sustainable development commission

The role of nuclear power in a low carbon economy

Paper 6:
Safety and security

An evidence-based report by the
Sustainable Development Commission
with contributions from Large & Associates
and AMEC NNC

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1 EXECUTIVE SUMMARY

1.1 Introduction

This report has been prepared as part of the Sustainable Development Commission's work on examining the role of nuclear power in the low carbon economy.
It covers matters relating to safety and security, under four main topic headings. It has examined relevant material in the public domain, and has reached the following conclusions for the topics under review:

1.2 Accident risk

- Nuclear power stations in the UK are designed to stringent standards with emergency arrangements to avoid on-site and off-site effects, and which ensure that all reasonably practicable steps are taken to avoid accidents, and to mitigate the consequences of any that might occur.
- Nuclear power stations are designed so that safety equipment is duplicated and segregated resulting in a robust approach and practice of the engineered system response to abnormal operation and fault conditions. The current safety assessment principles state that safety equipment should be actuated automatically, and that no human action should be necessary for at least 30 minutes.
- UK civil nuclear power stations have an excellent safety record (although this is on the basis of relatively few reactor years of operating experience) , and there have been no events recorded either with off-site consequences or where all safety measures had been exhausted (the 1957 Windscale accident occurred at a military reactor).
- Modern reactor designs are expected to reduce the very small accident risks still further. Wherever possible, passive safety systems are used in preference to engineered ones.

1.3 Security issues – vulnerability to terrorism

- There are high levels of security at nuclear power stations, which are regularly reviewed against current intelligence about the intents and capabilities of terrorist groups.
- While modern reactor designs have substantial containment buildings which are considered unlikely to be breached even by a crashing airliner, and the reactor fuel is protected against impact and fire by other structures, no current operating reactor design has been specifically designed to resist commercial aircraft impact – the Generation III EPR and AP series reactors have yet to have anti-terrorist measures specifically designed in
- Attempts at damaging the plant, either by external attack or sabotage, will probably cause the reactor to shut down safely once a fault is detected. However, it remains difficult to fully account for future changes in the *modus operandi* of terrorist groups and their capacity to exploit weaknesses in the design, operation or security of nuclear power stations and associated infrastructure.
- Reactor fuel cannot be easily processed to produce weapons-grade material – but a 'dirty-bomb' can be made from reactor-grade material. The ceramic pellets are not easily fragmented, but could be used in a 'dirty' bomb.
- Spent fuel is transported in heavily-shielded containers which have been successfully tested under conditions equivalent to a 30mph impact, although the one-off Magnox flask train collision demonstration is considered by some to be neither particularly demanding or

realistic. By their nature, these containers would be difficult to steal as they are heavy and cannot be moved quickly. Opening the containers without specialist equipment would expose the terrorists to life-threatening radiation, but this in itself could comprise a 'dirty bomb'.

1.4 Implications for nuclear proliferation

- The UK is a signatory to and therefore bound by the Non-Proliferation Treaty and the Euratom Treaty, and has agreed not to divert civilian nuclear materials to military use.
- Any attempt by a future government to withdraw from its treaty obligations would raise suspicions about the intention, and cause an international response.
- Independent international safeguards measures are in place at fuel manufacturing facilities, power stations and reprocessing facilities, to account for all nuclear material within the civil sector. These measures have proved effective over many years, and will be applied to any new-build stations.
- However, terrorist organisations almost by definition operate outside of national or international laws and treaties. Concerns remain about the wider uptake of nuclear power based on the emphasis on equity and non-discrimination in the UNFCCC, and the governance arrangements within and between sovereign states to ensure the separation of civil and military applications or that radioactive materials do not fall into the 'wrong hands'
- Pressurised water reactor fuel is unsuitable for weapons use – but if reprocessed, the plutonium extracted from light water reactor fuel is suitably fissile for nuclear warhead use .

1.5 Health impacts from background radiation

- Radiological protection of employees and the general public in the UK is covered by a strict legal framework. Permitted dose levels to the public, as a result of nuclear industry operations, are only a small fraction of natural background radiation. The average dose to a member of the public, due to radioactive discharges, is 0.015% of the annual average dose from all sources.
- 83% of the EU collective dose attributable to the nuclear industry is due to discharges from fuel reprocessing. Spent fuel from new nuclear stations may not be reprocessed.
- Dose levels to the public are expected to reduce from already low levels with modern reactor designs. The associated risk of developing a fatal cancer is extremely small, below the 1 in one million level considered 'broadly acceptable' by the HSE.
- Nevertheless, several commentators raise concerns about the consequences of radioactive release from accidents and terrorist acts, including the front and back-end fuel cycle. Although the risks may be small, the consequences are significant. An understanding of the public perception of risk is at least as important as its evaluation by experts.

2 INTRODUCTION

This report has been prepared as part of a study commissioned by the Sustainable Development Commission (SDC) into the role of nuclear power in the low carbon economy. The Government is conducting a fresh review of energy policy, and the SDC has therefore decided to conduct its own review of nuclear power, enabling it to update its position on the subject in advance of a formal consultation.

The study covers five areas, each being the subject of a separate contract. This document covers matters relating to Safety and Security (Contract 3), and other studies (not necessarily by AMEC NNC) deal with Economics, Waste and Decommissioning, Public Perceptions and Community Issues, and Resource Availability. Some of the matters covered in this report may impinge on these other topics.

For the purpose of the study, it is assumed that any new reactor will be an 'advanced'[i] pressurised water reactor (PWR) or similar advanced reactor, in line with industry expectations. Candidate designs include the Westinghouse AP-1000 and the Framatome-ANP EPR (European Pressurised [water] Reactor). This study makes no assumptions about possible locations for any new-build nuclear power station, although it is recognised that the site location may be relevant when considering some safety and security issues.

For instance, the vulnerability to terrorist attack may depend on the site location and the source of any perceived threat, which could change over time. In the 1970s and afterwards, the possibility of Irish Republican terrorist strikes on sites at Heysham and Wylfa were assessed because of their proximity to ferry ports – but the threat was considered to be low because the Republican movement was confined and restrained by its own constituents (resident in Ireland, locally in the UK and as fund raising in the United States) who would have been subject to any radiation detriment arising from a terrorist action on a UK nuclear power plant. New terrorism threats require a full re-evaluation of the risk to nuclear power installations, which has been ongoing since '9/11'.

Other considerations include the extent to which coastal locations could be compromised by the effects of changes in the climate that are already in the pipeline, including vulnerability of plant to sea level rise, storm damage and coastal erosion for several decades or hundreds of years hence. Site selection criteria should be 'climate change-proofed' – this is discussed further in Paper 2 – *Landscape, environment and community impacts.*

At this stage, it is not known whether or not the spent fuel will be reprocessed. It is also not certain whether the reactor fuel will be uranium dioxide or mixed oxide (which comprises depleted uranium and fissile plutonium oxides, MOX). Where appropriate, both options will be considered, with appropriate caveats.

This report covers four main topics:

- Accident risk - record in the United Kingdom (UK) and in major overseas countries
- Security issues (vulnerability to terrorism)
- Implications for nuclear proliferation
- Health impacts on workforce and local community from background radiation.

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[i] i.e. designs that differ from existing plants in the extent of the reliability on passive containment and close down systems, although the reactor and containment systems overall and in detail are not that 'advanced' on existing designs

These topics are discussed in sections 2 to 5 respectively. The conclusions from each section are contained in section 6.

3 ACCIDENT RISK

3.1 UK regulatory position

Within the UK, the operators of nuclear plants must conform to the general health and safety standards laid down in the Health and Safety at Work etc. Act 1974 (HSW Act). The HSW Act applies to all employment situations, but nuclear plant operators must also comply with the Nuclear Installations Act 1965 (as amended) and related legislation. Under the Nuclear Installations Act, no site may be used for the purposes of installing or operating any nuclear installation unless a licence has been granted by the Health and Safety Executive (HSE). The HSE exercises this responsibility through the Nuclear Installations Inspectorate (NII), which is the nuclear safety regulator for the UK nuclear industry. Radioactive discharges are regulated separately, by the Environment Agency in England and Wales and the Scottish Environment Protection Agency (SEPA) in Scotland.

The NI Act requires that no health harm shall arise from the operation of the nuclear facility. The NII interprets this in terms of the *Acceptability of the Risk of Accident and the Tolerability of its Consequences*, and, acting on behalf of the HSE, sets out the general safety requirements to deal with the risks on a nuclear site. This determines the general standards required which are set out in a number of documents discussed below including the Site Licence (Site Licence Conditions - SLCs), Basic Safety Limits, Basic Safety Objectives and dose limits. Guidance on complying with NII requirements is set out in the Safety Assessment Principles (SAPs)[1], which have been produced by the NII and reflect its approach to the regulation of risks. There are five *fundamental principles*, and over three hundred detailed principles which are derived from them. Two of the fundamental principles relate directly to accidents:

- P4: All reasonably practicable steps shall be taken to prevent accidents
- P5: All reasonably practicable steps shall be taken to minimise the radiological consequences of any accident

Nuclear plants are designed to cope with a wide range of potential accidents (Design Basis Accidents - DBAs), for which it must be shown that off-site doses will not exceed specified limits. The predicted frequency of accidents that would result in doses to the public must also remain within limits. These limits become more onerous as the predicted off-site dose increases, so that an accident which would result in a large off-site dose must have a very low probability of occurring. The limits are specified as Basic Safety Limits (BSLs) and Basic Safety Objectives (BSOs). BSLs are absolute minimum requirements, while BSOs must be met (or even exceeded) if it is reasonably practicable to do so[ii].

Nuclear power plants are therefore designed to minimise the potential for accidents, and to minimise the consequences to both workers and the general population in the event that they do occur. This is reflected in the international nuclear event statistics discussed below, which record very few instances of significant off-site risk or major plant damage.

[ii] *Reasonably practicable* means that 'measures necessary to avert risk must be taken until or unless the cost ... whether in money, time or trouble, is grossly disproportionate to the risk that would be thereby averted' ([1], paragraph 1). This may also be expressed as the ALARP (As Low As Reasonably Practicable) principle.

3.2 Review of accidents in the nuclear industry

The industry view is that accidents are extremely rare, and,when they have occurred, the significance of what happened (or did not happen) has not always been well-understood outside the industry. For instance, the Three Mile Island accident resulted in an almost-new reactor being written off, with major financial consequences for the plant operator.

