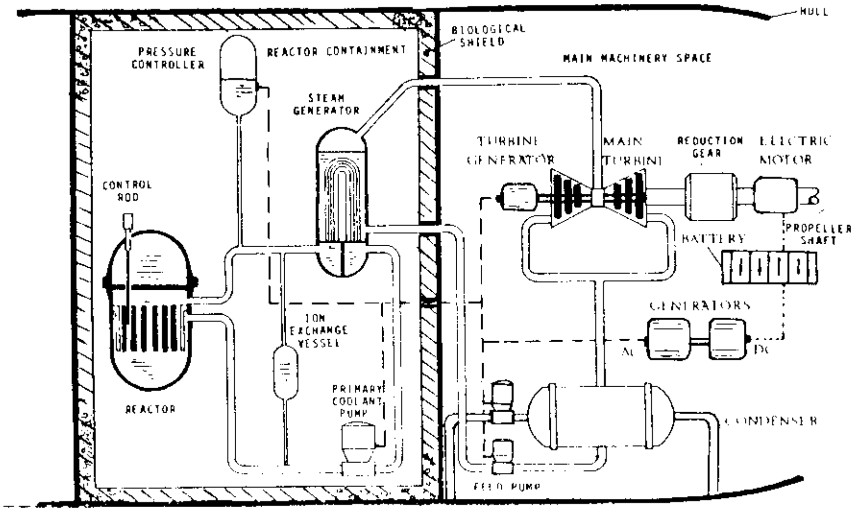
CHAPTER 4

NUCLEAR PROPULSION PLANT

CHARACTERISTICS OF PRESSURISED WATER REACTORS

Basic Features

4.1 All nuclear powered vessels known to be currently operated by the United States, British and French navies employ pressurised water reactors.[1] This type of reactor is also the most common type used for civil electricity generation.[2] A schematic diagram of a submarine's pressurised water reactor propulsion plant indicates the main features of this type of reactor.



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[1] Cdr M. K. Gahan, 'Nuclear Propulsion Systems - Technical Aspects', (Paper prepared for the Committee by the Department of Defence, February 1987), p. 3 (Evidence, p. 1300.34).

[2] International Atomic Energy Agency, Bulletin, 1988, vol. 30(2), p. 67: at the end of 1987, 225 of 417 reactors in civilian use worldwide were pressurised water reactors, and 82 of the 120 under construction were also of this type.

4.2 Nuclear power plants operate by using the heat provided by the fission of atoms and by the resulting radioactivity in order to produce steam. Fission is the splitting of a nucleus of an atom into two or more lighter nuclei. This occurs after the nucleus has been struck by a neutron. Fission results in the atom being split into atoms of two or three lighter elements. In this process a great deal of energy is emitted and two or three free neutrons are released.

4.3 The neutrons released when a fission occurs may cause further fissions, which in turn create further neutrons, and so on. In this way a self-perpetuating chain reaction can be established. A controlled chain reaction takes place if on average exactly one neutron created by each fission causes a further fission. A nuclear reactor is designed to sustain a steady chain reaction which will produce heat safely. This is done by controlling the number of neutrons which can cause further fissions. Control is achieved by raising and lowering rods of neutron absorbing material into the reactor. By manipulating these rods in a controlled way it is possible to start up, control, or shut down the reactor. Provision is made for some or all of these rods to be lowered automatically in an emergency. Such an emergency shutdown is referred to as a 'scram' or 'trip'.

4.4 The point at which a self-sustaining chain reaction begins is known as criticality. Departures from this point are measured by the 'reactivity' of the reactor. This is positive if the reaction rate is increasing, negative if the reaction rate is decreasing. Because neutrons arising from fissions are fast-moving, and less likely to cause fissions than slower moving neutrons, a moderator is used to reduce the speed of neutrons produced during the fission process.

4.5 In a pressurised water reactor, water serves as both coolant and moderator. Without the moderator a chain reaction cannot be sustained and comes to a halt. As the water heats up its ability to act as a moderator is decreased, and the reactivity of the reactor will be reduced. In turn, this will lead to a decrease in the temperature of the water which will increase its effectiveness as a moderator. This self-regulating characteristic of pressurised water reactors, independently of the use of control rods, makes virtually impossible any uncontrolled, very rapid, increase in power above normal operating levels.[3] Because the same water is used as both moderator and coolant, loss of coolant shuts down the chain reaction. This provides an important fail-safe characteristic.

4.6 For United States submarine reactors it has been said that because of this self-regulating characteristic:

> the hafnium control rods aren't actually used that much, except for reactor start-up and shut-down, for adjustments to compensate for fission product poisoning and fuel burnup, and for power load changes of more than 20 per cent.[4]

4.7 Typically, pressurised water reactors use uranium as fuel. Naturally occurring uranium is made up of two isotopes, U-235 which is fissile and which constitutes about 0.7%, and U-238 which is not fissile. For use as fuel uranium may be enriched, that is, the proportion of U-235 increased by anything from a very slight amount to over 90%. Naval reactors are thought to use highly enriched fuel, while most civil pressurised water reactors use uranium enriched by less than 4%. The fuel is made up into what are called fuel elements, which may take the form of rods, pins, plates or tubes.

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[3] e.g. see New York Times, 12 April 1963, p. 11, 'Rickover Cites Safety Factors': US Atomic Energy Commission had deliberately experimented to cause a rapid uncontrolled power increase (a 'runaway power excursion'), only to have the reactor automatically shut itself down..

[4] R. O'Rourke, 'The Nuclear-Powered Submarine', Naval Forces, 1986, vol. 7(1), p. 84. See also P. Tyler, Running Critical: The Silent War, Rickover, and General Dynamics, (Harper & Row, New York, 1986), p. 40.

4.8 The fission process produces energy in the form of heat. It also produces what are called fission products and the radiation from these is also a source of heat. The heat would melt the fuel elements if they were not cooled. In a pressurised water reactor cooling is achieved by passing the water in the primary circuit around the fuel elements. Even when a reactor is shut down the fuel elements take time to cool. The fission products continue to provide a source of heat which gradually reduces as the products decay. It is essential that coolant be available to remove this decay heat if core melting is to be avoided.

4.9 The primary circuit is a closed loop with five main elements: a reactor pressure vessel, a pressure controller, primary coolant pumps, a steam generator, and the primary circuit piping. Water heated by the fission process taking place within the fuel elements passes to the steam generator. In the steam generator the primary coolant transfers its heat to the secondary circuit and then is passed back to the reactor by the main coolant pumps. The water in the primary circuit is kept at a high pressure to stop it from boiling. The pressuriser maintains and controls the system pressure.

4.10 The secondary circuit consists of steam going from the steam generator to the turbine system which provides power to the propeller shaft. This arrangement is much the same as on any ship in which steam is provided by an oil-fired boiler. There is no direct contact between the water in the primary circuit and that in the secondary circuit.

4.11 Reactor sizes can be measured by the amount of thermal power produced, expressed in millions of watts (megawatts thermal, abbreviated to Mw(t)). The extent to which it is possible to convert this thermal power to useful (e.g. electric) power is limited to about 30 to 40%. This gives an alternative measure of the size of nuclear power plants in megawatts electric - (Mw(e)).

4.12 The United States does not publicly disclose the thermal output of its Navy's reactors.[5] Published sources provide information on the shaft horsepower of naval vessels.[6] From this it is possible to calculate the size of reactor needed to produce the given shaft horsepower. Only an approximation can be made because of the need to estimate the efficiency with which the thermal power is converted to useful power. In addition, an assumption has to be made as to how much thermal power is used for purposes other than driving the propeller shaft (e.g. providing the ship's electricity).

4.13 Approximations made in this way indicate that for United States warships, each of the two reactors of a Nimitz-class aircraft carrier might be about 320 Mw(t),[7] a Los Angeles-class attack submarine's reactor at least 85 Mw(t), and each of the two

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[5] HR, Hansard, 21 October 1982, p. 2479, and 19 August 1986, p. 160.

[6] e.g. see the annual volumes of Jane's Fighting Ships, (Jane's, London).

