Comparison of British and American submarine reactor designs

In a recent report on nuclear submarine safety, the Defence Nuclear Safety Regulator said "current UK practice falls significantly short of benchmarked relevant good practice".[1] The two areas he highlighted were "control of submarine depth" and a "Loss of Coolant Accident".

Control of submarine depth

Modern nuclear submarines use two methods to adjust their depth. The first is by changing the amount of ballast (water) they carry. The second method is by powering forward and adjusting the angle of the bow and stern hydroplanes. Once submerged to their operating depth it is the second method which is used. The hydroplanes act as "wings for the submarines ... They drive the submarine up and down through the water depths".[2] The submarine is "flown" underwater.[3]

The hydroplanes only work if the submarine is moving forward. This means that depth control is dependent on the availability of power. If the reactor shuts down and there is no propulsion then control of depth can be lost. If the vessel is operating at close to its maximum depth this can result in it sinking to a depth at which the hull is ruptured and the vessel and crew are lost.

On 10 April 1963 the American nuclear submarine USS Thresher sank, with all hands, in 2,600 metres of water East of Cape Cod. A Court of Inquiry concluded that the reactor had probably shut down, resulting in a loss of propulsion and that the ballast system had also failed.[4]

In July 1998 the crew of HMS Vanguard were terrified when the reactor shut down while submerged between Lands End and Ireland. There was a delay before sufficient back-up power was established.[5]

Reliable main propulsion system

The best protection against loss of depth control is a "high reliability main propulsion system". [6]

US – "US established practice is to provide a high reliability of propulsion, from the main propulsion system, even under reactor fault conditions".[7] This suggests that US submarines have reliable nuclear reactors which will continue to function even when there are defects in the primary circuit.

UK – "UK practice in current class submarines is to accept a much lower reliability from main propulsion system".[8] PWR1 and PWR2 reactors are not, on their own, sufficiently reliable to provide adequate protection against a loss of control over depth.

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[1] Safety regulators' advice on the selection of the propulsion plant in support of the future deterrent review note. DNSR/22/11/2, 4 November 2009, para 13 http://bit.ly/fYeAdY

[2] Comment by Australian submarine officer http://www.lookoutnewspaper.com/top-stories.php?id=315

[3] BAe Systems http://production.investis.com/astute/about/tour/cutonetwo/; There are diagrams explaining how submarine depth is controlled at http://www.heiszwolf.com/subs/tech/tech01.html

[4] Navy News 26 October 1993 http://www.strategypage.com/militaryforums/462-663.aspx

[5] Sunday Mail 19 July 1998 tp://bit.ly/dPxVv3

[6] DNSR/22/11/2 para 17

[7] DNSR/22/11/2 para 13

[8] DNSR/22/11/2 para 13

Back-up propulsion system

US - By implication, US submarines do not need an emergency propulsion system.

UK – Because of the lower reliability of the main propulsion system, this is backed up with a "very low power (but high reliability) emergency propulsion system".[9] However this back-up "will not provide sufficient dynamic lift".[10] An effective back-up motor would require "much higher power" than the current system and a "high energy submarine battery".[11] If the Navy did introduce an improved back-up motor this would still not, on its own, be sufficient. It would have to be supplemented with a rapid deballasting system.[12]

Procedural limits

US – By implication, the restrictions described below do not apply to US submarines.

UK – Because the emergency propulsion system does not provide enough power, there are "procedural controls constraining the combinations of speed and depth".[13] This probably refers to limits on the maximum or minimum speed when the submarine is operating close to its maximum design depth. These procedures are "backed up by the use of ballast systems".[14] But this does not provide comprehensive safety cover – "this may not be effective under all circumstances".[15]

Ballast

Submarines can adjust depth and trim by increasing or reducing the amount of ballast, in the form of water, they carry.

US – By implication, a rapid deballasting system is not required.

UK – Current submarines do not have a rapid deballasting system, but a future submarine design can only comply with good practice if it has either a new highly-reliable reactor, or a more powerful back-up propulsion motor combined with a rapid deballasting system.[16] By implication, the current ballast system does not operate quickly enough to enable the vessel to recover control over depth in some scenarios when there is no power from the main propulsion system.