Although there were no off-site health effects, the primary containment was breached: the Kemeney Commission Report gives a radioactive release from the secondary containment with an estimated collective dose of 2000 man Rem. The dose exposure to workers over the reactor clean up program may have been sufficient to result in on-site detrimental effects..

The International Nuclear Event Scale (INES [2]) has been developed by the International Atomic Energy Agency (IAEA), and was introduced in 1990. It is a scale to put nuclear and radiological events into perspective, explaining in simple terms their significance and relative importance to the public. The INES is now used by over 60 countries, including the UK. Events are graded on a scale 0 to 7, and are assessed against up to three criteria: off-site impact, on-site impact and impact on *defence-in-depth*[iii] (the extent to which safety protection has been degraded), as shown in Table 1.

The scale is designed for prompt use following an event, but on occasions it may be necessary to give a provisional rating only. The level will then be confirmed, or possibly revised, once the event has been fully assessed. However, critics argue that the INES serves more of a PR function than a meaningful index, pointing out that, like the Beaufort wind force scale, the INES has little meaning because the graduations are not at all linear and noting that the IAEA recommends[3] that it should not be used for international comparisons. Some of the classifications are disputed, as discussed below for the Windscale incident in 1957.

The vast majority of events that have been reported against INES criteria have been level 0, 1, or 2, and there have never been any events above level 2 at a UK civil nuclear power plant. The Windscale fire and release (at a military reactor) is given as INES level 5 (Table 2) although others consider it to have been INES scale 7 (the maximum level, and equivalent to Chernobyl) – these differences may result from the non-linear nature of the scale, inviting subjective interpretation of event characteristics. At level 2, there would be 'significant failure in safety provisions but with sufficient defence-in-depth remaining to cope with additional failures'. Examples of higher-level classifications are given in Table 2, and summary descriptions of some of these incidents are given in 10. Table 3 lists the incidents at INES levels 0 to 3 that have been reported to the UK Government since the last quarter of 1996. These have been extracted from the HSE web-site, excluding those incidents which met the HSE criteria for reporting to Government but did not receive an INES rating. The reporting requirements were initiated in the late 1970s by the then Secretary of State for Energy, Anthony Wedgwood Benn.

Similar arrangements do not always exist in other countries, and where they do the reporting criteria may differ significantly from those applying in the UK. This will particularly affect the numbers of low-level incidents reported, although the treatment of more serious (Level 2 and above) incidents should be consistent across national boundaries. In France, the reporting criteria for significant events defined by the

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[iii] *Defence-in-depth* can be considered as providing multiple physical barriers between the source of radioactivity and the environment, *or* a structured 'series' safety argument ('if this happens, then that will happen, but if that fails, then this will take place…' and so on), *or* a 'parallel' or 'multi-leg' safety argument which demonstrates that the outcome can be achieved in several different ways. See also section 4.3.

Autorité de Sûreté Nucléaire (ASN) were modified in 2002, and include environmental protection events such as releases of chlorofluorocarbons and high temperatures of discharged cooling water[iv]. Although such events do not necessarily attract an INES rating, nevertheless one Level 2, 148 Level 1 and 522 Level 0 incidents were declared in 2003[4]. The ASN annual reports do not cover all the Level 0 and Level 1 incidents in any detail, though individual incidents may be discussed, hence it is difficult to determine the reasons for the apparent discrepancy between the UK and France regarding these levels.[v] It can be seen that, while there are many more Level 0 and 1 incidents recorded in France than in the UK, the number of Level 2 incidents is of a similar order of magnitude.

The nuclear industry in Japan has suffered adverse publicity due to a sodium leak at the Monju fast reactor, two incidents at Tokai (including the criticality incident described in 10) and a scandal relating to falsification of inspection records. The latter involved a lapse of management controls at Sellafield and a BNFL MOX fuel shipment to Japan which had to be sent back to the UK. Industry sources state that the inspection issues were not safety-related[5] – but others point out that the fuel pellets and cladding gap were not to specification., In any event, a significant loss of public confidence resulted. It has not proved possible to obtain comprehensive data on INES-rated incidents.

Five of the accidents/incidents listed in Table 2 occurred at power stations. Of the reactors involved, two (Saint-Laurent and Vandellos) were to a design no longer built (the French UNGG, not dissimilar to the UK Magnox design), one (Bohunice A1) occurred on an experimental reactor of a type since abandoned, and one (Chernobyl) was to a design long considered unlicensable (Amec-NCC) in the UK (Reactor Bolshoy Moshchnosty Kanalny - RBMK - or high-power channel reactor). Apart from Chernobyl, no nuclear workers or members of the public have died as a result of exposure to radiation due to a commercial nuclear reactor incident[6]. Most of the serious radiological injuries and deaths that occur each year are the result of large uncontrolled radiation sources, such as abandoned medical or industrial equipment.

There have also been a number of accidents in experimental reactors and in one military plutonium-producing pile (Windscale, 1957), but, according to industry sources, none of these resulted in loss of life outside the actual plant or long-term environmental contamination[6] - although this is disputed. A fatality was recorded at the Idaho SL-1 reactor in January 1961.

Particularly following the Three Mile Island (PWR) accident, which was rated as INES level 5, reactor designers have striven to limit the potential for core damage under accident conditions. Increasingly, PWR designs rely on passive features (which use natural forces such as gravity, natural circulation and compressed gas) rather than engineered features to assure safety functions. Where engineered systems cannot be avoided, the standard engineered system design principles of *diversity* and *redundancy* (‘*defence in depth*’) apply (as they are on

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[iv] This is a particular issue in France, where inland power stations discharge their coolant into large rivers such as the Seine and the Loire: all operating UK stations discharge cooling water into the sea.

[v] The total of Level 1 incidents in France, at operating power stations only, was 116 in 1999, 134 in 2000, 88 in 2001, 99 in 2002, 148 in 2003 and 92 in 2004. The corresponding figures for Level 2 incidents were 3, 2, 2, 1, 1 and 1 for the same six years. There were no incidents rated at Level 3 or above. Over the same period, Table 3 shows that two Level 0, seven Level 1 and one Level 2 incidents were reported to Parliament. It should be noted that France has 59 operating reactors, compared to the UK’s 23 in late 2005. The ASN report for 2003 identifies that about 60% of the incidents (levels 0, 1 and 2) were attributable to organisational and human causes, and 21.3% were caused by equipment faults. Just 1.2% of the incidents involved an accidental release of activity, but in all cases the releases were contained within the plant.

most hazardous plants including the UK AGR reactors designed in the 1960s), so that:

- there are at least two ways of dealing with any identified fault, that do not rely on each other for any part of their operation
- there are multiple, segregated sets of safety equipment, each one with the capability of dealing with the fault on its own.

As a result, the manufacturers' claims for their products suggest that the risk of core damage is very much less than for current designs. For instance, the Westinghouse AP1000 is claimed to have a core damage frequency (corresponding to a level 4 event) nearly 100 times below that for current plants, and 250 times lower than the frequency required by the United States (US) regulator[7].

Although fuel from Sizewell B - the UK's first, and so far only, PWR used for electricity production (the Royal Navy has operated PWR powered propulsion systems for its submarine flotillas since 1965) - is currently not reprocessed, this remains as an option for new-build power stations. Many (though not all) of the incidents recorded in Table 3 for reprocessing plant relate to the old Magnox facilities that are due for closure around 2012, and are therefore of less relevant to plant built to modern standards (i.e. in accordance with the requirement of the Nuclear Installations Act to reduce the risk to a low as reasonably practicable). Inspection of Table 3 (page 53) shows that none of the incidents listed there resulted in the release of activity off site, and in most cases the release was contained within the building in question.

3.3 Summary

While it may not be possible to eliminate all risk, the regulatory requirement is that risks have be shown to be acceptable and the consequences have to be tolerable, and that any accident with potentially large off-site consequences must be shown to have a very low frequency of occurrence.

Modern nuclear power stations are built to a high standard, with multiple layers of protection to guard against faults and passive safety features which will come into play automatically when a fault condition occurs. As will be apparent from Table 2, some of the more serious accidents were due, in part, to human error – notably, Chernobyl which resulted when workers were under pressure to perform an experiment even though the load requirements of the plant were changed (Annex A). Current practice is to remove the need for prompt operator action and, with it, the potential for the wrong action to be taken. Ref [1], Safety Assessment Principle 77 states that a safety system should normally be automatically initiated, and that no human action should be necessary for approximately thirty minutes. Nevertheless, some commentators argue that it remains difficult to completely rule out human error whatever the cause – these faults are often easier to evaluate with the benefit of hindsight.

4 SECURITY ISSUES

4.1.1 Motivation and nature of terrorist threats

Some of the risks of terrorist attacks on nuclear facilities are discussed in[8]. There could be several possible motives for a possible terrorist attack on a nuclear power station. They will depend on the group or groups involved, and on their political aims. It could take up to ten years, following a public enquiry, eventual approval and the construction phase, before a new nuclear station will be ready to operate, and it could then be running for 40-60 years. Over that period, both the motives for and the nature of a terrorist threat could change. Currently, the perceived threat is generally linked to events in the Middle East, from terrorists with a desire to cause widespread death and destruction of 'Western' interests, and with a total disregard for their own lives. The situation in thirty years' time may be different yet again.

Although the detail of the threat will depend on the circumstances pertaining at the time, a number of general motives can be identified:

- to cause widespread death and destruction by direct action
- to acquire nuclear material which could then be used in an explosive device
- to cause economic damage to the UK
- to gain publicity for the group in question.

Nuclear plants might be considered 'attractive' targets for a number of reasons, including:

- the potential to cause wide scale economic and social disruption
- playing on the public fear and anxiety of radioactivity
- the possibility of causing a 'spectacular' event.

Various counter-measures are in place to combat these threats. Some of these are institutional (e.g. site security) and others are related to plant and equipment design. Section 3.3 presents two opposing views. The first is an industry view wherein nuclear plant is robust, and the containment buildings are able to withstand external impacts from, in the worst case, a civil airliner. Attempts at causing a major release of activity from commando-style operations are considered likely to be frustrated by the fail-safe nature of the plant where, if a fault is detected, several systems are available to shut the reactor down safely. Nuclear fuel (fresh or spent) is considered technically unattractive for use in a classical fission weapon, and difficult to fragment in the way that would be intended in a 'dirty' bomb. The problem is perceived to be mainly one of publicity, even though the more sinister motives are unlikely to be realised. The second is more critical, challenging the industry view on almost every count.

