the next generation of marine vehicle technologies and activities, stating that autonomy will be the most important development.

We can think about control of systems broadly in three ways: manual control, shared-autonomy, or persistent autonomy. The last is characterised as an operation with limited recourse to the human operator for extended lengths of time, adapting to and interacting with unknown environments and recovering from errors in task executions.

An example of a persistently autonomous vehicle is the Subsea 7, an advanced autonomous inspection vehicle developed by SeeByte and in use by Shell for deep water inspections. This exhibits independent decision-making capabilities and the ability to recover from a limited number of errors. However, the Subsea 7 is not well equipped to deal with the unexpected and requires a map of its environment to operate. This requires robust control in the presence of disturbances, and this is developed using machine-learning techniques.

Professor Lane showed that robots can be taught skills through real-life training sessions, in which the robot is controlled by an operator in a lab. Rather than learning a simple sequence of actions, the robot learns a series of probabilities to enable it to offset unpredictable external disturbances during deployments. In a video, one robot was being trained to clean anchor chains, while another was autonomously mapping a new and unfamiliar environment off western Scotland and adapting its mission in the presence of new objects of interest.

Professor Lane's team has been concentrating on an 'internet of things' approach, to allow various vehicles to synchronise their situational awareness and collaborate. Since bandwidth is limited in the undersea environment, these networks must be smart and synchronise the most important data first. As an example, Professor Lane showed a video of an aerial drone working in collaboration with, and providing navigational information for, a drone on the ground that had limited visual information about its environment. He stressed that these vehicles should not be thought about in isolation, but in a systems context and purpose of data collection.

Operators cannot always communicate effectively with a platform on mission under the ocean. Professor Lane's team invented the 'back to the future' engine, whereby the operator is given a prediction of what should be happening under the water based on vehicle mission plans, until connection is re-established and the displays are resynchronised.

Professor Lane predicts that, in future, the hardware of future robotic platforms will become increasingly generic and innovation will move towards downloadable software that increases the hardware's capabilities; he draws an analogy between apps and smartphones. In the marine environment, he believes that we will see a convergence in unmanned surface and underwater vehicle hardware, which could be assigned multiple kinds of mission.

He finished by quoting Bill Gates: 'We always overestimate the change that will occur in two years but underestimate the change that will occur in ten.' Professor Lane felt that change was coming faster than we know and that in ten years it would be very interesting to see where we are.

Professor Russell Wynn

Chief Scientist

Marine Autonomous and Robotics Systems (MARS)

National Oceanography Centre (NOC)

Southampton



Professor Wynn's presentation focused on the environmental research applications of developments in marine robotics but noted that the crossover to defence was self-evident. He said that there was a lot happening in this field. He talked of the huge discrepancy in cost between, for example, the National Environmental Research Council (NERC) vessel RRS Discovery, which cost £75M and upwards of £20K per day to run, and unmanned underwater vehicles (UUVs) that are much cheaper to purchase and operate. There is a huge investment at present in marine autonomy, with the long-term goal of gaining more high-quality data at a lower cost to support scientific research.

The NERC MARS fleet now operates more than 40 marine autonomous systems and the NERC community has the capacity to develop innovative sensors to measure marine environments.

A typical high-powered, short range, autonomous underwater propeller driven vehicle (AUV) can operate at up to 6,000 meters water depth for two or three days, and can do many different tasks, from mapping the seabed to performing biological measuring. These systems have been in use for a couple of decades.

Another platform is the submarine glider, the US Navy being the biggest purchaser of these. NERC MARS has 30 of these relatively low-cost vehicles. They have a buoyancy engine and can travel through the water, surfacing every few hours to transmit data and receive commands. These vehicles move relatively slowly but have an endurance of many weeks.

More recently, a number of unmanned surface vehicles (USV) have been deployed on high profile missions collecting data from the earth-sea interface, the most well known being the Wave Glider. Professor Wynn said there was a new USV coming out almost every month, with many different designs with different utilities, and that there would be many new designs in the next few years.

However, he added that training is key and that all these vehicles need experienced pilots to operate them.

The evolution of these vehicles is in developing different capabilities. One is in increasing endurance from a couple of hours to a few days to months at a time. Another is in flexibility, through platforms that do not require a ship but that can be rapidly and easily launched from a RIB or a slipway or beach.