[7] It appears that the reactors on Nimitz-class vessels provide an exceptionally large electricity generating power in addition to providing propulsion power: US Congress, Joint Committee on Atomic Energy, Naval Nuclear Propulsion Program - 1975 - Hearing, 5 March 1975, p. 6 (Admiral H. G. Rickover). The figures for total output and the amount available for electricity generation have been deleted from the transcript on the ground of security. If a high generating capacity is available, the total power output of each reactor may be considerably more than 320 Mw(t). ANSTO advised that in its safety assessment of visits by Nimitz-class vessels to Gage Roads off Fremantle, it adopted a figure of 450 Mw(t) for reactor size in order to ensure that its assessment contained a margin for safety.

reactors of the cruiser USS Truxtun at least 75 Mw(t).[8] For comparison purposes, the reactor involved in the 1979 accident at Three Mile Island had a maximum design power of 2,772 Mw(t), the reactor involved in the 1986 accident at Chernobyl was rated at 3200 Mw(t), and the proposed Sizewell B reactor subject to lengthy inquiry earlier in the 1980's is planned to produce 3411 Mw(t).[9]

Radiation Hazards

4.14 The radiation hazards created by a pressurised water reactor can be divided into two broad categories: those arising from an accident involving the reactor, and those arising from the release of radioactive wastes in liquid, gaseous or solid form. The former is potentially far more serious and was the main focus of the inquiry.[10]

4.15 The hazards immediately following a major reactor accident can in turn be divided into two categories, according to whether or not the reactor containment is breached. If the accident involves the release of fission products within the reactor compartment they will give off gamma radiation of sufficient intensity to penetrate the hull. Unless prevented by

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[8] Letter from Dr J. L. Symonds, 12 February 1987, p. 2. Prof W. J. Davis states that 'modern naval propulsion reactors range in power from 15 - 230 megawatts': submission from Prof W. J. Davis, p. 55 (Evidence, p. 502) citing A. Stirling, The Global Disposition of Nuclear Powered and Nuclear Armed Vessels Presently in Operation, (Greenpeace International, Lewes, England, 1986). The context makes it clear that Prof Davis is using megawatt thermal, not electric. The reactors on the other major category of United States nuclear powered warship to have visited Australia, the pre-Los Angeles class attack submarines, mostly are about half the power of those on the Los Angeles class, though the very early designs (now largely withdrawn from service) were even smaller. Contrast the submission from Mr R. Addison, p. 10: all visiting US nuclear powered warships except the early submarines have reactor powers greater than 100 Mw (again the context makes it clear that it is Mw thermal which is being referred to). No source is given as a basis for this claim.

[9] Nuclear Engineering International, World Nuclear Industry Handbook 1988, pp. 58, 64, and 56.

[10] See paras. 4.24-4.26.

shielding, this will pose a hazard to anyone in the immediate vicinity of the vessel. For a submarine reactor, British plans state that the area of risk from this 'gamma shine' is no more than 50 metres around the hull in air and 5 metres in water.[11]

4.16 The 'gamma shine' hazard, because of the limited area affected, is less serious than the second category. This arises if fission products are released to the atmosphere. Depending on the weather at the time and the quantity released, radioactive material could be dispersed a considerable distance from the vessel, affecting large numbers of people and property over a wide area. Therefore the possibility that this might happen is of particular concern to reactor designers and those responsible for reactor safety. It was also a central concern of that part of the Committee's inquiry that related to nuclear powered warships.

Accidental Release of Fission Products to the Atmosphere

4.17 Extensive precautions are taken in designing, constructing and operating nuclear reactors in order, first, to minimise the possibility of accidents and, secondly, to contain the fission products safely within the system should an accident occur. For the latter, what is sometimes referred to as defence-

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11. UK, Ministry of Defence, Devonport Public Safety Scheme, (1982 edn.) para. 0104. cf. ANSTO, Radiation Monitoring Handbook for Visits by Nuclear Powered Warships to Australian Ports, (ANSTO, Lucas Heights, NSW, 1985), p. 4 (Evidence, p. 298): after a reactor accident 'a severe external radiation hazard (dose rates greater than 500 mSv per hour) may exist alongside the vessel in the close vicinity, within say 30 metres, of the reactor compartment'. See also Evidence, p. 238.292: table provided by the Department of Defence indicates that at 30m from a submarine it would take 20 minutes for a person to reach the level of exposure at which evacuation should be considered (0.3 sieverts), while at 200m it would take 12 hours if (conservatively) no allowance is made for radioactive decay.

in-depth or a multi-barrier approach is employed.[12] Fuel elements are protected by cladding in order to prevent the escape of fission products.[13] The cladding may be made of alloys of zirconium, steel or other metals.[14] To cater for combat stresses, on United States warships the fuel modules are designed to survive without damage ten times more dynamic shock than commercial fuel modules.[15]

4.18 A second barrier is constituted by placing the fuel elements inside a pressure vessel, with its associated high integrity primary coolant circuit. If the cladding failed, fission products would be released to the coolant. The coolant

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[12] cf. US, H of R, Committee on Appropriations, Subcommittee on Energy and Water Development, Energy and Water Development Appropriations for 1988 - Hearings, 11 March 1987, p. 889 (Admiral K. R. McKee): for naval reactors 'we have several levels of containment'. The remainder of the explanation was deleted from the published transcript on security grounds. See also 'U. S. Navy Statement on Safety of Operations of U. S. Nuclear Powered Warships', January 1987 (Evidence, p. 238.244): specific features of the multi-barrier approach used on US warships are classified.

[13] In some US commercial reactors the fuel and fission products 'reside within a ceramic pellet which has a high melting temperature and will retain the vast majority of the fission products for essentially all operating and accident conditions': US, H of R, Committee on Science and Technology, Subcommittee on Energy Research and Production, Positive Safety Features of U. S. Nuclear Reactors: Technical Lessons Confirmed at Chernobyl - Hearing, 14 May 1986, p. 7 (Dr W. P. Chernock). These pellets reside within the cladding and therefore constitute yet another barrier to release of radiation from an accident. The Committee has no evidence as to whether these ceramic pellets are used in naval reactors.

[14] US Congress, Joint Committee on Atomic Energy, Naval Nuclear Propulsion Program - 1974 - Hearing, 25 February 1974, p. 13 (Admiral H. G. Rickover): US commercial reactors use the same basic cladding material as US naval reactors - zirconium - and it is engineered to the same quality standard.

[15] 'U. S. Navy Statement on Safety of Operations of U. S. Nuclear Powered Warships', January 1987 (Evidence, p. 238.244). See also US, Department of the Navy, Occupational Radiation Exposure from U. S. Naval Nuclear Propulsion Plants and their Support Facilities, (NT-86-2, February 1986), p. 28:

> The design conditions for reactor fuel are much more severe for warships than for commercial power reactors. As a result of being designed to withstand shock, naval reactor fuel elements retain fission products including fission gases within the fuel.

circuit is designed to contain the release.[16]

4.19 An accident sequence might start with the rupture of the primary coolant circuit. This failure of the second barrier would deprive the reactor of coolant, and is referred to as a loss of coolant accident or LOCA. The decay heat would, in the absence of any alternative supply of coolant, melt the cladding (the first barrier) and the fuel. To meet this sort of sequence a third level of barrier available to designers is to enclose the pressure vessel and the pressurised primary coolant circuit inside some sort of structure designed to contain radioactive gases, solids and liquids should the first and second barriers fail.

4.20 This structure is referred to as the containment, and is not necessarily the same thing as the biological shielding put in place to protect operating personnel from exposure to radiation. The major portion of the biological shielding for submarine reactors is concentrated around the reactor core, with the remainder built into the containment.[17] If as a result of an accident fission products escape from the core to the containment, the submarine reactor's containment will not provide sufficient shielding to reduce radiation intensities to insignificant levels.[18]

4.21 Containment must be strong enough to withstand any pressure surge ('blow-down') that would occur if the primary coolant circuit were to be breached. Because the distinction between a contained and uncontained accident is relevant to discussion later in this report, it is important to note that containment cannot be absolute. Slow leakage under maximum design pressure is inevitable due to imperfections in cable and pipe

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[16] J. E. Moore and R. Compton-Hall, Submarine Warfare: Today and Tomorrow, (Michael Joseph, London, 1986), p. 36; UK, Ministry of Defence, Liverpool Special Safety Scheme for Visits to Liverpool by Nuclear Powered Submarines, (April 1986), para. 4.

[17] UK, Ministry of Defence, Liverpool Special Safety Scheme for Visits to Liverpool by Nuclear Powered Submarines, (April 1986), para. 8.

[18] ibid.

penetrations of the containment.[19] For submarines, that part of the containment formed by the hull has to be leak-tight so as to keep water out at maximum diving depth. But the design specification allows for maximum leakage to adjoining compartments within the hull at up to 1% per day at accident pressure.[20]

4.22 A fourth level of barrier available is to take steps to prevent the containment and primary circuit being penetrated from the outside. For land-based reactors the threat for which such precautions might be required is an aircraft crashing onto the reactor. For maritime reactors ship collision is a more relevant threat.

4.23 In 1983, the American Physical Society formed a study group to carry out what was in effect a peer group review. The subject of the review was the technical base upon which rested the models of what quantities and types of radiation would be released from a severe commercial reactor accident. The quantity released is referred to as the 'source term'.[21] The study group reported:

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[19] Evidence, p. 238.291 (Department of Defence). See also UK, Ministry of Defence, Devonport Public Safety Scheme, (1982 edn.), para. 0103. For commercial land-based reactors, US Nuclear Regulatory Commission regulations specify a maximum allowable leak rate in the rgion of 0.1% to 0.5% per day: APS Study Group, 'Report to the American Physical Society of the study group on radionuclide release form severe accidents at nuclear power plants', Reviews of Modern Physics, July 1985, vol. 57(3)(part II), p. S93. The leakage rate from the Sizewell B reactor containment is designed to be less than 0.1% of containment volume per day: UK, Department of Energy, Sizewell B Public Inquiry: Report of Sir Frank Layfield, (HMSO, London, 1987), paras. 27.23 and 29.38.