4.2 Nuclear security

It is important to distinguish the probabilistic risk analysis (PRA) undertaken for <u>accidents</u> (that is unintelligent, random and unfocussed events) compared to terrorist actions which are intelligently driven, intentional events that seek out the vulnerabilities of the plant (and may also strive to disrupt or disable the emergency response actions to maximise the impact)[9]. The Office for Civil Nuclear Security (OCNS) regulates security arrangements for the protection of nuclear and radioactive material, on civil nuclear sites and while being transported between sites. It is part of the Department for Trade and Industry, and operates under the Nuclear Industry Security

Regulations (2003) and associated legislation. It reports each year to the Secretary of State for Trade and Industry, most recently in[10].

The Nuclear Industry Security Regulations require civil nuclear operators to have site security plans in place, dealing with the measures for protection of sites and the nuclear material on them. The OCNS is responsible for approving these security arrangements, which include the deployment of armed police at designated power stations[10] – a consequence of which is that not all nuclear plants have armed UKAEA police in attendance all of the time.

In line with international best practice[11], security measures are regularly reviewed against the Design Basis Threat, which is based on the best available intelligence about terror groups, their motives and capabilities – although the tragic events in London on July 7 illustrate the difficulties of designing a system to cover all eventualities especially unknown future *modus operandi*. For obvious reasons, the Design Basis Threat is classified as Secret, and no further details can be published. However, different countries have different approaches to Design Basis Threat – for example in the US and France specific actions are taken into account whereas in the UK it is considered sufficient to have intelligence about the motives and intention of the terrorist. This could lead to different perceptions and assessments of threats.

Access to nuclear power stations is tightly controlled. Measures to prevent or at least delay unauthorised access include:

- double lines of fencing with razor wire, high intensity lighting and CCTV linked to a permanently-manned security building
- turnstiles at personnel access points where entry and exit is only possible with a site-specific electronic pass
- random searches of personnel and vehicles
- double barriers at vehicle access points and chicanes to prevent the barriers from being rammed at high speed
- additional barriers within the station to protect sensitive areas such as the reactor building, to which only certain personnel will have access.

These measures may not always deter the determined intruder, but will delay access to sensitive areas, to buy enough time to both shut down the reactor and limit any possible release, and to mobilise off-site counter-terrorist measures.

There have been instances of intrusions by groups protesting about nuclear power (e.g. Greenpeace), who have used such events to highlight supposed breaches in nuclear security. The activities of groups such as *Fathers for Justice*, though so far not directed at the nuclear industry, also pose security concerns. Some of the Greenpeace incursions at Sizewell in 2002-3 were conducted with a large number of activists, and OCNS claims that they were different in character and scale from a possible terrorist attack, which would be conducted with far fewer participants who would seek to avoid detection for as long as possible. The second Greenpeace incursion into Sizewell B was by a group of 11 campaigners in the early hours of the morning without the glare of publicity – Greenpeace's intrusion was modelled on the NRC Design Basis Threat scenario for an armed insurgency group. Although the Sizewell incidents were identified as a demonstration, and the authorities reacted accordingly, attempts by terrorists to infiltrate protest groups cannot be ruled out, and armed police could be faced with the dilemma of whether or not to use extreme force if the nature of the incident was not immediately obvious[8]. As a result, OCNS is pressing for legislation to make unauthorised entry into licensed nuclear sites a specific offence[10].

OCNS supervises a comprehensive personnel clearance programme ('vetting'), which is undertaken to minimise the possibility of stations being infiltrated by untrustworthy individuals. This was extended in January 2005 to encompass all personnel working within the perimeter fence of a nuclear power station (including secretarial, administrative and cleaning staff amongst others), not just those requiring access to a radiologically-controlled area or inner security barrier. Personnel without such clearance are not permitted unescorted access to site.

4.3 Design of plant

A full discussion of this subject should consider existing plants, both nuclear power and the front and back-end fuel plants, and the so-called Generation III nuclear power plants.

Areas where nuclear fuel is present (the reactor itself and spent fuel stores) are mostly protected by heavily-reinforced concrete buildings. The main exception is with the existing Magnox steel reactor pressure vessel designs (Sizewell A, Dungeness A etc) in which the reactor primary circuit extends outside the concrete biological shield (which vents to atmosphere and is not a pressure vessel) and this part of the primary circuit is entirely unprotected against aircraft impact. A typical PWR containment building is cylindrical, with a domed roof, and has walls some 1 to 1.5 m thick, with an internal steel liner. The buildings are designed to withstand earthquakes, forces generated by postulated internal explosions and, in some parts of the world, hurricane force winds. Before 9/11, they were only specifically designed against the impact of a light aircraft – i.e. aircraft up to 2.7 tonnes gross weight and with the assumption that the pilot will endeavour to steer clear of hazardous parts of the plant[12] - However, in meeting the requirements mentioned above, the buildings could withstand much larger aircraft impacts – although no current operating reactor design has been specifically designed to resist commercial aircraft impact and the Generation III EPR and AP series reactors have yet to have anti-terrorist measures specifically designed in[13]. A report by the mainly industry-funded Electricity Power Research Institute (EPRI) in the USA, summarised in[14], showed that a Boeing 767-400, impacting at 350 mph, would not breach the containment structure. Any future reactor to be constructed in the UK will be specifically assessed against the possibility of impact by a large commercial aircraft – although concerns remain about the existing nuclear power and fuel plants.

Assuming that the *modus operandi* of future terrorist attacks is similar to that of '9/11', then the potential threat to nuclear plant may be small. Compared with either the World Trade Center or the Pentagon building, a containment building is a relatively small target, close to the ground (Figure 1). It would be difficult for a trained commercial pilot to control a large airliner at 350 mph near to ground level[14], so it is less likely that a terrorist, possibly with only basic training and minimal experience, would be able to impact the building at the most onerous impact site. Furthermore, although it is not shown in Figure 1, the containment building is surrounded by other buildings, making a direct hit on the containment even more difficult to achieve.

The OCNS has been working with operating companies and the NII on measures to counter the risk of a deliberate large aircraft crash[15], though details may not be disclosed for security reasons. While these measures relate to existing nuclear plant, they can be expected to apply to any new-build power station.

Figure 2, also taken from Ref[14], shows a typical light water reactor containment building (actually a Boiling Water Reactor (BWR), though the general layout is not dissimilar to that of a PWR). It shows that the reactor pressure vessel (which contains the fuel) is low down inside the containment building, and protected by further reinforced concrete structures. The vessel itself is several inches thick, so is built to withstand considerable forces and will withstand significant impacts.

It can be seen, therefore, that if a crashing airliner did penetrate the containment building[14] suggests would be most unlikely), there are still substantial barriers to prevent an uncontrolled release of radioactivity. Most of the energy would be used up in the initial impact, leaving the contents of the containment building largely undamaged.[vi][16]

However, this line of reasoning is not comprehensive for the following main reasons:

- it fails to explore and understand the way that the civil engineering structures react to and dissipate impact;
- it doesn't take into account the penetration capacity of hard missiles from the aircraft, such as turbine shafts, undercarriage spars, which may themselves be able to penetrate the reactor and fuel storage pond containments; and,
- it incorrectly assumes that the terrorists' *modus operandi* would be the same as the '9/11' attacks, rather than targeting a specific vulnerability in, for example, plant design, operation or security – the '9/11' attack was targeted at buildings which were successfully demolished, thus Al queada correctly identified the vulnerability of the World Trade Towers and obviously had a good understanding of the structure to identify the optimum impact zone.

As noted in section 2.1, UK nuclear power stations have to meet NII requirements as expressed in the SAPs. One of the most important principles on which modern nuclear plants are based is 'defence-in-depth', whereby several different systems perform the same function, so that the plant safety does not rely on any single feature. This involves three concepts:

- redundancy (multiple ways of shutting a reactor down, providing fuel cooling, or multiple barriers to contain any release)
- diversity (ensuring that systems with the same function are not designed in the same way or do not rely on common features, so that a particular fault on one system does not affect other systems)
- segregation (reducing the possibility of a common hazard, such as fire, damaging more than one system).

The SAPs were not designed to assess security threats, but many of the measures taken to enhance safety also provide defence against terrorist attack[8].

'Defence-in-depth' means that terrorists would have to damage several systems or components to cause a significant release of activity, with the possibility that an immediate reactor shutdown would be caused once a fault on one safety system had been detected – although others point out the possibility that an active insider might sabotage the plant by arranging for it to cascade down a self-destructive path. It is unlikely that a terrorist group, acting without inside assistance, would have the detailed knowledge required to disable enough safety systems to cause a major uncontrolled release, without the resulting disruption initiating a reactor shutdown – although it's difficult to rule out the possibility that a passive insider could not be a long

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[vi] In an appraisal for Greenpeace of the EPR to be built at Okliluoto, Finland, Large states that the original EPR containment was not specifically designed to withstand any impact greater than a light aircraft crash[16]. While this is technically correct, in practice the conditions that the containment was designed to meet were more severe than the specific hazard of an accidental light aircraft impact. Although details of the EPR containment design have not been released, drawing adverse comment from Large, the analysis summarised in[14] strongly suggests that pre-9/11 designs are strong enough to withstand the deliberate crash of a large commercial aircraft. Any specific
assessments in the light of 9/11 can be expected to confirm this. It should be no surprise that the design authorities refused to release sensitive design details on security grounds.

established employee acting as an undetected sleeper in the plant.

4.4 Shipments of radioactive materials and wastes

Both fresh and spent fuel are transported to and from power stations under appropriate security arrangements. Fresh fuel presents no particular radiation hazards and is delivered by road, whereas spent fuel is highly radioactive and has to be transported in heavily-shielded flasks, by road to the nearest railhead and then by rail to Sellafield. At present, it is uncertain whether or not spent fuel from any new build nuclear station will be reprocessed. If it is not, it will remain at the power station until such times as a national repository is available. In the meantime consideration may need to be given to the management of spent fuel accumulating in the station fuel ponds to avoid the possibility of it becoming a large, effectively uncontained, radioactive source.

Fresh fuel has no attractions for the terrorist (but see next paragraph for a discussion on unirradiated MOX fuel). It is only enriched to 4% uranium-235 (the isotope of uranium that takes part in fission reactions), whereas weapons-grade material has to be extremely pure, in excess of 90% uranium-235. Furthermore, the fuel is in the form of ceramic pellets, which are extremely hard, and difficult to process (they can only be dissolved in very strong acid).