Another development is in increasing compatibility of AUV to work together with other platforms. For example, a long-range AUV working at depth for a few weeks can transmit to a USV via an acoustic link and then to the operating vehicle via satellite, rather than to have to surface to transmit data. This procedure also improves navigational accuracy of the AUV.

Other combination examples are a USV that can release several small AUVs for rapid response; submarine gliders that can be dropped from a plane; or vehicles that can fly to an area and then into the water to do AUV work. Hybrid vehicles are frequently coming online.

Professor Wynn said that NOC deliberately operates 'dumb' vehicles, with intelligent pilots and scientists, but the trend is to have more intelligence onboard the vehicles. He gave an example of an AUV at 6,000 meters depth that can recognise when it has found something interesting and, rather than continue with its pre-programmed mission, will hone in on that feature of interest. Vehicles can also process the huge amount of data they gather to determine which data are of interest for transmission, so keeping costs down and reducing the burden on the interpreters at base.

Platforms are reducing in cost, from around £1m for a large deep-water AUV with multiple high-power sensors to smaller USVs costing just tens of thousands, with miniaturized platforms even cheaper.

To achieve long endurance, speed has to be kept down, so many research vehicles travel at walking or running speed for long periods.

AUVs can now operate under ice and in the deepest parts of the ocean, at 6,000 meters for example, and in very challenging environments. They are able to map a canyon, for example, in 3D in high resolution and, if they note a feature of interest, can be used in conjunction with a Remotely Operated Vehicle (ROV) to obtain a map resolution of millimeters if needed. The ROVs can relay this information in real time.

By keeping speed down, with developing battery performance and miniaturizing sensors, efficiency is maximized enabling the vehicles to occupy choke points for weeks or months at a time.

Another development is in propeller-driven AUVs that can be deployed for weeks or months at a time, dive to 6,000 meters and travel thousands of kilometers. By keeping speed down, with developing battery performance and miniaturizing sensors, efficiency is maximized enabling the vehicles to occupy choke points for weeks or months at a time. Other vehicles can potentially be deployed to an area then hibernate for months, wake up to switch on sensors and then hibernate again, repeating the process.

NERC MARS assets anywhere in the world can be controlled from NOC Southampton and any of the fleet data can be controlled from an Internet connection.

From his iPhone, Professor

Wynn can see the location of any member of his fleet and the data they are collecting, and can communicate with the pilots to direct the UUVs as needed in real time. There is also the ability to switch sensors on and off, and access images and other data via satellite link-up in real-time.

Submarine gliders are particularly useful for collecting and compressing many thousands of profiles, while communicating in real-time. USVs are best used in hostile open ocean environments with many different types of sensors and data layers, communicating continuously by satellite.

A current aim is to network existing infrastructure with these new autonomous platforms and to handle efficiently the massive amount of data generated.

Professor Wynn mentioned the coming exercise 'Unmanned Warrior', in which the National Marine Facilities MARS fleet will take part. He said that the stated aim of this exercise is to demonstrate how unmanned capabilities can enhance and potentially replace manned forces for defence.

Brendan Hyland

Founder and Chairman of WFS (Wireless For Subsea) Technologies



WFS Technologies builds primarily radio-based underwater wireless communications systems that are branded as Seatooth. Mr Hyland gave a presentation on undersea WiFi and LiFi.

Radio-based communications underwater have a short-range functionality, akin to Bluetooth or WiFi. Mr Hyland noted that the potential for underwater electromagnetic (EM) communications has been noted sporadically since the Victorian period, but little progress has been made until recently. During the Cold War, systems were developed in the US, UK, France and Russia for very low frequency radio communications for submarines (around 78-82Hz), but work stopped after the 1960s, largely because of the challenging nature of EM propagation in water and because states were more interested in longer range communications technologies.

WFS Technologies began developing EM communications technologies in 2004, and today sell off-the-shelf products for a range of applications, primarily in the oil and gas industries. Mr Hyland gave the example of an oil platform in the North Sea, in which his team placed around a dozen wireless nodes 30 metres apart to carry out long-term asset integrity monitoring. In the last 12-18 months, they have been investigating the possibilities of defence applications.

WiFi systems are effective in littoral waters, as they are not affected by turbidity, bubbles or sea-life; they can easily cross the water-air boundary; they can be easily encrypted at each end; and the signal ranges can be limited, which could be useful in defence applications. Using carrier frequencies in the orders of several kHz or MHz, the propagation velocity of EM is also significantly higher than that of an acoustic equivalent, leading to low latency within systems.