[20] Evidence, p. 238.291 (Department of Defence), and p. 392 (ANSTO).

[21] cf. C. Kelber, 'The Radiological Source Term of Nuclear Power Reactors', Nuclear Safety, January-March 1986, vol. 27(1), p. 36:

> No single definition of the source term really exists. Three definitions, however, are encountered more than others: They identify the source term as the inventory (by nuclide) of radionuclides (1) available for dispersal from the containment, (2) dispersed over the area outside the containment, and (3) potentially available for release to the containment during a hypothesized accident.

The author notes that the third of these is not often used today.

> The severe accident sequences that may result in large source terms must proceed not only through core melt, but also through containment failure.[22]

This underlines the importance of adequate containment.

Release of Radioactive Wastes

4.24 According to the United States Navy, its fuel is fabricated so that fission products are not released to the primary coolant in a way that is often the case with commercial reactors.[23] As the coolant water passes through the primary circuit, however, any impurities in it become radioactive. In addition it may pick up traces of corrosion or wear products from the piping. These impurities in the coolant undergo neutron bombardment as they pass through the reactor core and constitute the main source of radioactivity in liquid waste. Radionuclides of elements such as cobalt, manganese, tungsten and iron are produced.[24]

4.25 Coolant is released from the primary coolant system mainly as a result of expansion when it is heated to reactor operating temperature. The released coolant is passed through a

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[22] APS Study Group, 'Report to the American Physical Society of the study group on radionuclide release from severe accidents at nuclear power plants', Reviews of Modern Physics, July 1985, vol. 57(3)(part II), p. S28.

[23] 'U. S. Navy Statement on the Safety of Operations of U. S. Nuclear Powered Warships', January 1987 (Evidence, pp. 238.241-42).

[24] The ways in which radioactive wastes are created, the degree of radioactivity present, the quantities released, and the places where release occurs are described in detail in annual US Navy reports on monitoring: see for example US, Department of the Navy, Environmental Monitoring and Disposal of Radioactive Wastes from U. S. Naval Nuclear-Powered Ships and their Support Facilities 1984, (NT-85-1, February 1985), pp. 3-9 (Evidence, pp. 238.298-301). The description in this section of the report is based primarily on these annual reports. For an alternative source, based on nuclear powered merchant ships, see UK, Department of Industry, Second Report on the Nuclear Ship Study, (HMSO, London, 1975), paras. 107-121.

purification system. The coolant is then held on board.[25] Eventually most of it is transferred ashore at ports outside Australia, when the vessel undergoes maintenance or repairs. If accidental discharge to the environment is ever going to occur, it is during this transfer that the risk is greatest. Some coolant is also released at sea outside Australian waters, under strict United States Navy controls.

4.26 The quantity of radionuclides in coolant will vary depending on the length of time the coolant water has been in use. Following reactor shutdown radioactive decay will reduce radioactivity. But unless there has been damage to the fuel cladding, the coolant that might be inadvertently released to the environment will not constitute more than a low-level hazard. According to a United States Navy statement, a few hours after reactor shutdown a person could drink the coolant without harmful effect.[26]

4.27 Radioactive wastes in solid form arise from maintenance and overhaul activities. According to the United States Navy, most of these activities take place in shipyards,[27] and hence are not relevant to port visits to Australia. Some solid wastes may, however, be on board as a result of activities since the vessel was last in a United States dockyard or base. Solid wastes include contaminated rags, filters, plastic bags and scrap

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[25] See also for British vessels, UK, Parliamentary Debates (Commons), 6th series, vol. 146, Written Answers, 3 February 1989, col. 448: Royal Navy submarines are equipped with retention tanks to store excess reactor coolant.

[26] 'U. S. Navy Statement on Safety of Operations of U. S. Nuclear Powered Warships', January 1987 (Evidence, p. 238.242). See also US, Department of the Navy, Environmental Monitoring and Disposal of Radioactive Wastes from U. S. Naval Nuclear-Powered Ships and their Support Facilities 1984, (NT-85-1, February 1985), pp. 4-9 (Evidence, pp. 238.298-301), for detail on the quantities and types of radionuclides present in coolant.

[27] US, Department of the Navy, Environmental Monitoring and Disposal of Radioactive Wastes from U. S. Naval Nuclear-Powered Ships and their Support Facilities 1984, (NT-85-1, February 1985), p. 13 (Evidence, p. 238.303).

materials.[28] Coolant water is filtered through ion exchange resin beds to remove suspended radionuclides. The resin then constitutes a solid waste. All solid radioactive wastes from United States Navy reactors are disposed of in the United States at burial sites.[29]

4.28 The Committee was told that the amount of gaseous radioactivity created by the normal operation of a pressurised water reactor is extremely small.[30] United States Navy reactors are designed to ensure that there are no significant discharges of radioactivity in airborne exhausts.[31]

4.29 The United States has provided an assurance in respect of its nuclear powered vessels visiting Australia that:

> No effluent or other waste will be discharged from the ship which would cause a measurable increase in the general background radioactivity of the environment.[32]

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28. See ibid., p. 11 (Evidence, p. 238.302) for the sources, etc of solid wastes, and for the strict US Navy controls in place to account for such wastes.
29. ibid., p. 11 (Evidence, p. 238.302). Prior to 1970, some disposal at sea occurred.
30. Evidence, p. 1300.51 (Department of Defence). Because the amount released is within the daily variation in the level of natural background radiation, it is not detected by monitoring in place during visits. The monitoring is set to detect only levels above the natural background level: ibid. For details of the gaseous radionuclides generated in the primary coolant of a submarine's reactor, see UK, Parliamentary Debates (Commons), 6th series, vol. 143, Written Answers, 9 December 1988, col. 345. One of these, 'argon, which accumulates over time, is routinely released when necessary, with appropriate safety precautions'.
31. US, Department of the Navy, Environmental Monitoring and Disposal of Radioactive Wastes from U. S. Naval Nuclear-Powered Ships and their Support Facilities 1984, (NT-85-1, February 1985), pp. 25-26 (Evidence, p. 238.309).
32. 'Standard Statement' by the United States Government, para. 2(a) (Evidence, p. 1078). The corresponding UK statement contains an identical assurance (Evidence, p. 1300.16). See also US, H of R, Committee on Armed Services, Subcommittee on Procurement and Military Nuclear Systems, Naval Naval Nuclear Propulsion Program - 1988 - Hearings, 26 February 1987, p. 7 (Admiral K. R. McKee): 'We do not discharge any radioactivity in port from these ships that would cause an increase in the general background levels radioactivity already there'.

Monitoring for radioactive waste discharge during visits has been carried out by Australian authorities during each visit. No discharge has ever been detected.[33]

4.30 Nonetheless the Committee considered the possibility of such discharge as part of its inquiry, as a discharge, were it to occur, might have some harmful impact.[34] Without belittling the need to have regard for the possibility for radioactive waste discharge, the Committee considers it important to maintain a sense of proportion. It is clear that the major potential source of harm lies in release of fission products, not discharge of radioactive wastes during occasional port visits.[35]

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[33] See above, para. 2.31.

[34] The most significant exposure pathway for humans is through the possibility of the concentration of contamination in the marine food chain. This possibility is much lower where only occasional port visits occur than for a homeport or base where numbers of nuclear powered vessels may be frequently present. In the latter context, individual discharges, insignificant in isolation, may have a cumulative effect leading to measurable harm.

[35] No figures appear to be available for the quantity of radioactivity present in wastes aboard an average nuclear powered vessel. However, the following figures give a rough comparison of the potential harm that might be caused by reactor accidents and waste discharges. In 1984, the 144 US nuclear powered vessels and their support facilities generated 41 curies of solid waste: USN Environmental Monitoring Report, above note 31, pp. 1 and 12 (Evidence, pp. 238.297 and 238.302). Significant radioactivity in liquid waste discharges from the same sources totalled less than 200 curies of tritium, less than 100 curies of carbon 14, and less than 0.4 and 0.002 curies at sea and within 12 miles of land respectively of other radionuclides with long half-lives (ie. more that a few hours): ibid., pp. 7, 8, 9, and 2 (Evidence, pp. 238.300, 238.301 and 238.297). In comparison, British figures state the maximum fission product release from the equivalent to the ANSTO reference accident could be 101,000 curies, and for an uncontained accident the release could reach 10,100,000 curies: UK, Parliamentary Debates (Commons), 6th series, vol. 112, Written Answers, 20 March 1987, cols. 634-35 (Evidence, p. 1300.19).