Compared with uranium ores or metal, they are unattractive as a starting-point for producing weapons-grade material. Because fresh fuel is only weakly radioactive, it would have little value in a ‘dirty bomb’, and the ceramic pellets are resistant to fragmentation – although the use of such materials could nonetheless be used to play on public fears and anxieties over radioactive materials.

However, unirradiated MOX fuel contains significant quantities of plutonium-239 which is the highly fissile material capable of providing the fissile pit of a nuclear warhead. The United States Department of Energy considers MOX fuel to be ‘Stored Weapons Standard’ and thus requires the utmost standards of security during transport[vii].
If it is decided that spent fuel should be reprocessed, it is possible that a shipment from the station to the reprocessing plant could be attacked *en route*, either to spread contamination over a wide area or to steal the material for future use in a nuclear weapon. Spent fuel containers are robust and undergo stringent testing, including dropping onto rigid surfaces (the equivalent of a 30 mph impact) and steel spikes, immersion in deep water, and an 800°C fire (in accordance with IAEA TS-R-1). One-off tests have also been carried out, such as crashing a train travelling at 100 mph into a Magnox flask - although some consider this to be neither particularly demanding or realistic. The industry argues that the pellets themselves are not easily dispersed even under severe impact and fire, and any intention to contaminate the surrounding area is unlikely to be achieved.

However, the IAEA *Transport Safety Standards Advisory Committee* (TRANSACC) has yet to accept MOX to be within this transport category, so Type B(M) transportation flasks are a prerequisite for its transport in order to minimise its release and

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[vii] See NRC Hearing Disposition of Surplus Weapons Plutonium Using Mixed Oxide Fuel, US Nuclear Regulatory Commission Hearing, 2004:

- Comments on Opinion on the Applicability and Sufficiency of the Safety, Security and Environmental Requirements and Measures as these Apply to the Transatlantic Shipment, European Waters and France
- The Role of PNTL Ships in the Atlantic Transit Phases, United States of America Nuclear Regulatory Commission, 26 November 2003,
- Summary of the Findings of the French-sourced Plutonium Dioxide Transportation, 23 March 2004, http://www.largeassociates.com/NRC1.pdf

airborne dispersion upon failure of the flask containment[viii].

A container for spent PWR fuel weighs around 100 tonnes and is several metres long, which makes theft and subsequent concealment extremely difficult. Anyone opening the container to extract the fuel would subject themselves to life-threatening radiation doses before they could carry out any operations on the fuel itself – although this is unlikely to deter a fanatic especially if death were not immediate. Even then, the fuel could not easily be processed. However, the container could in itself make for a dirty or radiological bomb (NRPB study).
The IAEA itself recognises the transportation stage of nuclear and radioactive materials to be particularly vulnerable to terrorist attack, calling for special arrangements, especially for Category 1 materials[17].

Analysis and tests have demonstrated that the transportation flasks are vulnerable to terrorist actions, both from shaped or propelled explosive charge[18] from fire being deliberately set when the flask(s) are trapped within a confined space[19] such as a tunnel or ship hold, generally with the security arrangements overall for the transportation of new, unirradiated MOX fuel and spent fuel[20] and acts of sabotage[21].

The risk posed by nuclear reactor spent fuel in transit is not so much absconding with it, but more a terrorist action that might entrap the flask(s), for example in a siding where an explosive charge might breach the containment[22], or within a tunnel where the flask might be subject to fierce fire.
Modelled by the National Radiological Protection Board (NRPB), a hypothetical terrorist attack on a PWR spent fuel flask standing at Willesden Junction in London, gave one airborne dispersion condition prediction of 1,300 fatalities over the interim and longer terms[23].

4.5 Summary

Security at nuclear power stations has been under constant review since 9/11 and provisions have been strengthened as deemed necessary. Modern designs of nuclear power station are resistant to external attack, and the duplication of safety systems makes it likely that the reactor will be shut down safely even if some safety systems are disabled. However, it remains difficult to fully account for future changes in the *modus operandi* of terrorist groups and their capacity to exploit weaknesses in the design, operation or security of nuclear power stations and associated infrastructure.

Security measures are reviewed against a Design Basis Threat, which is based on intelligence about the terror groups, their motives and capabilities – but different approaches to DBT may create different perceptions and evaluations of risk.
Intelligence cannot be comprehensive, and it is possible that some threats can be underestimated or even overlooked altogether, as may have been the case with the London tube and bus bombers on 7 July 2005.

The possibility that a power station might be infiltrated by terrorists, who could then use knowledge gained in their work to disable critical safety systems, cannot be ruled out. Although it might, take several years for such people to achieve the required knowledge, it's possible that terrorist groups

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[viii] The substance qualifies as LDM if, during and following the tests, does not release an amount of activity greater than 100 times the A2 index in gaseous and particulate forms of up to 100 microns in diameter - Requirements for Very Low Dispersible Material (VLDM), TC-946, F Lange, F Nitsche, F-W Collin and M Cosack, Working Paper No 11, IAEA Technical Committee Meeting, Vienna, 15-19 May 1995 5
Large J H, Review of the Sea Transportation of Mixed Oxide Fuel: i) Transportation Risks and Hazards , ii) Physical and Dispersion Characteristics of MOX Fuel, iii) MOX Fuel, a UK Perspective, Evidence to the New Zealand Government Foreign Affairs, Defence and Trade Select Committee, May 2001
http://www.largeassociates.com/R3063-MOX1.pdf . . ./ R3063-MOX2.pdf . . . / R3063-MOX3.pdf

and their *raison d'être* could persist for many decades.

5 IMPLICATIONS FOR NUCLEAR PROLIFERATION

5.1 International treaty obligations

5.1.1 General

The materials used for both nuclear power generation and nuclear weapons manufacture are both ultimately derived from natural uranium – including sources such as MOX or plutonium which are derived from spent fuel. There are long-standing concerns that material and technologies intended for power generation could be diverted to weapons use, and several international treaties have been concluded to ensure either that this does not take place or that any attempts to do so are detected. Some of these treaties are regional in nature (e.g. the Treaty of Tlatelolco, covering South American states) while others concern the supply of uranium ores by non-nuclear weapons states such as Australia and Canada to other states. The two principal treaties that concern the UK are the 1970 Treaty on the Non-Proliferation of Nuclear Weapons (NPT)[24] and the Euratom Treaty[25], to which the UK became a partner on joining the European Community in 1973.

These are discussed below, but it should be noted that these obligations relate to the compliance of signatory states and not to the activities of terrorist groups (which, almost by definition, act outside of national or international laws). The view below represents an 'industry' view. A further section is added below as a commentary on proliferation concerns from a more critical perspective.

5.1.2 The NPT

The only states that have not signed the NPT are India, Pakistan and Israel, all of which are known to have nuclear weapons, while North Korea has chosen to withdraw from the treaty. Out of the 188 states that have signed the NPT, the UK is one of five declared Nuclear Weapons States (NWS), the others being France, the USA, the USSR and China. Along with the other four declared NWS, the UK has signed voluntary agreements with the IAEA[26,27] which allow the Agency to apply *safeguards* to its civil nuclear activities, to verify that civilian nuclear material is not being diverted to military use. The Non-nuclear Weapons States (NNWS), who have agreed to use nuclear energy for exclusively peaceful purposes, also allow inspections of their civil facilities to confirm that there are no clandestine military programmes.

The nature of the safeguards agreements has been refined over the years. Before the NPT came into force, the IAEA's safeguards regime was defined in INFCIRC/66[28]. Following the NPT, *comprehensive safeguards agreements* have been made with many of the signatories, with *voluntary offer agreements* [26] applying to the five NWS. These agreements cover the application of safeguards at declared facilities, with the onus being placed on the NNWS (via the treaty itself) to declare all nuclear activities (the NWS may choose not to declare certain facilities on the grounds of national security).

The weakness of the comprehensive safeguards agreements was that, if a state chose not to comply with its treaty obligations, and failed to declare certain nuclear facilities (as did Iraq in the 1990s), detecting the non-compliance was not straightforward.[ix] Accordingly, a system of *additional protocols* was developed, which gives IAEA inspectors greater rights of access and requires administrative procedures to be streamlined so that, for instance, states

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[ix] Iraq probably had access to indigenous sources of uranium that were not declared, and was able to pursue a military goal without the need to divert nuclear materials from a parallel civilian programe.

cannot delay the issuing of visas as a means of delaying an unwanted inspection. The states also have to provide significantly more information, including details of nuclear-related imports and exports, which the IAEA is then able to verify. The five NWS have signed modified additional protocols [27]which reflect their particular status.

Individual states can terminate their NPT agreement, as North Korea has done. Given that almost all states have signed the NPT (and those that have not done so have agreed to limited safeguards[28]), any withdrawal from the treaty would immediately raise suspicions of clandestine activities.[x] There have been a few failures to detect undeclared nuclear activities. For instance, South Korea had conducted some experiments into the separation of uranium and plutonium in the 1980s, which were not declared at the time and only came to light in 2004[29]. However, the IAEA has concluded that, without the NPT, there might be perhaps 30 to 40 NWS, and points out that more states have abandoned nuclear weapons programmes than started them[30].

It is also worth noting that all five of the declared NWS had developed nuclear weapons before beginning electricity generation from nuclear power. In India and Pakistan the development of nuclear weapons and nuclear power appears to have been concurrent, and in both cases the emergence of weapons programmes led to a cessation of overseas assistance with nuclear power development, at least by countries that had by then signed the NPT. Israel does not generate electricity using nuclear power.

5.1.3 The Euratom Treaty

The Euratom Treaty and its supporting regulations, specifically Commission Regulation (Euratom) 3227/76[31], empowers the European Commission to verify that nuclear materials are not being diverted from their intended uses. This responsibility is exercised by the Euratom Safeguards Office (often known simply as ‘Euratom’), part of the Directorate-General for Energy and Transport. It is also required to ensure that member states comply with their international treaty obligations. Consequently, there is a degree of overlap between Euratom and the IAEA.

There is no provision for a EU member state to withdraw from the Euratom Treaty. This could only be achieved by a general renegotiation of the treaty, which would then have to be ratified by all (currently 25) member states. Consequently, unless a major upheaval took place in the European political system, safeguards would be maintained in the event that a future UK government was minded to withdraw from the NPT.