Finally, wireless communication systems are relatively low cost and resilient. However, EM systems are relatively short range in seawater, with aggressive attenuation (around 55Db per λ , or wavelength) and a maximum practical range in the order of 2λ ; the range is, to an extent, a function of the carrier frequency of the system in water.

Mr Hyland suggests that EM communications are neither better nor worse than acoustic or optical, but rather, have different functionalities and applications. Optical systems can deliver high bandwidth, but require a good line of sight and are relatively susceptible to turbidity. Acoustic systems, though long range in deeper water, struggle in littoral waters. Accordingly, Mr Hyland advocates creating fused communications systems, whereby underwater communications nodes use whatever means are available to transmit the data, just as smart phones swap seamlessly between Bluetooth, 3G and 4G, without any obvious change to the user.

WFS Technologies' EM devices communicate typically at around 100 bits per second (bps), which is fit for purpose in process control systems transmitting simple data. With relatively low propagation losses, they have ranges of around 40m through seawater, 200m through air, or 200-250m through the seabed (but he suggested this could increase to around 1km). These types of wireless communication can penetrate concrete blankets or several meters of ice; Mr Hyland built a demonstrator system a few years ago to find an AUV lost under 5m of ice, with a further range of 750m in air. Bandwidth increases to 100,000 bps in 5m seawater ranges, and WiFi-type devices can be used to communicate around 10-100m bps at about 1cm, replacing wet mating connectors.

Mr Hyland presented a number of future scenarios for these technologies, echoing Professor Lane's expectation of a subsea 'internet of things'. He imagines long networks of wireless sensors extending for several miles into littoral waters from the shore, for environmental and shipping channel monitoring, and which could even function as undersea 'landing strips'. He expects data processing to take place increasingly on the seabed, to minimise the energy requirements of transmission. Although these technologies are already energy efficient, staying in an always-on condition for 10-20 years on modest battery packs, the technologies will benefit from further improvements in battery technology.

In addition WFS Technologies is working on wireless (inductive) power transfer systems, seeing a need for wireless docking for AUVs permanently deployed at the seabed in 5-10 years. He also envisages wireless networks being a key enabler for collaboration between divers and AUVs, allowing them to communicate, transmit data including video and locate themselves in relation to others. Finally, WFS Technologies is exploring ways to integrate existing conventional, above-surface wireless systems with their underwater systems.

Audience and panel discussion

Optimum systems for undersea communications – and a comparison between acoustics, optics and wireless in terms of data transfer, bandwidth and range – were discussed. It was felt that users would keep it simple and match the communications solution to the requirements. It was said to be a question of systems engineering, designing the architecture for the vehicle's capabilities and communications networks together. It was noted that it was information, rather than raw data, that was typically required. The 'smarter' the vehicle, the less data will need to be transferred, and therefore, the less bandwidth needed.

The most likely direction of development for undersea WiFi will be undersea docking stations. At the moment, this is being driven by the US Department of Defense with the Office of Naval Research.

For example, in one scenario in which the operation lasted weeks at a time and at a depth of thousands of meters, the optimum communications would be acoustic, giving low bandwidth but able to maintain communication for long periods over a long distance. In another scenario, in a field installation in the oil and gas industry, where there is a seabed infrastructure, ROVs can communicate using optical communications using a high bandwidth over a short distance of around 100 meters maximum. Both these systems are being developed at present.

The most likely direction of development for undersea WiFi will be undersea docking stations. At the moment, this is being driven by the US Department of Defense with the Office of Naval Research, and will incorporate various levels of wireless communications.

One issue that was felt to need more focus for collaborative effort was in third party software security networks for marine vehicles, particularly for use in defence.

Session 4:

Strategic challenges specific to the UK and *Successor*

Paul Ingram Executive Director of BASIC



Mr Ingram introduced the final session, stating that it would pick up the discussion from the first session on the consequences of this emerging technology on strategic related decisions on deployment, declaratory policy, submarine patrols, deterrence and arms control.

He posed the question of whether the future possibility of an emerging capability to neutralize SSBNs would change the security calculus of nations. Should the US achieve a significant advantage through the deployment of such technology would it, for example, be tempted to pursue a policy of strategic dominance, and what effect would this have on strategic stability?

In the context of the UK and the parliamentary decision on *Successor*, he reminded the audience that in the 16-17 years until the current predicted 'in service' date for *Successor*, there will be a large number of ASW technology iterations. The technologies considered in the conference involved, sensors, platforms, networked systems, cheap disposable UUVs (but probably not nuclear powered UUVs), a mix of static and unmanned mobile underwater, and surface and airborne assets.