DIFFERENCES BETWEEN NAVAL AND LAND-BASED REACTORS

Introduction

4.31 In the previous chapter the lack of relevant information on naval reactors due to military secrecy was noted. Information on civil pressurised water reactors is widely available, creating the possibility that it may be used to fill gaps caused by military secrecy. It cannot be assumed that this information is always relevant to naval reactors because there are differences between the two types. Therefore it is important to indicate what the major differences are. It is convenient to begin to do this by dealing with the claims made in many submissions that naval reactors may be or are inherently less safe than their land-based counterparts.

4.32 There were a number of respects in which it was argued in submissions and by witnesses that the design, construction and operation of naval reactors may make them less safe than land-based reactors. These were:

- lack of any independent safety evaluation;
- high level of enrichment of the fuel used;
- longer life of fuel giving an increased inventory of fission products;
- design considerations, in particular the need for minimum weight and volume, leading to reduced containment, lack of an emergency core-cooling system, and a general lack of safety features;
- operational requirements, especially the need for more rapid power production and reduction;
- operator training and working conditions;
- the ageing of the United States nuclear powered fleet; and
- the risks arising from the fact that the reactor is in a warship: these include collision, grounding, capsize, and the need to store explosives and other dangerous items in the warship.

4.33 Before considering these specific points individually the Committee makes two general comments. First, it is acknowledged that the tasks required of a naval reactor differ from those of a land-based reactor designed for electricity generation, and as a result the reactor designs differ. Many submissions tended to assume that the differences meant naval reactors were less safe. The Committee was not prepared to accept this assumption. It is a question to be determined from the available information in each respect whether the designers and operators of naval reactors have overcome the different design and operating constraints imposed upon them. The remainder of this chapter addresses this question.

4.34 Secondly, on a more technical level, the Committee agrees with the following comment by Dr John Symonds on many of the submissions critical of the safety of naval nuclear power.

> It has been observed that, in some submissions, technical facts are stated with little supporting information which would assist the intelligent layman in following the line of argument satisfactorily. In other submissions, technical facts are stated, but out of context, without the precise situation mentioned and without any reference or qualifying remarks. These situations are then used to expand on the significance of the fact, leading to erroneous impressions. Neither of these approaches is truly enlightening.[36]

Lack of Independent Safety Evaluation

4.35 It has come to be accepted as important that land-based reactors should be subject to some measure of independent safety review both at the design stage and throughout their operating life.[37] With respect to naval reactors, one submission stated:

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[36] Letter from Dr J. L. Symonds, 12 February 1987, p. 1.

[37] See for example, US, H of R, Committee on Appropriations, Subcommittee on Energy and Water Development, Energy and Water Development Appropriations for 1987 - Hearings, 6 May 1986, p. 157 (Commissioner Asselstine, Nuclear Regulatory Commission): with respect to the Department of Energy's military nuclear reactors, 'there is a benefit in having an independent review to make sure that the military needs question isn't driving things to the point where safety gets sacrificed'.

> The design of nuclear power reactors for military ships and submarines is not subject to the sort of safety evaluation enforced upon civilian design, and yet the specifications and performance required by the military are often more demanding and so allow narrower safety margins. Once deployed, there exists no body with responsibility for monitoring, let alone regulating, the operation of nuclear power at sea.[38]

4.36 In contrast, the official Australian view in 1976 was that:

> nuclear warships are subject to a detailed safety assessment by recognised independent safety review authorities in the USA and UK. ... In the United States reviews are undertaken by the Reactor Licensing Division of the Nuclear Regulatory Commission (NRC) in conjunction with the Advisory Committee on Reactor Safeguards, a statutory body which advises the NRC on reactor safety. In the United Kingdom the reviews are undertaken by the Safety and Reliability Directorate of the UK Atomic Energy Authority in conjunction with the Nuclear Powered Warships Safety Committee, a civilian committee which advises the Minister of Defence independently on these matters.[39]

4.37 In response to this, Professor Jackson Davis told the Committee:

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[38] Submission from Greenpeace Australia (NSW) Ltd, p. 4.

[39] Australia, Environmental Considerations of Visits of Nuclear Powered Warships to Australia, (May 1976), p. 7 (Evidence, p. 124). Note the US 'Standard Statement' of assurances, para. 1 (Evidence, p. 1078), in which the US Government:

> certifies that reactor safety aspects of design, crew training and operating procedures of the nuclear propulsion plants of United States nuclear powered warships are reviewed by the United States Atomic Energy Commission and the Statutory Advisory Committee on Reactor Safeguards, and are as defined in officially approved manuals.

The Nuclear Regulatory Commission succeeded to some of the functions of the Atomic Energy Commission in 1974. See also 'U.S. Navy Statement on the Safety of Operations of U. S. Nuclear Powered Warships', January 1987 (Evidence, p. 238.241): 'the reactor safety aspects of design, crew training and operating procedures are reviewed by the U. S. Nuclear Regulatory Commission and the Statutory Advisory Committee on Reactor Safeguards'.

> With respect to the independent safety assessment[s] by authorities in the U.S., ... these do not in fact occur. The primary civilian nuclear regulatory authority in the U.S., the Nuclear Regulatory Commission (NRC), has no jurisdiction whatever over naval propulsion reactors, which are accountable only to classified military review.[40]

4.38 Some background is useful to understanding the present position. Statutory responsibility for United States naval reactors rests with the Naval Nuclear Propulsion Program and the Program's director.[41] This program controls all aspects of naval nuclear propulsion[42] and is the joint responsibility of the Departments of Energy and the Navy. Its director is appointed jointly by the two Departments with the approval of the President. Both Departments are required to assign to the director their responsibilities relating to, amongst other things:

> the safety of reactors and associated naval nuclear propulsion plants, and control of radiation and radioactivity associated with naval nuclear propulsion activities, including prescribing and enforcing standards and regulations for these areas as they affect the environment and the safety and health of workers, operators, and the general public.[43]

4.39 Prior to 1974, the United States Atomic Energy Commission (AEC) had responsibility for nuclear matters, including the design of naval reactors, and also had (ambiguous)

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[40] Submission from Prof W. J. Davis, p. 14 (Evidence, p. 461). See also the submission from Mr R. Bolt, p. 7 (Evidence, p. 957).

[41] The governing text is Executive Order No. 12344, 1 February 1982, (47 CFR 4979) but the Department of Defense Authorization Act 1985, s. 1634 provided that this Presidential Executive Order shall remain in force until changed by legislation. The basic structure set out in the Executive Order has existed since 1954: see R. G. Hewlett and F. Duncan, Nuclear Navy 1946-1962, (U. of Chicago, Chicago, 1974), pp. 342-45 and 362-65.

[42] This includes 'all technical aspects of U. S. policy relative to the entry of U. S. nuclear powered ships into foreign countries or waters ...': US Congress, Joint Economic Committee, Economics of Defense Policy: Adm. H. G. Rickover, 28 January 1982, Part 1, p. 91 ('A Description of the Naval Nuclear Propulsion Program, January 31, 1982').

[43] Executive Order 12344, 1 February 1982, (47 CFR 4979), ss. 5(c) and 8(a).

statutory responsibility for their safe operation.[44] The working arrangement arrived at was that the AEC would design naval reactors, have them built, and transfer them to the Navy.[45] The Navy would be responsible for the safe operation of the reactors, including the establishment and enforcement of its own safety standards. The AEC would, on request from the Navy, evaluate operating procedures and general safety standards. The Navy undertook to make available to the AEC the safety and security standards it established and all pertinent data on operations under these standards.[46]

4.40 The functions of the AEC were split in 1974. Broadly, its regulatory functions went to the newly created Nuclear Regulatory Commission (NRC). Its design, construction and nuclear energy promotion functions eventually went to the Department of Energy (DOE), which was created in 1977. The AEC's evaluation and advisory role in regard to naval reactors has passed to the NRC. A 1983 description of the Naval Nuclear Propulsion Program stated:

> Although the activities of the program are not subject to licensing by the Nuclear Regulatory Commission, the Director obtains comments from the Nuclear Regulatory Commission and Advisory Committee on Reactor Safeguards on all new shipboard and prototype reactor plant designs and on other nuclear safety matters related to

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[44] See R. G. Hewlett and F. Duncan, Nuclear Navy 1946-1962, (U. of Chicago, Chicago, 1974), pp. 362-65 for details. The relevant legislation was the Atomic Energy Act 1954, ss. 91(b) and 161(b).

[45] ibid., p. 343.