5.2 Application of safeguards at UK nuclear power stations

Euratom applies a range of safeguards at both power stations and fuel fabrication and reprocessing plants, to ensure that civil nuclear material is not diverted to military use. These measures include materials accountancy, analysis, surveillance and inspections. The precise level of safeguards applied to each plant will depend on the activities taking place there. For instance, a power station with on-site spent fuel storage (interim or long-term) will be subject to accountancy audit, containment and surveillance measures (closed circuit television - CCTV, seals) and, if practicable, occasional re-verification (checking that identified fuel assemblies are still present). To avoid unnecessary duplication of effort, IAEA will generally only apply its own safeguards to verify that Euratom’s conclusions are correct. Discrepancies have emerged, for instance the European Commission identified shortfalls in accounting procedures at Sizewell[32], the absence of an irradiated fuel element at Wylfa (believed to have been dispatched to Sellafield in error) and discrepancies involving elements shipped from Bradwell to

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[x] For North Korea, the reverse was actually the case. Non-compliances were detected and the state decided to withdraw from the NPT, rather than put matters right.

Sellafield. Any new-build nuclear power station will be subject to Euratom and IAEA safeguards requirements. The plant operator is required to supply Euratom with the plant's technical characteristics, from which Euratom will determine how safeguards will be implemented. This is likely to include CCTV surveillance of fuel storage areas, with tamper-proof seals that can only be broken with the approval (and presence) of the inspectors. The inspectors will monitor refuelling operations which, on a modern PWR, will take place at 12-18 month intervals. This will confirm that fuel movements and disposals are in accordance with a predetermined plan and that there are no unexplained aspects (e.g. early removal of a fuel assembly) that could indicate an attempt at diverting material.

5.3 Proliferation – a summary of more 'critical' perspectives

A chief concern with reprocessing is that the plutonium could be diverted to develop nuclear weapons. Several industrial countries have, in the past, provided reprocessing as well as enrichment technology and services to other countries, raising concerns about increasing the opportunities for theft or transfer of technology, equipment, or products. (ref. Chicago study). Reprocessing is carried out in Belgium, China, France, Germany, India, Japan, Russia, Switzerland, and the UK. These countries engage in reprocessing to separate plutonium and uranium from fission products for further use as fuel for reactors (see Waste and Decommissioning). Direct disposal without reprocessing is carried out in the United States, Canada, Finland, South Korea, Spain, and Sweden.

Although, as discussed above, the UK is itself not likely to directly aggravate proliferation issues as a result of replacement or enhancement of nuclear power, this remains an important issue for any UK decision because of the international implications of such a decision. These implications arise from the United Nations Framework Convention on Climate Change which indicates that if nuclear power is part of the solution to climate change for the UK, then it is a suitable solution for all countries based on the emphasis on equity and non-discrimination in the Convention. For example, Article 4 – Commitments include:

- "1c) Promote and cooperate in the development, application and diffusion, including transfer, of technologies, practices and processes that control, reduce or prevent anthropogenic emissions of greenhouse gases… in all relevant sectors, including the energy…"; and,
- "5. The developed country Parties and other developed Parties included in Annex II shall take all practicable steps to promote, facilitate and finance, as appropriate, the transfer of, or access to, environmentally sound technologies and know-how to other Parties, particularly developing country Parties, to enable them to implement the provisions of the Convention."

The use of a nuclear reactor to produce military products is mainly a management choice depending on the duration and frequency of reactor shut-down that can be tolerated to extract the relevant feedstocks (see sections 4.4.2 and 4.4.3). While transparency and scrutiny by a variety of stakeholders may preclude the use of commercial civil reactors for clandestine plutonium production in the UK, this cannot be guaranteed in all countries.

In 1977 the USA decided not to reprocess spent fuel, largely due to concerns over nuclear proliferation because of the separation of pure plutonium by PUREX reprocessing. Although more proliferation-resistant reprocessing techniques have since been developed, the USA continues to use a 'once-through' fuel cycle in which spent fuel is treated and stored, or sent for reprocessing in other countries.

A number of difficulties in the relationship between civil and military applications continue to cause concern among many commentators[33], including:

- the difficulties of enforcing international treaty obligations;
- proliferation risks associated with the widespread use of nuclear technologies in countries with very diverse systems of governance;
- the resources available to enforce international obligations in a potentially growing number of states with a nuclear capacity; and,
- how to deal with states that withdraw from treaties (e.g. North Korea) or develop nuclear capability outside of them, such as India, Pakistan and Israel, and the suspected development of a nuclear military capability in Iran.

All of these lead to a general concern about making clear distinctions between civil and military uses of nuclear power especially where reprocessing is used.

5.4 Safeguards activities

This section discusses some of the processes designed to account for the amounts of radioactive materials entering and leaving various key stages in the fuel cycle.

5.4.1 Declaration of basic technical characteristics

The operator of any nuclear plant is required to submit design information to Euratom and the IAEA. These *Basic Technical Characteristics* include a description of the plant and the processes that take place within it, details of the arrangements for handling nuclear material, and a description of the materials accountancy system to be employed. From an understanding of the plant, the safeguards agency (Euratom or IAEA, as appropriate) will be able to determine the nature and extent of safeguards to be applied. It will also enable the agency to identify locations where material diversion or process interference could take place, and to apply appropriate measures.

5.4.2 Materials accountancy

It is desirable that knowledge of the quantity and whereabouts of nuclear material should be maintained as long as the material poses a potential threat to society. Nuclear material enters the safeguards system when it is separated from the naturally-occurring ores, and leaves only when the agency can determine that it has either been consumed, been diluted in such a way that it is no longer usable for weapons purposes, or become practically irrecoverable[34]. However, Barnaby (2005)[35] argues that safeguarding plutonium and highly enriched uranium in a commercial reprocessing plant dealing with up to 10 tonnes a year is problematic: with acceptable measurement errors of 0.5-1%, 50-100kg could be unaccounted for (as discussed further below). He further notes that about 13kg of reactor grade plutonium would be sufficient to make a crude nuclear device.

Certificates are generated at all stages of the fuel cycle, and accompany the material through all stages from mining to final disposal. Essentially, they indicate the origin of the material, any particular safeguards *obligations* (restrictions placed on its use by the supplying state), quantity, chemical and isotopic composition, state of enrichment, storage location and date of transfer. As the material moves through the fuel cycle, the certification 'bundle' is added to, and completed fuel assemblies are marked with unique numbers that can be read and correlated with the certification.

The power station operator will be obliged to maintain a system of nuclear materials accountancy, which is subject to scrutiny by the safeguards agency. This requires the setting up of *Material Balance Areas*, for which details of all material entering or leaving must be recorded. For a power station, the new fuel store, the reactor itself and the spent fuel ponds will be included. The system must include periodic inventory checks, the results of which must be reported to the agency. The agency will, in turn, carry out audits of the accounting system, including (where appropriate and practicable) inspections to confirm the correctness of declared records.

Materials accounting is less straightforward in the fuel manufacture and reprocessing sector, as indicated above. At power stations, keeping inventories is relatively simple, because the fuel exists in discrete assemblies. It is delivered, used, stored after use and (where appropriate) sent for reprocessing in fixed amounts. In fuel manufacture, materials accounting requires that, for instance, estimates are made of the amount of uranium that can be extracted from a given quantity of ore. The amount recovered never precisely matches the amount estimated in the ore. Similarly, quantities of uranium and plutonium reprocessed from spent fuel may not match the estimated amounts. Furthermore, there are uncertainties associated with measuring materials passing through a continuous process, since it is usually not possible to 'freeze' operations to get a snapshot of what is present at any one time.

For these reasons, materials accounting will include a proportion of Materials Unaccounted For (MUF). The MUF figures may indicate an apparent gain of material in some years, and a loss in others. The IAEA standard on uncertainties is 1% of the total throughput. The latest figures produced by BNFL (2005) represent 0.5% of throughput and have been accepted by Euratom as satisfactory[36].

5.4.3 Containment and surveillance

Containment[xi] and surveillance operations are performed to ensure that there is continuity of knowledge about nuclear material, in particular that it has not been removed or tampered with since it was last verified. These measures may include:

- tamper-resistant seals at storage locations, which cannot be removed without the agency being notified and an inspector witnessing any movement of material
- the presence of inspectors on site to identify any suspicious operations
- continuous surveillance of storage locations using CCTV or other electronic techniques
- fitting monitors on potential exit routes, including those which would not normally be used (e.g. ventilation ducts) but might be employed for clandestine activities.

Any indications of tampering (e.g. seal damage, cameras being turned off) would trigger investigations and, potentially, full inventory checks.

5.5 Disincentives to diverting PWR fuel

It is likely that any attempt to divert nuclear material to military use would be detected by the safeguards agencies. However, there are several reasons why such action would be unattractive, and these are discussed below.

5.5.1 Difficulty of processing the fuel

Irradiated PWR fuel consists of a matrix of fuel pins, composed of uranium dioxide (or occasionally MOX – although at present, no thermal reactors in the UK are licensed to burn MOX fuel) formed into hard, physically and chemically stable ceramic pellets, and then encased in a Zircaloy cladding. The pellets are difficult to fragment and have to be dissolved in strong nitric acid when undergoing reprocessing. Compared with uranium ores or metal, they are unattractive as a source material for producing weapons-grade materials, although they could be used in crude reactor-grade devices as indicated below. However, should any diversion of material occur, it would probably take place earlier in the fuel cycle, when the extraction process would be much

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[xi] In this context, 'containment' refers to the requirement to contain nuclear materials in specified locations, to which access for adding, inspecting or removing materials is controlled.

less complicated. There is little point in fabricating fuel pellets and then reversing the process, at great expense and difficulty. However, others (e.g. Barnaby, see Footnote 15) argue that the pellets themselves could be used for a crude device based on reactor-grade material, and unirradiated MOX could be used to procure its plutonium content. Further, short burn fuel illicitly removed from the reactor core during an unscheduled outage would have a high Pu-239 yield that might be diverted to the unsafeguarded stockpile once reprocessed or chemically separated. Whilst unlikely in the UK, such matters do require consideration in the case of widespread uptake of nuclear power as discussed in Section 4.

5.5.2 Unsuitability of spent fuel

Uranium consists of two principal *isotopes* (atoms with the same atomic number - and therefore the same chemical behaviour - but different atomic weights), uranium-235 and uranium-238. As stated in section 4.4, only uranium-235 is of use for fission reactions, whether for producing power or explosions. As the fuel is burnt up in the reactor, the proportion of uranium-235 progressively reduces, making spent fuel even less attractive for producing weapons-grade material than fresh fuel at 4% enrichment.