Taken together, and with manned assets, these innovations could lead to a situation in which enhanced ASW compromises the stealth of SSBNs, to an extent that strategic stability is affected.

Given that the rationale for SSBNs is based on stealth, this raises the question of whether SSBNs are the appropriate platform for UK's nuclear weapons.

The question, he stated, was about assessing and managing risk. A challenging judgement to make in a deeply uncertain future, in which neither continued submarine stealth nor a technical revolution can be reliably assured. However, one certainty is that there will be relevant technological changes, and the need to address reducing risks and managing responsibilities was a driver in putting together this conference.

Should the US achieve a significant advantage through the deployment of such technology would it, for example, be tempted to pursue a policy of strategic dominance, and what effect would this have on strategic stability?

Dominick Jenkins

Independent philosopher



Dr Jenkins noted that recent historical research shows that the Admiralty developed a highly-effective machinery for managing public perceptions in the early twentieth century.

He described how the operations of large battleships and naval reviews were well reported, yet while the Admiralty was sceptical of sensationalist claims that German battleships were making Britain vulnerable to invasion, these claims were not denied publically and Britain's actual strategy was kept secret.

Resultantly, while the public believed that the big battleship was the ultimate weapon, men at the centre of decision making – such as First Sea Lord Admiral Sir John “Jackie” Fisher and his pupil, the civilian head of the Royal Navy, Winston Churchill – took a very different view. Rather, they believed that industrialisation had made countries more dependent on world trade for food and raw materials.

They developed new technologies – such as submarines and torpedoes for defence, and fast cruisers and radio to destroy commerce – as a way of maintaining British naval supremacy, at a time when Britain could no longer out-build its rivals. However, in order to gain the necessary funds for this development, they let the public, Parliament, and ministers believe that more battleships were needed to deter a German invasion.

Dr Jenkins questioned whether the machinery for managing public perceptions of naval capabilities had been abandoned, or simply refined?

His perception was that, in the British case, the real official view may be that advances in ASW may have already made nuclear submarines vulnerable to detection. Indeed, Dr Jenkins concluded, in the case of America, naval officials openly state that the United States should fund new ASW and new SSBNs to maintain US naval supremacy across the world's oceans, rather than for defence.

Baroness Miller of Chilthorne Domer

Liberal Democrat member of the House of Lords



Baroness Miller highlighted the importance of the humanitarian conferences initiative, bringing together many of the nations of the world to address nuclear dangers when the nuclear weapons possessors have failed to do so. She pointed to the 16-year stalemate in the Conference on Disarmament, and more recent stalled progress in arms control.

Baroness Miller expressed disappointment in the quality of recent Parliamentary debates, which were dominated by the split within the Labour Party, leaving more substantive issues such as emerging vulnerabilities and risk overlooked.

She also said that the younger generation was disengaged, even though these decisions will strongly affect their future.

She drew parallels with the changed approach to climate change, which originally had been characterised by prejudice and fixed positions. This changed with a draft bill to discuss consensus around climate change that drew out the issues. She called for a cross-party discussion on Trident around consensus-building.

Baroness Miller also raised Brexit and attendant uncertainties over Britain's position in the world, making it difficult to take firm decisions on military and foreign policy.

Tom McKane

Former DG Security Policy MoD
Visiting Senior Fellow LSE Ideas
Senior Fellow RUSI



Mr McKane began by defining the UK's current nuclear weapons policy: one in which a UK nuclear weapon would be fired in only narrowly defined circumstances. The phrase used by all governments has been, and remains, that it is to protect the 'UK's vital national interests'. He conceded that it was extremely difficult to define these precisely in the current domestic or international security climate, but still felt that one could not rule out future threats and that not having the nuclear deterrent could place the UK in severe peril. Mr McKane said that the government was not complacent, however, and that there were regular serious debates within government looking at different aspects of nuclear policy and options. He gave the Trident Alternatives Review (TAR) as an example of this.

This was not to dismiss concerns on the technical vulnerability of SSBNs, but rather to note that there was little reason to consider this a revolution so much as an evolution in the old competition between the detector and the submarine.