<u>Loss of Coolant Accident (LOCA)</u>

The ongoing accident at Fukushima is a Loss of Coolant Accident. Systems to reduce the likelihood of a Loss of Coolant Accident on a submarine include:

Direct Head Injection

The most important design feature which can be introduced to reduce the likelihood of a LOCA is to have an emergency system which can inject coolant directly into core through the head of the

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[9] DNSR/22/11/2 para 13
[10] DNSR/22/11/2 para 13
[11] DNSR/22/11/2 para 13
[12] DNSR/22/11/2 para 17
[13] DNSR/22/11/2 para 13
[14] DNSR/22/11/2 para 13
[15] DNSR/22/11/2 para 13
[16] DNSR/22/11/2 para 17

reactor pressure vessel – "for the dominant fault sequence of a LOCA, the ability to protect against reasonably foreseeable leaks can only be achieved by injection of emergency core cooling through the reactor pressure vessel (RPV) head directly into the core (direct head injection)".[17]

US – US submarine reactors have systems for direct head injection of coolant.[18]

UK – British submarine reactors do not have systems for direct head injection of coolant – "the current PWR2 emergency core cooling system does not inject coolant to the reactor pressure vessel head".[19] A diagram of the PWR1 reactor shows that the same applies to that earlier design.[20] In a reply on 5 April 2011, the Defence Minister Peter Luff deliberately misled Parliament when he was asked whether British submarines have this vital safety feature. Asked if submarines have "systems for the safety injection of coolant into the reactor pressure vessel **head**", he replied - "All submarines in service have ... the ability to add coolant into the reactor pressure vessel if necessary".[21]

Automatic emergency cooling system

The Safety Assessment Principles for nuclear safety say that automatic safety measures are preferable to ones that require on manual intervention. [22]

US – This issue is not specified.

UK – The PWR2 emergency core cooling system "is highly dependent on manual procedural control".[23] A diagram of the PWR1 reactor shows that two valves must be opened, and several others closed, before the emergency cooling system will function.[24]

Passive cooling system

The Safety Assessment Principles for nuclear safety say that passive features in the reactor design are preferable to active engineering measures.[25] Reactors with passive cooling systems are designed to operate without cooling pumps. If a reactor requires cooling pumps then safety depends on the availability of a back-up power supply to run the pumps if the reactor shuts down.

US – US submarines reactors have passive core cooling systems.[26]

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[17] DNSR/22/11/2 para 17
[18] DNSR/22/11/2 para 13
[19] DNSR/22/11/2 para 13
[20] Illustration of the fault on HMS Tireless in 2000, based on a Navy manual http://www.banthebomb.org/archives/images/pwr1b.gif
[21] Hansard 5 April 2011 Col 761W http://www.publications.parliament.uk/pa/cm201011/cmhansrd/cm110405/text/110405w0001.htm#11040583000058
[22] DNSR/22/11/2 para 11
[23] DNSR/22/11/2 para 13
[24] Illustration of the fault on HMS Tireless in 2000, based on a Navy manual http://www.banthebomb.org/archives/images/pwr1b.gif
[25] DNSR/22/11/2 para 11
[26] DNSR/22/11/2 para 13

UK – British submarine reactors do not have passive core cooling systems, in the way the term is normally used. In a statement to the Defence Committee Steve Ludham of Rolls Royce said that passive cooling was a new feature that they would like to introduce in a new PWR3 reactor for the Vanguard replacement – "a new design of reactor would be quite important to make it what we might call a 'passive' plant."[27] The Emergency Core Cooling system on PWR1 and PWR2 may have some features of a passive system, but it is a back-up system with limited capability which requires manual intervention to bring into operation. Peter Luff's reply to Parliament on 5 April 2011, saying that British submarines have passive cooling, was misleading.[28]

Simple design with suitable materials

US – By implication, US reactor designs are simpler, with fewer welds and use suitable materials.

UK – A structural failure equivalent to a 15 mm diameter hole is more likely on a British submarine "due to the materials used, the complexity of systems and the number of welds".[29]

As a result of the poor design features in PWR1 and PWR2 there are consequences in terms of the severity and likelihood of an accident on a British submarine:

Ability to tolerate a crack in the primary circuit

US – By implication, US reactors can tolerate a structural failure which is greater than equivalent to a 15 mm diameter hole.

UK – British submarine reactors have "the ability to tolerate only a structural failure equivalent to a 15 mm diameter hole".[30]

Likelihood of a structural failing which would lead to a LOCA

US/US – "the initiating structural failure causing a LOCA is twice as likely to occur as in equivalent civil and submarine reactor good practice" – ie twice as likely on a British submarine as on an American submarine.[31]

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[27] The Future of the UK's Strategic Nuclear Deterrent: the Manufacturing and Skills Base, House of Commons Defence Committee, HC 59, 12 December 2006. Evidence page 8.
[28] Hansard 5 April 2011 Col 761W
http://www.publications.parliament.uk/pa/cm201011/cmhansrd/cm110405/text/110405w0001.htm#11040583000058
[29] DNSR/22/11/2 para 13
[30] DNSR/22/11/2 para 13
[31] DNSR/22/11/2 para 13