Although the majority uranium-238 content is not fissile, it is able to capture neutrons while in-reactor and eventually produce isotopes of plutonium. Plutonium-239 is fissile and has military applications, but weapons-grade plutonium is over 93% plutonium-239, whereas the plutonium in spent fuel is a lower grade as well as being intimately mixed with uranium and contaminated with other radioactive species. In some cases extraction of plutonium-239 from spent fuel is only possible if the fuel removed from the reactor within a short time, and reprocessed promptly. This principle was used on the Windscale plutonium piles and the Magnox reactors at Calder Hall and Chapelcross, but this is less likely with PWR fuel, as discussed in section 5.5.3. However, THORP has extracted quantities of Pu-239 from spent light water reactor (PWR and BWR) fuels.

5.5.3 Inaccessibility of fuel when loaded in the reactor

Once PWR fuel is loaded into the reactor, it cannot be removed while the reactor is operating. Unlike the UK gas-cooled reactors, which were designed to be refuelled on-load and have machines to remove individual assemblies or elements, the PWRs have to be shut down for refuelling. The vessel head (a substantial steel component weighing up to 100 tons) has to be unbolted and removed, and part of the reactor building must be flooded with water to provide personnel shielding. Only then can the spent fuel be removed. PWR refuelling outages take place every 12 to 18 months, and require significant planning, as well as extra personnel on site. Generally, one-quarter to one-third of the assemblies are removed, and the rest are repositioned (along with the new fuel) to optimise fuel burn-up.

As noted in section 5.5.2, it is suggested that extracting plutonium from spent fuel for weapons use is only possible if the fuel is removed from the reactor after a few months of being loaded, before contamination by other radioactive species becomes excessive. This was achieved routinely on the Calder Hall and Chapelcross reactors (which were originally designated for military use, with power generation as a byproduct), but cannot be done on a PWR without shutting it down every few weeks. As is apparent from the previous paragraph, this would be extremely disruptive, and it is unlikely that either the preparations or the operations themselves could be concealed from the safeguards agencies. But this is essentially a management decision, and, as discussed in section 4, while transparency and scrutiny by a variety of stakeholders may preclude the use of commercial civil reactors for clandestine plutonium production in the UK, this cannot be guaranteed in all countries.

Further, the United States detonated a ‘reactor-grade’ plutonium implosion type warhead in 1962, which demonstrates that plutonium need not be purified to ‘weapons-grade’ to be used in a nuclear device (including a ‘dirty bomb’). Also, the inclusion of around 7% of impurities (mainly prompt isotopes of plutonium and the decay daughter Am-241) does not preclude this material being further refined or used straight in a nuclear device.

5.5.4 Unfavourable economics

As well as the on-site disruption, any reduction in output for clandestine fuel extraction would be extremely uneconomic (as would the replacement of assemblies intended for a 4-6 year dwell after a few months at best). Any new nuclear power station in the UK is likely to be provided commercially. Hiding the poor performance from shareholders, and the market in general, would need to be part of an elaborate cover, which would be very difficult for a public company. But as suggested above, this does not necessarily apply to all countries if nuclear power is taken up more widely, as discussed in Section 4.

5.5.5 Conflict with declared intentions

If a decision is taken not to reprocess the spent fuel, it will remain on site before being transported to a final repository. Consequently, there will be no need for movements of fuel off-site for many years. Spent fuel must be moved in heavily-shielded containers, which need specialist heavy lifting equipment and wagons for transport by road or rail. It is unlikely that any off-site movements of spent fuel could be concealed, whether they took place early in the fuel life or at the end of a normal fuel dwell (ignoring the unsuitability of such material - section 5.5.2). Such movements, when none were expected, would be highly suspicious. However, as indicated above, the on-site storage facilities and transport containers could themselves be used as a ‘dirty bomb’.

5.6 Summary

There are major technical difficulties involved in obtaining weapons-grade material from PWR fuel, and any diversion of nuclear material would be more practicable early in the fuel cycle, before the fuel had been made into pellets, and certainly before it reached a power station. However, the pellets themselves could be used for a crude device based on reactor-grade material, and unirradiated MOX could be used to procure its plutonium content. The safeguards measures that are in place have been effective to date in proving that materials diversion has not taken place. At some time in the future, a government could decide to withdraw from the NPT (as North Korea has done), but this would signal to the international community that something untoward was intended and would almost certainly result in international sanctions – although it can take many years to bring such breaches to a satisfactory conclusion. Withdrawal from the Euratom treaty is not possible, and any attempt to hinder Euratom inspectors from carrying out their duties would again raise suspicions. It is unlikely that either scenario would occur without a major breakdown in international order.
It has not been decided whether or not spent fuel from any new-build nuclear power station will be reprocessed.

Reprocessing of spent fuel is also subject to international safeguards, although there are concerns about the measurability of the stocks of plutonium and highly enriched uranium in a commercial setting dealing with large volumes of these materials. Comments above about potential withdrawal from international treaties also apply here, as do concerns about the effective implementation and policing of treaties. Otherwise, spent fuel will be despatched to a final repository after an undefined period in interim storage. It could potentially be retrieved from either an interim store or a final repository (depending on how inaccessible the final repository was made).

Some commentators (e.g. the MIT study on *the Future of Nuclear Power*, 2003[37]),consider that current international safeguards are inadequate to meet the security challenges of an anticipated global nuclear expansion. The concern is that fuel reprocessing systems as currently practised in Europe, Japan and Russia, has the potential to produce plutonium in a form that could be put to weapons use[37] prefers the adoption of fuel cycles that e.g. leave some contaminants (such as actinides or fission products) with the separated plutonium, though considers a once-through cycle (i.e. without reprocessing) as the best option.

6 HEALTH IMPACTS

This section mainly deals with normal operation. Should it also deal with the likely disproportionate health consequences of untoward releases of radioactivity, the burden of future decommissioning closed down reactors and, in the longer term, any detriment arising out of this generation's disposal of radioactive waste? – or is this too speculative? – or should more work be done on this?

6.1 Potential health impacts of low effective dose exposures

6.1.1 Cancers in general

The current safety standards, for protecting the health of workers and the general public against the dangers arising from ionising radiations, are based on risk factors extrapolated to low dose and low dose rate situations. This is the so-called linear-no threshold (LNT) hypothesis. There are inherent limitations in obtaining empirical information on the health effects of radiation exposure at dose levels that are small fractions of natural background.

Although doubts continue to be expressed about the LNT approach, the consensus is that the LNT model continues to provide an adequate basis (Rowney and Brindon, Amec/NCC). It is therefore adopted in the latest guidance documents from the ICRP[38]. This guidance document states that for the dose response factors at low doses and dose-rates for cancer and heritable effects, the 'uncertainties are considerable but the balance of evidence weighs in favour of the use of a simple proportionate relationship between increments of dose and risk'. However, the hypothesis that there is a threshold dose, below which there are no health effects, cannot be ruled out (Rowney and Brindon, Amec/NCC).

For individuals within identified critical groups, the nominal annual risk of developing a fatal cancer due to nuclear industry activities can be estimated, using the dose-risk factors recommended by the ICRP[38,xii], as:

> *Annual risk of cancer = dose received per year x risk factor*

Taking the estimated critical group annual doses for Hinkley Point C (0.006 mSv) and Louviisa (0.001 mSv) as, respectively, upper bound and typical values for a new-build PWR, the calculated annual individual risks of fatal cancer are 3.6×10^{-7} (approximately 1 in 3 million) and 6×10^{-8} (approximately 1 in 16 million). These risks are clearly extremely low. It should be noted that an involuntary annual risk of 1×10^{-6} (1 in one million) is deemed to be 'broadly acceptable' by the HSE[39].

6.1.2 Leukaemia

Leukaemia is a rare disease and, apart from ionising radiation, little is known about its causes, although its existence pre-dates the nuclear age. UK guidance[40] concludes that the risk factors currently calculated for radiation-induced leukaemia (fatal and non-fatal) are around an order of magnitude lower than the risk factors for fatal cancers. Whilst raised levels of leukaemia in young people have been identified around some nuclear sites, studies of wider groupings have tended not to show increased population risks[41]. In the mid-1980s, evidence of a leukaemia cluster (additional material required here on the two Black reports) around the Sellafield reprocessing plant emerged with seven recorded cases in young people below 25 years of age between 1955 and 1985. A further cluster of

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[xii] These factors are currently under review, and the proposed values are slightly lower than those currently in use. It is conservative, therefore, to use the 1990 recommendations (0.060 Sv^{-1} for the population as a whole and 0.048 Sv^{-1} for the adult working population).

five reported cases emerged at Dounreay a year later. Following on from these local studies, multi-site studies were performed. The largest study so far concerned 4100 cases in children, aged 0 to 14 years, around 29 sites throughout England. Multi-site studies have also been performed in Scotland, USA, Canada, France, Germany, Japan, Sweden and Spain. The general conclusion from such studies is that the probability of leukaemia clusters is no higher near nuclear sites than elsewhere[41]. However, cluster studies tend to have inherent biases in both the analytical methodology and the interpretation of results, and their usefulness is questioned by some[41].

Case control studies have allowed specific hypotheses for causes of childhood leukaemia to be tested. The three main ones are:

- environmental exposure to ionising radiations,
- paternal pre-conception exposure,
- infectious cause.

Such studies have allowed some hypotheses to be rejected, but they do not provide an explanation for the clusters *per se*. Radiological assessments performed around Sellafield and Dounreay do not support a link with environmental exposure; however, in other case control studies around Cap de La Hague (the French nuclear fuel reprocessing plant), this hypothesis could not be ruled out[41] and work is continuing internationally in this area. The paternal pre-conception hypothesis emerged from a UK case study[42] but several subsequent studies, attempting to validate this hypothesis, have effectively invalidated it[41]. The possibility of an infectious agent during the construction of large industrial facilities, combined with a high rate of population mixing in previously rural areas, was first proposed in the 1990s[43]. However, no such agent has yet been found in any child with leukaemia. A more recent study in all Cumbria also supports the association between population mixing and leukaemia risk for ages below 15 years, on the basis of geographical and individual data[44]. Generally, this hypothesis is gaining support but it has not yet been proved[41].