He commented on the assumed correlation between studies of the emerging technologies discussed at the conference and the efficacy of SSBNs. He asked what other nuclear weapon system would give a better second-strike option for the UK. This was not to dismiss concerns on the technical vulnerability of SSBNs, but rather to note that there was little reason to consider this a revolution so much as an evolution in the old competition between the detector and the submarine. One reason for this is the size of the oceans and the available space for submarines to operate in; these operational advantages, he stated, are unlikely to be overcome. Continuous at-Sea Deterrence (CASD) would remain the best option for all the reasons set out in the TAR, in any circumstance short of complete transparency of the oceans. He agreed with other speakers on the difficulties of verifying the non-use of these new technologies.



Audience and panel discussion

In the final discussion, a number of participants gave their views on points made throughout the conference.

It was pointed out that the humanitarian initiative was not intended purely to be a discussion on the morality of nuclear weapons, but was also intended to awaken the non-nuclear weapon states, as well as the nuclear states, to their responsibilities for multilateral nuclear disarmament. It came through a desire for actual disarmament rather than arms control and the initiative has helped to change the normative and legal context of nuclear weapons, leading to discussions in the UN on the prohibition of nuclear weapons.

One participant expressed the opinion that the technologies discussed at the conference were evolutionary and not revolutionary and that there was already in existence a group of extremely able, independent scientists and technical experts in the UK who have a full time role in monitoring and analysing the vulnerability of SSBNs and the countermeasures available.

Various points were made on arms control in relation to emerging technologies discussed in the conference. It was suggested that ways forward could include a limitation on the development and / or use of these technologies, but this was felt to be unrealistic because of the dual-use nature of the technologies discussed and the difficulties in verification.

The suggestion of 'bastions' for submarines discussed earlier in the conference was also felt to be unrealistic, given the number of other technologies available that we had not touched on in the conference and the possibilities of ballistic missile interception from the boundaries of the bastion; moreover, the development of stealthy unmanned vehicles such as the US Navy's GhostSwimmer could penetrate a bastion covertly.

The difference to historical technological changes was thought to be the speed with which technologies are being developed, the likely uneven development of ASW technologies compared to the submarines themselves, and the subsequent changing role for submarines.

It was felt to be undeniable that change is coming, and the issue is how this could be managed. The difference to historical technological changes was thought to be the speed with which technologies are being developed, the likely uneven development of ASW technologies compared to the submarines themselves, and the subsequent changing role for submarines.

One of the limitations in discussing this issue was the secrecy that surrounds it. However, it is clear that the US is spending a vast amount on both developing UUVs and in looking at the vulnerability of submarines, while they and other nations are continuing to pursue sea-based strategic nuclear arsenals.

It was reiterated that the overarching issue was one of risk assessment. Analysts approach this from their own perspectives, and often from a polarized conception of risk, with respect to what nuclear weapons do, both positively and negatively, to the international system, strategic stability, alliance relationships, global governance, costs and moral calculations. It was recognised to be a complex issue, and one that until now had not been properly debated.

About the conference organisers

British Pugwash

British Pugwash is the UK arm of the Pugwash Conferences on Science and World Affairs. We use the best scientific expertise, including from Pugwash's international network, to inform the government and the public about issues relating to weapons of mass destruction - especially nuclear weapons and nuclear power - issues of war and peace, the environment and the social responsibility of scientists.

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The University of Leicester, in association with the UK **Economic and Social Research Council** (grant number ES/K008838/1) were proud to support this initiative. The University of Leicester is a leading international university with a reputation for excellent teaching and world-class research. The newly formed School of History, Politics and International Relations at the University of Leicester supports a wide range of research into contemporary nuclear weapons issues, and offers a wide range of both undergraduate and graduate courses in International Relations and Strategic Studies. The ESRC is the UK's largest organisation for funding research on economic and social issues. It supports independent, high quality research which has an impact on business, the public sector and civil society. At any one time it supports over 4,000 researchers and postgraduate students in academic institutions and independent research institutes.

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BASIC

BASIC (British American Security Information Council) is a think tank based in Whitehall, London, taking a uniquely non-partisan, dialogue-based and inclusive approach to promoting global nuclear disarmament and non-proliferation. The organisation works closely with policy makers and seeks to facilitate constructive engagement between individuals from different geographical, political or cultural backgrounds on traditionally sensitive or complex issues, and create space for new and diverse perspectives. In addition to emerging undersea technologies, BASIC's research programmes include the UK's role in multilateral disarmament and the emerging concept of responsibility in nuclear governance.

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*The organisers are grateful to The Liberal Club for their hospitality.
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