[46] Pursuant to a Presidential directive of 23 September 1961, 'any disagreement as to safety aspects, arising as a result of comment by the AEC which cannot be directly resolved by the two agencies will be referred to the President for decision'. The terms of the directive are set out in 'Derivation and Execution of Responsibilities of the Director, Naval Nuclear Propulsion Program', 24 May 1979, para. II(C) incorporated in US, H of R, Committee on Science and Technology, Subcommittee on Energy Research and Production, Nuclear Powerplant Safety Systems, 24 May 1979, p. 981.

program work as he deems appropriate.[47]

4.41 A formal United States Navy Instruction in 1978 made the Commander, Naval Sea Systems Command, in cooperation with the Director, Division of Naval Reactors of the DOE, responsible for, among other matters related to nuclear safety:

> Submitting a Safety Analysis Report on each new reactor type to the Nuclear Regulatory Commission for review and comment.
>
> Making available to the NRC and the DOE, on a continuing basis, information on any changes in design or data on operations in which reactor safety is involved.
>
> Through the Director, Division of Naval Reactors, DOE, keeping the NRC and Advisory Committee on Reactor Safeguards properly informed with regard to naval nuclear propulsion matters.[48]

4.42 Statements that independent review occurs do not, as far as the Committee can determine, mean that the independent review bodies have statutory power to initiate any review or enforce

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[47] US, H of R, Committee on Armed Services, Subcommittee on Procurement and Military Nuclear Systems, Naval Nuclear Propulsion Program - 1983 - Hearing on H. R. 2496, 4 March 1983, Appendix C, p. 53 ('A Description of the Naval Nuclear Propulsion Program, January 1983'). It appears that the position has not altered since 1983: see for example US, Senate, Committee on Armed Services, Subcommittee on Strategic Forces and Nuclear Deterrence, Safety Oversight for Department of Energy Nuclear Facilities - Hearings, 22 October 1987, p. 111 (J. D. Peach, General Accounting Office): 'NRC also reviews the designs of DOE's naval reactors'.

[48] 'Derivation and Execution of Responsibilities of the Director, Naval Nuclear Propulsion Program', 24 May 1979, paras. II(D)(4), (5) and (10) incorporated in US, H of R, Committee on Science and Technology, Subcommittee on Energy Research and Production, Nuclear Powerplant Safety Systems, 24 May 1979, p. 982. It is unclear from this source if the parts quoted are a directly from, or merely a paraphrase of, OPNAVINST C3000.5C of 19 June 1978. This 1978 USN instruction replaced earlier versions, which extend back to at least 1958. The Committee is not aware if the 1978 version is still the current version. The Director of the Division of Naval Reactors, DOE, referred to in the text and quote also holds the position of Director, Naval Nuclear Propulsion Program, described in para. 4.38 above.

sanctions.[49] Nonetheless, review does occur, although the results of reviews that have taken place since 1974 are not publicly available as far as the research of the Committee's staff can discover.[50] The exact subjects reviewed are similarly difficult

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[49] cf. the exchange in US, H of R, Committee on Science and Technology, Subcommittee on Energy Research and Production, Nuclear Powerplant Safety Systems, 24 May 1979, p. 1072:

> Mr Anthony: ... as I understand it from your testimony... NRC does review the design of the naval plant.
> Admiral Rickover: Yes, sir.
> Mr Anthony: They issue some type of authorization or permit based on their approval of the design?
> Admiral Rickover: Yes, sir. They issue a formal report not actually a permit or a license.
> Mr Anthony: What has been your experience with the NRC in reviewing the extensive training programs that you have indicated by your testimony that you have instituted in the naval program and do they monitor it on a continuing basis?
> Admiral Rickover: Well, the NRC conducts reviews, they do not monitor on a continuous basis.
> Mr Anthony: So NRC does not monitor your training program on a continual basis, so it is really left up to you --
> Admiral Rickover: They pretty well know, they are quite familiar with our training program and they know over a period of years how we operate and we certainly need no urging to continue this.

[50] e.g. see US, Senate, Committee on Governmental Affairs, Reactor Safety Issues at Department of Energy Facilities - Hearing, 12 March 1987, pp. 34-35 (F. J. Remick, Vice Chairman ACRS): since 1974, the ACRS has 'participated in the review of some DOE facilities and activities, including, for example, ... the Naval Reactors Program'. The aspects reviewed are not stated. See also US, Senate, Committee on Armed Services, Subcommittee on Strategic Forces and Nuclear Deterrence, Safety Oversight for Department of Energy Nuclear Facilities - Hearings, 22 October 1987, p. 111 (J. D. Peach, General Accounting Office): the NRC reviews the designs of DOE's naval reactors. NRC Budget Estimates include under the heading 'Nuclear Reactor Regulation Programs' an item called 'Other Reviews'. This item includes 'safety reviews of projects covered by the Department of Defense and the Department of Energy': NRC, Budget Estimates FYs 1988-1989: Appropriation: Salaries and Expenses, (NUREG-1100, vol. 3, January 1987), p. 22. But no details of the topics to be reviewed are provided.

to determine, at least from this distance.[51] The Australian Department of Defence had no better information that it could provide to the Committee.[52]

4.43 The position appears to be similar for British naval reactors. The Australian Department of Defence informed the Committee:

> Since reactors which are part of a form of transport are specifically excluded from the UK Nuclear Installations Act, the UK Nuclear Installations Inspectorate does not have powers equivalent to those which require it to audit or inspect the safety arrangements for civil power reactors. Internal Royal Navy safety audits are therefore conducted to maintain comparable standards.[53]

In addition, the Royal Navy as a matter of practice refers

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[51] One subject reviewed by the ACRS was the safety of the prototype and production versions of the S8G reactor used to power Ohio-class ballistic missile submarines (a submarine type that does not visit Australian ports), and in 1978 the ACRS concurred in the reactors' operation: see 'Derivation and Execution of Responsibilities of the Director, Naval Nuclear Propulsion Program', 24 May 1979, para. IV(A) incorporated in US, H of R, Committee on Science and Technology, Subcommittee on Energy Research and Production, Nuclear Powerplant Safety Systems, 24 May 1979, p. 984. The NRC has reviewed the Navy's standard instructions defining radioactive waste release limits and procedures to be used by its nuclear powered vessels: US, Department of the Navy, Environmental Monitoring and Disposal of Radioactive Wastes from U. S. Naval Nuclear-Powered Ships and their Support Facilities 1986, (NT-87-1, February 1987), p. 3.

[52] In response to the Committee's request for further information, the Department replied (Evidence, p. 1300.50):

> Information is available from unclassified United States documents to the effect that procedures exist for the NRC to review the safety of United States nuclear powered warships. At the time the ... document [cited at para. 4.36 above] was written ANSTO received information from confidential sources that such reviews did take place. ANSTO is not able to provide documentary evidence of this and does not have details of the procedures or the requirements placed upon the parties to these procedures.

[53] 'UK Nuclear Powered Warships Safety Procedures', (Paper prepared for the Committee by the Australian Department of Defence, July 1988), para. 11 (Evidence, p. 1300.15).

matters relating to nuclear safety to independent assessors.[54]

4.44 It does not automatically follow, however, that lack of legally enforceable civilian review of naval nuclear safety means that naval reactors are less safe than commercial ones. It is clear from abundant testimony presented to United States Congressional committees over a long period of time that safety is taken very seriously within the Naval Nuclear Propulsion Program.[55] The Program operates in many respects independently of those having line responsibility for the operation of Navy

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[54] ibid., para. 4 (Evidence, p. 1300.13). In its 'Standard Statement', para. 1 (Evidence, p. 1300.16), the UK Government certifies that the safety aspects of its nuclear powered warships 'are reviewed by the UK Nuclear Powered Warships Safety Committee and other appropriate UK authorities'. See also 'SRD celebrates quarter century', Atom, 1984, no. 335, p. 30: an independent safety unit within the UK Atomic Energy Authority, the Safety and Reliability Directorate (SRD), has among its 'current important projects' that of 'providing nuclear safety advice to the Royal Navy'. The SRD also acts as advisor to the consortium which builds reactors for the Royal Navy: D. Fishlock, 'Navy lifts veil on PWR research', Nature, 2 March 1978, vol. 272, p. 4. For further indication of the SRD's role in relation to the Royal Navy's nuclear program, see for example United Kingdom Atomic Energy Authority, Annual Report 1986-87, p. 42. Note also Vice Admiral Sir Ted Horlick RN, 'Submarine Propulsion in the Royal Navy', Proceedings of Institution of Mechanical Engineers, 1982, vol. 196, p. 76: ways in which the Royal Navy has met 'the steadily increasing demands of the nuclear safety authorities for demonstrable validation of safety'; and R. Pengelley, 'Stealth in practice: the Royal Navy's Trafalgar-class submarines', International Defense Review, 1989, vol. 22(1), p. 30: the crews' safety and operating logs 'are subject to scrutiny by both civilian and naval shore-based agencies'.