The 2005 report from the Committee on the Medical Aspects of Radiation in the Environment (COMARE)[45] found no evidence for increased rates of childhood cancers within 25 km of NPP sites. There is no reason to believe that a programme of new-build PWRs will change this situation. As discussed above, increased rates of leukaemia and non-Hodgkins lymphoma were confirmed around the Sellafield, Dounreay and Burghfield licensed sites (non-reactor licensed nuclear sites). For other childhood cancers, raised incidence rates were found around Aldermaston, Burghfield, Harwell and possibly Rosyth, although the report [41]suggests these findings may reflect generally raised rates of solid cancers in these areas. The next COMARE report will consider clustering of childhood cancer across the whole of Great Britain rather than specifically around licensed sites.

6.2 Policy context

The Radioactive Substances Strategy within the OSPAR Convention seeks progressive and substantial reductions of discharges, emissions and losses of radioactive substances with the ultimate (long-term) aim of achieving ‘close to zero’ concentrations of artificial radionuclides. In the medium term, the aim is to reduce discharges of radioactive substances such that additional concentrations in the marine environment above historic levels are ‘close to zero’ by the year 2020.

As part of this strategy, national plans are expected to include ‘modifications of discharge authorisations, technical improvements to reduce discharges’. The UK environment agencies, in implementing this strategy, will seek to reduce UK discharge authorisations and, consequently, any potential environmental and human impacts of these discharges.

The UK government strategy, which applies only to liquid wastes, has as one of its aims the reduction of discharges such that '[annual] critical group doses will be less than 0.02 mSv from liquid discharges to the marine environment, as a result of discharges made from 2020 onwards'.

Many environmental groups, such as Greenpeace International, advocate an end to all radioactive discharges, based on a precautionary approach to environmental protection[46] centred on:

- damage prevention
- decisions informed by scientific information
- a progressive reduction of the presence of environmental stressors.

Reference [46] argues that the effect of continued releases of radioactive material into the environment are unpredictable in the long term, that accumulations may be difficult to reverse and that any detrimental effects may be undetectable until it is too late to reduce their overall impact. Inherent in the objective of ceasing all releases of radioactive materials is the presumption that all such releases are potentially detrimental.

6.3 Regulatory framework

There is a strict legal framework for radiological protection of both employees in the nuclear industry and the wider population. The fundamental tenets, in Europe, are laid out in[47], under the Euratom treaty. This is implemented in the UK by the Ionising Radiations Regulations 1999[48].

Under UK law, all employers are responsible for ensuring the safety of employees and the public under the Health and Safety at Work Act. Further provisions apply to nuclear sites, as outlined in section 3. Nuclear site licences contain 36 conditions which set out the safety requirements to ensure the risks on a nuclear site are properly managed. Breach of these Site Licence Conditions is an offence under the Nuclear Installations Act.

The HSE is responsible for regulating nuclear safety, including the safe management, storage and conditioning of nuclear wastes on licensed sites. However, the UK environment agencies (the Environment Agency (EA) in England and Wales, and the Scottish Environment Protection Agency (SEPA) in Scotland), are responsible for regulating discharges of radioactivity into the environment from licensed sites. The discharge of radioactive wastes in the UK are regulated by the Radioactive Substances Act 1993 and the Environment Act 1995. There is a further range of legislation that also applies, including the Environmental Protection Act 1990 and the Pollution Prevention and Control Regulations 2000. The memorandum of understanding[49] between the HSE and the EA to co-ordinate these regulatory roles states that:
'The goals of both HSE and EA are, together:

- To deliver effective and efficient regulation of the nuclear industry in England and Wales
- To maintain and improve standards of protection of people and the environment from the potential hazards from ionising radiations, and
- to ensure that radioactive wastes are appropriately managed in both the short and long term , in accordance with legislation, UK Government policy and international obligations.'

Similar working arrangements are in place in Scotland[50].

In addition, the UK has signed up to two conventions, the North Sea Conference and the Oslo-Paris (OSPAR) Convention, whose objective is to reduce the load of contaminants discharged to the North Sea, including all UK coastal waters. Additional legislation is in place to cover emergency preparedness and decommissioning of existing facilities, but this is outside the scope of the current study.

6.4 Worker doses

6.4.1 Collective radiation exposure

Industry groups like the World Association of Nuclear Operators (WANO) exist with the aim of improving safety at civil nuclear power plants (NPPs) around the world - although some commentators regard this as industry PR. Part of this process is the plant performance indicator programme. Data on performance indicators has been collected and published by WANO since 1991. Among the indicators considered is collective radiation exposure (CRE) for the workforce. This monitors the effectiveness of worker radiation protection across the current civil reactor types. CRE information between 1990 and 2004 is summarised in Table 4 for the three most common reactor types, PWR, BWR and Gas-Cooled Reactor (GCR). It can be seen that, with occasional exceptions, CRE has consistently reduced over time.
A more detailed breakdown of CRE data for European PWRs over the period 2000 to 2004, taken from [51] and [52], is summarised in Table 5. It can be seen that, over this period, the UK CRE is consistently among the lowest in Europe.

6.4.2 Individual radiation exposure

Individual radiation exposure in the nuclear industry is controlled by the implementation of strict health physics procedures. The average occupational dose received by workers in the UK nuclear industry is around 1 mSv per year. – need to clarify and reference – not clear which workers are being referred to: Ionising radiation regulations Classified or are Written Scheme workers included, or could it include all workers at the plant? This is contrasted with other occupational doses in Table 6, where is seen that this is around half the average annual dose received by air crew and substantially less than the dose received by workers in radon-prone areas.

Within any group average dose, there are individuals who receive higher and lower doses than the average. The Nuclear Energy Agency of the Organisation for Economic Co-operation and Development collates occupational exposure data for the nuclear industry. In France, which operates 59 PWRs, generating 78 % of total electricity supply, the average individual dose of all exposed workers (Électricité de France - EdF - and contractors) for 2002-3 was about 1.9 mSv[53]. From October 2001 to September 2003, no one received an annual dose in excess of 20 mSv[xiii] - although we should also discuss the ‘three-tenths’ investigative level of 6mSv at which no further exposure is permitted unless justified. In September 2003, due to an incident at Bugey unit 2, a worker received 17 mSv in the month, bringing his accumulated dose over 12 rolling months to 24.5 mSv. At the end of 2003, 53 workers, working in specialist areas that resulted in high exposure, received doses over 16 mSv on 12 rolling months. Naturally, there would have been many workers with doses below the 1.9 mSv average during the same period.

Corresponding information for the UK’s Advanced Gas-cooled Reactor (AGR) and PWR stations can be found in the British Energy Safety, Health and Environment report series. For example, in 2001 no worker exceeded the company’s internal annual dose limit of 10 mSv, and more than 97% of the workforce received doses below 2.24 mSv[54]. In 2003, the highest individual dose on a British Energy site was 9.14 mSv (for contractor’s staff), with 5.31 mSv being the highest dose to a British Energy employee[55].

[xiii] The International Commission for Radiological Protection (ICRP) individual dose limit for radiation workers is 100mSv, averaged over five years. This is normally treated as an annual limit of 20mSv, as for instance in Ref [1], Principle 11, to ensure that the five-year limit is not exceeded.

6.5 Doses to members of the public

6.5.1 Radioactivity in the environment: Marina II study in the OSPAR region

The European Commission has funded major research programmes to provide information on radiological conditions in the North East Atlantic (OSPAR region). The latest review[56] shows that, by the end of the 1990s, inputs of radioactivity from all sources (excluding the Chernobyl accident in 1986) had decreased by several orders of magnitude since peaking in the 1960s and 1970s. This has resulted in reductions in radionuclide concentrations in the marine environment, individual doses to critical groups and collective doses to European populations. Since the mid-1980s, the main contribution to discharges of beta activity into the OSPAR region has been from nuclear reprocessing plants (Sellafield and Cap de la Hague). either clarify (e.g. discuss significance of alpha, beta and gamma radiation) – or delete

The study also found that nuclear industry discharges were still dominated by the reprocessing of nuclear fuel. In terms of contributing to collective dose, discharges from nuclear power generation, fuel fabrication and research reactors were small (2%) compared with discharges from nuclear fuel reprocessing (10%). Hence, the effect on collective population dose from a new nuclear power station will be very low, especially if spent fuel is not reprocessed[xiv].
Assessment of doses to the UK population
The National Radiological Protection Board (now part of the Health Protection Agency) has assessed the annual average dose to a member of the UK population from all sources of radioactivity (natural and man-made) as 2.6 mSv[xv]. The breakdown from the various sources is shown in Table 7, where it can be seen that over 80% of this is due to natural radioactivity. The natural background activity varies across the country, and is higher in areas where there is radon in the ground or where there are significant amounts of granite. The largest contribution from man-made radionuclides, at 0.37 mSv (14%), is due to medical exposures. This dose is equivalent to around 20 single film chest X-rays, although some individuals can receive doses a few hundred times higher than this and many individuals will receive no dose at all.

The latest available results (2003) of monitoring of man-made radionuclides in food and the environment by the Environment Agencies throughout the United Kingdom, the Channel Islands and the Isle of Man are presented in RIFE-9[57, xvi]. The primary purposes of the monitoring programmes are ‘to provide an independent check on the effects of discharges of radioactive materials in the United Kingdom’, and ‘to ensure that any radioactivity present in food and the environment due to discharges does not compromise environmental or public health’. The environmental surveys are conducted independently of the industries that discharge wastes to the environment[57].

The dose estimates presented in [57] are likely to be overestimates due to the conservative approach taken. The monitoring programme results show that even the most exposed members of the UK public received effective doses from all man-made sources (through the consumption of food and exposure to environmental radioactivity) below the

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[xiv] Assuming that the contribution to collective dose due to reprocessing remains unchanged. In practice, as older plant is retired and efforts to reduce discharges continue, there may be a reduction in this area also.

[xv] This is calculated as the total assessed dose to the UK population divided by the population of the UK. Inevitably there will be variations on this figure, as discussed in the main text.

[xvi] RIFE-10 was published as this report was being prepared. The Foreword to RIFE-10 states that ‘in 2004, there were no major changes in levels of radioactivity in food or environmental materails compared to those in our report for 2003’.

statutory annual dose limit of 1 mSv[xvii]. The most exposed individuals, at 0.62 mSv per year, were people in Cumbria that are assumed to consume large quantities of locally-caught fish and shellfish. This dose is predominantly due to *legacy discharges* (discharges that have occurred in the past, and are now very much lower or have ceased altogether). Of these, 67% were contributed by enhanced natural radionuclides, as a by-product of the phosphate industry in Whitehaven, and 33% came from discharges of man-made radionuclides from the Sellafield reprocessing site.