[55] e.g. see US, H of R, Committee on Science and Technology, Subcommittee on Energy Research and Production, Nuclear Powerplant Safety Systems - Hearings, 24 May 1979, pp. 915-17 (Admiral H. G. Rickover) for a description of some of the examinations, inspections and incident reporting that occur with respect to USN reactors.

vessels.[56] To this extent the Program acts as an independent inspector and watch-dog on safety matters.[57]

4.45 The United States Department of Energy operates non-naval reactors substantially free of independent scrutiny. The Committee notes that the safety record with respect to these has come under considerable criticism recently.[58] One solution proposed by the critics is to bring Department of Energy reactors under the statutory oversight of the Nuclear Regulatory

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[56] e.g. ibid., pp. 1046-47 and 1049-50 (Admiral H. G. Rickover). See also US Congress, Joint Committee on Atomic Energy, Subcommittee on Legislation, Naval Nuclear Propulsion Program - 1975 - Hearing, 5 March 1975, p. 26 (Admiral H. G. Rickover): in the Navy program

> we have inspection boards that make very thorough inspections of all our nuclear-powered ships, spending several days at a time for each ship. I have my own representatives at every shipyard working on nuclear-powered ships and at every prototype reactor site who regularly inspect those operations. They report directly to me what is going on.

The position appears to be broadly similar with respect to British submarines: 'UK Nuclear Powered Warships Safety Procedures', (Paper prepared for the Committee by the Australian Department of Defence), para. 4 (Evidence, p. 1300.13).

[57] See Lt R. E. Chatham USN, 'Leadership and Nuclear Power', US Naval Institute, Proceedings, July 1978, pp. 78-82 for a critique of the way responsibilities for nuclear safety are carried out in operational US nuclear powered warships. The author alleged, in part, that there was excessive regard for reactor safety; the watch-dog activities of the Program interfered with the ordinary chain of command; safety exams and inspections of crews were excessively demanding and time consuming; there appeared to be a policy for reactor crews 'that no one should be permitted to know that he has done well: hubris causes mistakes' (p. 81); and the constant safety-checking of crew actions led to a perception by crew members that they could not be trusted to do things properly on their own. This critique generated a large correspondence from other officers serving, or who had served, in US nuclear powered warships: see the following 6 issues of the Proceedings. Some agreed with the critique, others strongly disagreed and regarded the steps taken as necessary to ensure reactor safety and reliability. The correspondence as a whole provides many details of the checking, inspecting and examining that occurs with regard to the day-to-day operation of USN reactors. See also Captain F. G. Satterthwaite USNR, 'Manning Nuclear Submarines', US Naval Institute, Proceedings, February 1985, p. 65: the frequent safety inspections and the commitment to zero defects and no nuclear safety violations can result in low morale and high operational costs on USN nuclear vessels.

[58] e.g. US, Senate, Committee on Governmental Affairs, Report on the Nuclear Protections and Safety Act of 1987, 24 September 1987, pp. 3-8.

Commission. But, as far as the Committee can discover, the criticism does not extend to reactors on Navy vessels.[59]

4.46 The Committee does not attach great significance to the fact that there is apparently no legally enforceable civilian oversight of the United States Naval Nuclear Propulsion Program with respect to technical safety matters. The Committee notes that this position is not unique. Legally enforceable independent civilian monitoring of the safety aspects of conventional warships is not the norm. Moreover, it is clear that prior to 1974 significant civilian oversight occurred in practice.[60] The evidence indicates that since then there has not been any reduction in concern with naval reactor safety in the United States.[61]

Highly Enriched Fuel

4.47 Two submissions claimed that plutonium was used as a fuel in naval reactors.[62] The Committee is not aware of any authoritative evidence that plutonium fuel is used in the United States Navy's reactors. All the indications of which the

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[59] e.g. US, Senate, Committee on Armed Services, Subcommittee on Strategic Forces and Nuclear Deterrence, Safety Oversight for Department of Energy Nuclear Facilities - Hearings, 27 October 1987, p. 191 (J. Salgado, Department of Energy).

[60] For extracts from correspondence from the Advisory Committee on Reactor Safeguards (ACRS) and others relating to oversight in the late 1950's, see US Congress, Joint Committee on Atomic Energy, Naval Nuclear Reactor Program and Polaris Missile System - Hearing, 9 April 1960, pp. 10-18 and 37. Further examples of correspondence and of extracts from the minutes of the ACRS relating to oversight of naval reactor safety are included in US Congress, Joint Committee on Atomic Energy, Tour of the USS "Enterprise" and Report on Joint AEC-Naval Reactor Program, 31 March 1962, pp. 40-43.

[61] In addition to sources already cited, see para. 4.133.

[62] Submissions from Assoc Prof P. Jennings, p. 1 (ships 'use highly-enriched plutonium fuel'); Mr R. Addison, p. 4 (evidence that ships 'are now using metallic plutonium fuel rather than metallic uranium').

Committee is aware suggest that uranium is used,[63] and that it is enriched to more than 90% uranium-235.[64] The Committee has adopted this assumption.

4.48 Some submissions remarked that the uranium used in naval reactors is much more highly enriched than that used in land-based reactors but did not explain the relevance of this to the inquiry.[65] The advantage of using highly-enriched fuel is that it enables a more compact reactor to deliver the same power as a less compact one using fuel enriched to the commercial level of less than 4%. As noted later in this chapter, compactness in a naval reactor facilitates safer containment.

4.49 A high level of enrichment does not affect the inventory of radionuclides available for release in the event of an accident. This fission product inventory depends on the energy output of the reactor.[66] A 100 Mw(t) reactor with fuel enriched to 3 per cent uranium-235 would not have a significantly different radionuclide inventory from a 100 Mw(t) reactor using fuel enriched to 95 per cent.

4.50 The only explicitly stated safety allegation relating to the use of highly enriched fuel was that it created a risk of an uncontrolled nuclear reaction:

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[63] e.g. see US, H of R, Committee on Merchant Marine and Fisheries, Disposal of Decommissioned Nuclear Submarines - Hearing, 19 October 1982, pp. 8, 9 (Mr C. H. Schmitt, Naval Nuclear Propulsion Program); US, H of R, Committee on Appropriations, Subcommittee on Energy and Water Development, Energy and Water Development Appropriations for 1982 - Hearings, 4 March 1981, pp. 554-55 (Admiral H. G. Rickover); Department of Energy National Security and Military Applications of Nuclear Energy Authorization Act 1988 (PL100-180, Division C, Title 1), s. 3111(2)(A), (appropriation of $141.5 m 'for uranium enrichment for naval reactors' for FY 1988).

[64] e.g. see letter from Dr J. L. Symonds, 12 February 1987, p. 1; T. B. Cochran and others, Nuclear Weapons Databook, Volume II: U. S. Nuclear Warhead Production, (Ballinger, Cambridge, Mass., 1987), p. 71 (enriched to 97.3% U-235).

[65] Submissions by Inner City People for Nuclear Disarmament, p. 1; Illawarra People for Nuclear Disarmament, p. 4; Friends of the Earth, p. 1.

[66] Submission from Prof W. J. Davis, p. 55 (Evidence, p. 502).

> If a large mass of fuel melts and forms a pool, an uncontrollable chain reaction may occur. Because the fuel is the same material used in bombs, a sufficiently large mass may cause a 'fizzle' explosion.[67]

4.51 Dr Symonds informed the Committee:

> While it is true that a bomb can be made with as little as five kilograms of uranium-235 ... this quantity of material is only significant as an explosive device if it is highly compressed first to produce a very super-critical nuclear condition and neutrons inserted at the correct instant in the compression. The potential of an energy release through a nuclear excursion in a molten aggregate of highly enriched nuclear fuel has been known for a considerable time. For a significant explosion to occur, the configuration of the molten mass must be such that it forms into a shape which will produce a supercritical nuclear condition. Experiments with highly enriched metal fuel have given guidance on the extent of the energy produced. Very conservative estimates suggest that the explosion might reach the order of the equivalent of hundreds of pounds of TNT.
>
> Designs have been put forward to ensure that the molten fuel never aggregates into, say, a near spherical shape which would increase the probability of a secondary criticality accident.[68]

A similar view was put to the Committee by the Department of Defence.[69]

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[67] Submission from Mr R. Addison, p. 6.

[68] Letter from Dr J. L. Symonds, 12 February 1987, p. 7.

[69] Evidence, p. 1300.53 (Department of Defence):

> We do not have access to sufficiently detailed information on core enrichment levels, core mass and composition or below-core geometrical design for naval propulsion reactors to assess that re-criticality [ie. formation of a critical mass] would be impossible following a core melt. However, in view of the long-standing recognition of the theoretical possibility of such events, it seems hardly credible that design provisions would not have been made to ensure sub-criticality of any fuel re-assembly.

4.52 A United States Navy report states with respect to its naval reactors: 'the reactor core is so designed that it is physically impossible for it to explode like a bomb'.[70] The Committee has no reason to interpret this narrowly so as to exclude a nuclear 'fizzle' from the meaning of 'explode like a bomb'.

4.53 A further possible significance of the use of highly enriched fuel relates to its effect on cooling requirements. Although not set out clearly in any submission, the Committee assumed that the concern was that the use of enriched fuel leads to higher power-density.[71] This enables production of the same amount of heat in a smaller space and thereby makes constant provision of adequate cooling more critical. Put simply, if there is a loss of coolant the fuel will melt more quickly in a high power-density reactor than in a low density one.[72]

4.54 As explained earlier in this chapter, the melting of fuel breaches the first barrier that is designed to prevent the release of harmful radioactivity to the environment. The most likely cause of the loss of coolant would be the failure of the second barrier, the pressurised primary coolant circuit. Thus the

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[70] US, Department of the Navy, Environmental Monitoring and Disposal of of Radioactive Wastes from U. S. Naval Nuclear-Powered Ships and their Support Facilities 1984, (NT-85-1, February 1985), p. 9 (Evidence, p. 238. 301. For a similar statement in 1963 by the head of the US naval reactors program, Admiral H. G. Rickover, see 'Rickover Cites Safety Factors', New York Times, 12 April 1963, p. 11. See also UK, Ministry of Defence, Liverpool Special Safety Scheme for Visits to Liverpool by Nuclear Powered Submarines, (April 1986), para. 10: 'it is impossible for a reactor accident to result in an atomic-bomb type explosion ...'. Dr R. Webb, in a letter to Senator Vallentine, raised the possiblity of an atom bomb-type explosion in a US naval reactor: see Evidence, p. 1364. But he also claimed the US Government had never stated that this could not occur (ibid.), apparently being unaware of the sources cited above, and many other US Government documents containing similar statements.

[71] 'Power-density' refers to the fission rate per unit volume of core.

[72] Evidence, p. 438 (ANSTO). In response to a further question, the Committee was told that the time available for response to loss of coolant could only be properly determined by detailed analysis of the reactor design: Evidence, p. 1300.53 (Department of Defence).

scenario would lead to reliance on the third barrier, the containment, more quickly than in a low power-density reactor.

4.55 The Australian Nuclear Science and Technology Organisation (ANSTO) suggested that this did not increase the hazard to the public:

> although the fuel would melt more rapidly, the escape of fission products to the environment would be governed by the pressure rise in the containment. Since the heat capacity of the fuel is small compared with that of the total system, the rate of this pressure rise is almost independent of the enrichment level of the fuel. Thus the hazard posed to the public from a meltdown accident is not related to the enrichment level.[73]

4.56 The Committee accepts that, from the point of view of containment integrity, the rapidity of the fuel melt may not matter. However, the speed of the fuel melt does have relevance to the possibility of automatic or manual intervention to prevent the onset or continuation of fuel melting. In simple terms, it reduces the possibility of preserving the first barrier. The more that the first barrier remains intact, the less the third barrier needs to be relied upon. In this sense the use of highly enriched fuel weakens the defence-in-depth against accidental release to the environment. This has, however, been taken into account in assessing accident likelihood.[74]

4.57 The Committee asked the Department of Defence and ANSTO if there were any other respects in which the use of highly enriched fuel creates a greater safety hazard. The response stated that there were none that were relevant in the context of

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[73] Evidence, p. 438 (ANSTO).

[74] See below, para. 7.15 where it is indicated that in its assessment of accident likelihood, ANSTO have made the very conservative assumption that no automatic or manual intervention will occur once an accident sequence has commenced.

port visits to Australia.[75]

Higher Inventory of Fission Products

4.58 The inventory of fission products available for release from a given quantity of fuel in a reactor depends, among other things, on the period for which the fuel has been irradiated. This in turn will depend on the time between refuelling, and it was pointed out in submissions that naval reactors have longer refuelling cycles than commercial land-based ones.[76] The reactors on United States aircraft carriers now have to be refuelled only once every 15 years, when the whole core is replaced.[77] In contrast, commercial reactors tend to have part of their fuel replaced each year because it is more economical and because there is no need to run for long periods without refuelling.[78]

4.59 The Committee agrees that the longer refuelling cycle used by the United States Navy means that the inventory of fission products available for release is greater than for a

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[75] Evidence, p. 1300.53 (Department of Defence). Hazards not relevant to the Australian context relate to fuel handling and storage: ibid.

[76] Submissions from Mr R. Addison, p. 4; Prof W. J. Davis, p. 56 (Evidence, p. 503).

[77] US, Departments of Defense and Energy, A Review of the United States Naval Nuclear Propulsion Program, (June 1986), p. 22. See also US, H of R, Committee on Armed Services, Subcommittees on Procurement and Military Nuclear Systems, and on Seapower and Strategic and Critical Materials, Naval Nuclear Propulsion Program - 1979 - Hearing on H. R. 2603, 1 March 1979, p. 51 (Admiral H. G. Rickover): ' a modern [reactor] core is capable of propelling nuclear ships for 10 to 15 years and over 400,000 miles'; US Congress, Joint Committee on Atomic Energy, Naval Nuclear Propulsion Program - 1974 - Hearing, 25 February 1974, p. 11 (Admiral H. G. Rickover): 'the liftime of cores we are installing in nearly all submarines now is 10 years, and in some surface ships it is 13 years'. The operating profiles, the details of reactor design, the fuel configurations and the fuel usage rate all vary between the four different classes of nuclear powered vessels (ie. ballistic missile submarines, attack submarines, aircraft carriers and cruisers). Hence the possiblity exists of variation in core life as between classes.

[78] See for example F. J. Rahn and others, A Guide to Nuclear Power Technology, (Wiley, New York, 1984) p. 461: 'Refueling operations, in current LWRs, take place annually ... . Only partial fuel replacement takes place, typically one-third or one-fourth of the core.'

reactor of equivalent output using a typical commercial refuelling cycle. This does not affect the likelihood of an accident. But it is important that this difference be taken into account when calculating the consequences of an accident involving breach of containment. The extent to which calculation of the current reference accident does this is considered in chapter 7.

Lack of Adequate Containment

4.60 The authors of many submissions put the view that the need to integrate a reactor into a ship's hull would result in a loss of safety. The authors of some submissions took the view that because civilian power plants can be built without the same need to limit weight, size or shape, they are potentially much safer than naval reactors.[79] A number of ways in which this could be the case were put forward.

4.61 The single most common and possibly the most serious allegation made about naval reactors was that their containment is inferior to that of land-based reactors.[80] The seriousness of this allegation results from the fact that it casts doubts on the reference accident used for emergency planning purposes. This reference accident assumes a contained full-core meltdown. A breach of containment would result in consequences which are significantly greater than those used for emergency planning purposes.

4.62 The authors of submissions were not in a position to provide any details of naval reactor containment. Claims of lesser safety were based in part on the absence of any visible substitute on ships for the large concrete structures that

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[79] e.g. see submissions from Assoc Prof P. Jennings, p. 1; Mr R. Addison, p. 4; the Manly Warringah Peace Movement, p. 1.

[80] Submissions from Assoc Prof P. Jennings, p. 1; Albany Peace Group, p. 3; Mr R. Addison, p. 4; Derwent Valley Peace Group, p. 2; Mr R. Bolt, p. 7 (Evidence, p. 957); Scientists Against Nuclear Arms (Tas), p. 3 (Evidence, p. 822); People for Nuclear Disarmament, p. 3 (Evidence, p. 1305). See also Evidence, p. 980 (Mr R. Bolt).

feature in photographs of nuclear power stations. Assumptions were made that weight and dimension constraints on ship designers would result in less safe solutions to the need for containment. The Committee itself could obtain only limited information on naval containment.

4.63 On United States submarines, the items from which high levels of radiation are emitted during reactor operation (reactor vessel, primary coolant circuit, the steam generator) are all contained in the reactor compartment. This is formed by a section of the steel cylinder of the hull bounded on either end by thick steel bulkheads, which on the older United States submarines measures 30 feet (9.15 m) by 30 feet and weighs about 900 tons (816 t).[81] On British submarines the compartments on either side of the reactor compartment are designed to act as further containment.[82] The pressurised hull obviously is designed to be strong enough to resist the pressures encountered during deep dives.[83] It also is designed to resist depth charge attacks and other combat stresses: very high integrity is one of the main design objectives.[84]

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[81] See the description and diagram provided by a representative of the Naval Nuclear Propulsion Program in US, H of R, Committee on Merchant Marine and Fisheries, Disposal of Decommissioned Nuclear Submarines - Hearing, 19 October 1982, pp. 16 and 26. See also the diagram in N. Friedman, Submarine Design and Development, (Conway, London, 1984), p. 135. The new naval submarine reactor being developed in Britain is contained, with the steam generator and associated equipment, in a reactor compartment 10 m in diameter and 23 m long, weighing about 1300 t: Nuclear Engineering International, July 1985, p. 3.

[82] UK, Ministry of Defence, Liverpool Special Safety Scheme for Visits to Liverpool by Nuclear Powered Submarines, (April 1986), para. 7. See also J. E. Moore and R. Compton-Hall, Submarine Warfare: Today and Tomorrow, (Michael Joseph, London, 1986), p. 37. The point referred to is stated in general terms, but the authors have close links to the British Navy and it may be that their point applies only to submarines of that Navy.

[83] Evidence, p. 1300.52 (Department of Defence):

> In the case of a submarine, ... the hull would be required to remain leaktight during normal operations at pressure differentials greater than would occur as a result of the reference accident.

[84] US, H of R, Committee on Merchant Marine and Fisheries, Disposal of Decommissioned Nuclear Submarines - Hearing, 19 October 1982, p. 22 (C. H. Schmitt, Naval Nuclear Propulsion Program).

4.64 In response to a question from the Committee, ANSTO stated:

> The primary containment design specification allows for internal pressures due both to complete blowdown of the reactor primary coolant circuit, and to the hydrogen which might be generated by metal-water reactions under accident conditions.[85]

4.65 ANSTO also told the Committee that the reactor containment on a submarine 'is designed for the order of two megapascals internal pressure'.[86] This pressure is over four times the design pressure of the containment for the reactor involved in the 1979 Three Mile Island accident.[87] Marine reactor containments generally are designed to withstand greater pressure than those of land-based reactors, due to the more compact construction of the former.[88]

4.66 The Committee was able to confirm the basic features of containment design with respect to British submarines. The Liverpool safety scheme states: 'the reactor compartment is designed and constructed to provide primary containment and to withstand the severe pressure rises associated with the Maximum Design Accident'.[89] This accident is one involving a large coolant leak leading to core melting. The Committee has no reason

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85. Evidence, p. 443.462.
86. Evidence, p. 372.
87. Nuclear Engineering International, World Nuclear Industry Handbook 1988, p. 79 gives the containment design pressure as 4.9 kg/sq cm, which equals about 480 kilopascals.
88. W. Vinck and others, 'Technical Safety Problems in Nuclear Naval Propulsion as Related to Port Entry Considerations' in International Atomic Energy Agency and others, Proceedings of the Symposium on Nuclear Ships, Hamburg, 10-15 May 1971, (GKSS, Hamburg, 1971), p. 149. In simple terms, a containment is a box surrounding another box which is under pressure. The closer the outer box is to the inner box, the stronger it needs to be to contain the effects of a failure of the inner box.
89. UK, Ministry of Defence, Liverpool Special Safety Scheme for Visits to Liverpool by Nuclear Powered Submarines, (April 1986), para. 6.

to consider the containment has been designed to any lower specification on United States submarines. This design specification is the same as that for land-based commercial reactors.[90]

4.67 For nuclear powered surface ships the arrangement of the reactor compartment is said to be similar to that of submarines, except that the hull does not form part of the containment. The reactor compartment is a box-like structure designed to resist collision damage, action damage, and blowdown pressure following a loss of coolant accident.[91] Reactor compartments are located within the most protected places in the ship.[92]

4.68 There is no reason to expect surface warship containment to be designed to any lesser design specification than that of submarines. There is ample evidence that design specification of this type can be met with respect to nuclear powered merchant ships of various sizes, whatever other difficulties those ships

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[90] F. J. Rahn and others, A Guide to Nuclear Power Technology, (Wiley, New York, 1984) p. 367:

> The containment building is designed to contain the energy and materials released in a complete, double-ended break of the largest pipe of the reactor coolant system and to withstand the impact of internally generated missiles.

[91] Cdr M. K. Gahan, 'Nuclear Propulsion Systems - Technical Aspects', (Paper prepared for the Committee by the Department of Defence, February 1987), p. 3 (Evidence, p. 1300.34). The Committee lacks information on whether, as on British submarines, compartments adjacent to the reactor containment on surface warships provide secondary containment. For nuclear powered merchant ships, see W. Vinck and others, 'Technical Safety Problems in Nuclear Naval Propulsion as Related to Port Entry Considerations' in International Atomic Energy Agency and others, Proceedings of the Symposium on Nuclear Ships, Hamburg, 10-15 May 1971, (GKSS, Hamburg, 1971), pp. 149-50: 'the containments of the NS Savannah and the NS Otto Hahn are surrounded by an additional almost gas-tight reactor compartment which is vented through an elaborate filtering system'.

[92] 'U. S. Navy Statement on Safety of Operations of U. S. Nuclear Powered Warships', January 1987 (Evidence, p. 238.244).

may have experienced.[93] On surface ships, there is no counterpart to the strong pressure hull which is used on submarines to form part of the containment. But this is offset by the fact that the space and weight constraints are less severe on surface ships.[94]

4.69 Any comparison of land-based and naval reactor containment must have regard to the much lower power and smaller size of the naval reactors. The difference in power and the use of highly enriched fuel in naval reactors have already been noted. These factors enable naval reactors to be much smaller than the typical land-based reactors which seem to have been used in a number of submissions for comparative purposes.

4.70 While this does not mean that naval reactor containment can be flimsy, adequate containment of a naval reactor is clearly more feasible the smaller the reactor is. Dr Symonds told the Committee that a naval reactor producing about 100 Mw(t) would contain about 150-200 kg of enriched uranium in a pressure vessel

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[93] See for example the following papers in Organisation for Economic Co-operation and Development, Nuclear Energy Agency, Symposium on the Safety of Nuclear Ships: Proceedings, Hamburg, 5-9 December 1977, (OECD, Paris, 1978): M. Kawasaki and S. Yaguchi, 'Safety Studies on LOCA for N. S. Mutsu', pp. 202-05; K. Schmidt and others, 'Engineered Safety Equipment and Safety Analysis of NCS 80', pp. 268-70; N. Battle and R. V. Killingley, 'The Influence of Safety and Licensing Requirements on the Selecetion of a Reactor Plant for an Icebreaker', p. 667 and 672. See also D. W. Brideweser, 'The Path Ahead for Nuclear Merchant Ships', Society of Naval Architects and Marine Engineers: Transactions, 1966, vol. 74, p. 73 (NS Savannah, after modifications, had a containment leak rate of 0.7% per day at 60 psig, while its approval specification permitted 1.2%); R. F. Pocock, Nuclear Ship Propulsion, (Ian Allan, London, 1970), pp. 79 (NS Savannah), 147-48 (NS Otto Hahn).

[94] For the way in which the US nuclear powered Nimitz-class aircraft carriers have been designed to withstand direct hits from conventional bombs, missiles and torpedoes, and the blast and shock effects of near misses by nuclear weapons see US, H of R, Committee on Armed Services, Subcommittee No. 3, Hearings on Nuclear Aircraft Carrier CVN-70, 27 March 1972, pp. 11,439-44 (Rear Admiral I. Linder). This illustrates the ways in which weight and cost penalties have been accepted in order to ensure safety and survivability.

of roughly one metre internal diameter and four metres high.[95] A scale diagram supplied by the United States Navy to Congress indicates a submarine's reactor pressure vessel is about 4.5 metres high, while that of a Nimitz-class aircraft carrier is nearly 10 metres high.[96]

4.71 For comparison, the pressurised water reactor involved in the 1979 Three Mile Island accident had an initial fuel inventory of 82.8 tonnes of 2.98% enriched uranium in fuel elements whose active length was 3.64 metres, supported in a pressure vessel whose height was 12.4 metres, internal diameter 4.8 metres, and wall thickness 214 mm.[97]

4.72 Additionally, Commander Gahan, RAN informed the Committee of other reasons why naval reactor containments could be made proportionally smaller than land-based reactor containments without loss of safety:

> Part of the volume of the commercial plant is taken up with pools of heavy water used to store fuel and irradiated reactor components. Additionally, heavy shielding required during fuel handling occupies a significant volume. These are not features of a Naval ship installation, since the reactor remains sealed

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[95] Letter from Dr J. L. Symonds, 12 February 1987, pp. 3-4. On fuel quantities, see also T. B. Cochran and others, Nuclear Weapons Databook, Volume II: U. S. Nuclear Warhead Production, (Ballinger, Cambridge, Mass., 1987), p. 71: 'modern cores average about 200 kg' of highly enriched uranium each. Contrast the submission from Prof W. J. Davis, p. 56 (Evidence, p. 503), where, using the same basic data as Cochran, an average of 500 kg per core is calculated. This is done by allocating the total quantity of uranium known to be used for US naval reactors (about 5 tonnes per year) only to refuellings, without allowing for the portions of the total used for new reactors and for research. The submission from Assoc Prof P. Jennings, p. 2 appears to assume that several tonnes of (plutonium) fuel are present in a submarine's reactor, and the submission from Mr R. Addison, p. 6 states that up to 2 tonnes of fuel may be in an aircraft carrier's reactor. Neither submission provides a basis for the claims.

[96] US Congress, Joint Committee on Atomic Energy, Naval Nuclear Propulsion Program 1970 - Hearings, 20 March 1970, p. 83.

[97] Nuclear Engineering International, World Nuclear Industry Handbook 1988, p. 79.