Analyses of food and drinking water in the general U.K. diet, in areas remote from nuclear sites, were also reported in[57]. The estimated annual exposure for a one year old child, as a result of consumption at average rates, is 0.33 mSv, as summarised in Table 8. In all cases the estimated exposures of infants were higher than older age groups. The results show that radioactivity from natural sources was by far the most significant source of exposure, with man-made radionuclides contributing only 0.023 mSv (7%). Of these, the dominant radionuclide detected was strontium-90, derived from weapons test fall-out, and the remaining man-made radionuclides only contributed around 0.003 mSv (1%). There was some evidence for the effects of radioactive waste disposal into the environment (via discharge of liquids or gases) reaching the general diet, in the form of positively detected amounts of sulphur-35 and tritium. However, for many man-made radionuclides, the results were close to the detection thresholds for the analytical methods in use.

6.5.2 Estimated dose uptake from operational discharges (current UK nuclear power stations)

The annual critical group[xviii] doses estimated from radioactivity measured in food and the environment around current UK NPP sites are summarised in Table 9, taken from [57]. These dose assessments estimate the combined impact of all discharges of radioactivity, both local and remote, current and historic. However, the implication is that the dose estimates are mostly due to discharges from the local site. Several UK NPP sites have more than one reactor design, generally both Magnox and AGR although Heysham has two different designs of AGR and Sizewell has two Magnox reactors and one PWR. Some of the reactors are in the early phase of decommissioning.

The highest dose, at 0.075 mSv, is to seafood consumers at Heysham in Lancashire. However, it is stated that this dose is predominantly due to legacy discharges of liquids from the Sellafield site. The second highest critical group dose, at 0.057 mSv, is at the Sizewell site in Suffolk. Analysis of seafood, sediment, sand, seawater, freshwater, milk crops and fruit near the site generally showed low levels of man-made radionuclides, resulting in critical group doses below 0.005 mSv. However, a further dose contribution is added from radionuclide concentrations in air.

For some sites, in particular the steel pressure vessel Magnox stations, discharges of argon-41 to air are significant whilst the reactors are generating electricity. Argon-41 is a noble gas with a short radioactive half-life (1.8 hours) and does not become incorporated into food produce; however, people living or working nearby may be exposed to external radiation as it disperses downwind from the discharge point (given the half life, the exposure could be for around 12 hours). An allowance for this

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[xvii] The statutory annual dose limit only applies to doses received by the public as a result of practices controlled under[48], such as the operation of nuclear plants. Higher limits apply to classified workers working with ionising radiation. These limits do not apply to patients receiving medical exposure, their comforters or carers.

[xviii] The critical group in any locality are those persons whose lifestyle leads (or is assumed to lead) to the highest radiation exposure in that area.

contribution was included in the assessments performed in [57] for Oldbury[xix], Dungeness A and Sizewell A. These stations will cease electricity generation between 2006 and 2008.

Excluding the argon-41 discharges and the Heysham results (which, it could be argued, have been inflated by Sellafield discharges), the highest critical group doses are in the range <0.005 to 0.03 mSv, and are typically to seafood consumers. For those individuals in the critical group, this adds around 1% of the UK average individual annual dose.
As previously stated, there is some evidence for the effects of waste disposal into the environment (via discharge of liquids or gases) reaching the general diet in the form of sulphur-35 and tritium. Man-made radionuclides from all sources, excluding strontium-90 (derived from nuclear weapons testing and therefore not relevant to this review), contribute around 0.003 mSv, and add around 0.1% to the UK average individual annual dose.

6.5.3 Prospective dose uptake from new build

As stated in section 5.2, the UK strategy on radioactive substances has, as one of its aims, the reduction of discharges such that 'critical group doses will be less than 0.02 mSv from liquid discharges to the marine environment, as a result of discharges made from 2020 onwards'. Hence, if new stations were constructed to replace the electricity generation capacity lost by the Magnox and AGR closure programme, there would be a reduction in overall discharges compared to recent years. It is expected that the discharge authorisations granted to any potential new build plant would be no higher than those currently in force for the most recently constructed reactor, the PWR at Sizewell.

The latest available site specific analysis was performed for the UK PWR build programme, based on the Sizewell 'B' design, in support of the Hinkley Point C public enquiry[58]. The results, summarised in Table 10, show that the highest critical group dose of 0.006 mSv/y was predicted to be due to liquid discharges. This level of dose is comparable to the best of the current operating fleet.

As stated in section 1.1, it is likely that any new reactor build programme would be based on a standardised advanced PWR design, as represented by the Westinghouse AP1000 design and the Areva/Framatome EPR design. These concepts have been developed to be licensable in many countries around the world without modification to the basic design, and the first EPR is currently being built in Finland.

Quantities of radionuclides discharged to the environment during periods of normal operation will depend on the way the plant is operated as well as on the design. European guidance on performing dose assessments for planned discharges of radioactivity is available, e.g. [59]. Such assessments would be performed to support any planning application for NPP construction, as part of the environmental impact assessment (EIA) process. EIAs in support of new NPP construction in Europe have been performed in Finland for sites at Loviisa[60] and Olkiluoto. The estimated critical group exposure at Loviisa [60] was 0.001 mSv/y.

In terms of contributing to public exposure, discharges directly attributable to electricity generation are small, compared to those from the reprocessing of spent nuclear fuel. Although there has also been a reducing trend in these discharges in recent decades, there are still legacy issues in this area causing public concern. Current expectations are that spent fuel from any potential new stations would be stored on site for some time, potentially up to the whole operating lifetime of the station, before a final disposal option is selected. Therefore, in terms of public perception in the longer term, the

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[xix] Oldbury seems to have been included in this list in error: it has reinforced concrete pressure vessels, as does Wylfa, the last of the Magnox stations.

decision to reprocess fuel, or dispose of it directly, is a significant one.

7 CONCLUSIONS

7.1 Conclusion on accident risk

Nuclear power stations in the UK have to be designed to stringent standards which ensure that all reasonably practicable steps are taken to avoid accidents, and to mitigate the on- and off-site consequences of any accidents that might take place. UK civil nuclear power stations have an excellent safety record, with no events reported above INES level 2 (no off-site consequences, enough *defence-in-depth* to cope with additional failures). However, the 1957 Windscale fire, at a military reactor was at least Level 5 INES, with off-site environmental impacts.

Modern reactor designs incorporate safety features that reduce the already small accident risks to very low levels.

7.2 Conclusion on security issues

There are high levels of security at nuclear power stations, and the provisions are regularly reviewed against a Design Basis Threat which is based on current intelligence about terror groups, their intentions and capabilities. Stringent personnel vetting procedures are in place to minimise the possibility of infiltration by undesirable individuals.

PWRs have substantial containment buildings which, on the basis of post 9-11 studies, are unlikely to be breached even by a crashing airliner – although none has been designed with this in mind, and the results might differ if for example specific strikes on a structure including response to hard missiles from the aircraft rather than the overall impact of the crashing airliner were considered. Within the buildings, the fuel is protected against impact and fire by other structures. The defence-in-depth principle means that several layers of protection would have to be disabled to cause an uncontrolled release of activity, with the probability that the reactor would be shut down once a fault was detected. However, it remains difficult to fully account for future changes in the *modus operandi* of terrorist groups and their capacity to exploit weaknesses in the design, operation or security of nuclear power stations and associated infrastructure.

If it is decided to reprocess spent fuel, it will be shipped from the station in heavy, shielded containers that are resistant to attack and theft, although the containers themselves could be regarded as a potential 'dirty-bomb'. The industry argues that the pellets themselves are not easily dispersed even under severe impacting and fire, thus negating any attempt to achieve widespread contamination – but others argue that they could be used in crude reactor-grade devices, Sandia argues that they could be dispersed, and IAEA do not consider MOX to be LDM. Although the fuel would be difficult to convert into weapons-grade material, a crude nuclear device can be made with reactor-grade material, and the possibility of being exposed to life-threatening doses of radiation might not deter fanatics.

The industry view is that although the possibility of a terrorist attack on a nuclear power station cannot be ruled out, nor the ensuing publicity even if the attack failed, it is unlikely that widespread public harm could result. Others disagree on almost every count.

7.3 Conclusion on nuclear proliferation

The UK is bound by the NPT and the Euratom Treaty, which include measures to prevent the spread of nuclear weapons, and has made specific agreements not to divert civilian nuclear materials to military use. Under these agreements, Euratom and the IAEA apply safeguards to verify that no diversion has taken place. Over the years, there has been no transfer of civilian nuclear material to weapons production, which would breach the UK's treaty obligations.

Nevertheless, a number of difficulties in the relationship between civil and military applications continue to cause concern among many commentators[61], including:

- the difficulties of enforcing international treaty obligations;
- proliferation risks associated with the widespread use of nuclear technologies in countries with very diverse systems of governance;
- the resources available to enforce international obligations in a potentially growing number of states with a nuclear capacity; and,
- how to deal with states that withdraw from treaties (e.g. North Korea) or develop nuclear capability outside of them, such as India, Pakistan and Israel, and the suspected development of a nuclear military capability in Iran.

All of these lead to a general concern about making clear distinctions between civil and military uses of nuclear power especially where reprocessing is used.

Safeguards will be applied to any new-build nuclear power station as a matter of course - although there are concerns about the measurability of the stocks of plutonium and highly enriched uranium in a commercial setting dealing with large volumes of these materials.

7.4 Conclusion on health impacts

Radiological protection of both nuclear industry employees and the population in general is covered by a strict legal framework. Statutory dose limits to both groups are a small fraction of naturally occurring levels.

Doses due to the nuclear industry are dominated by spent fuel reprocessing, while those from nuclear power stations mostly originate from older designs which will soon be retired. Dose levels from modern PWRs are very low, and are expected to reduce still further for new-build stations. The calculated risks of a member of the public developing a fatal cancer, due to a new-build NPP, are correspondingly small and considered 'broadly acceptable' by the HSE.

There is no evidence of increased rates of childhood cancers, including leukaemia, around any nuclear power station site. It is not expected that this will change with a programme of new-build stations.

8 GLOSSARY

AGR	Advanced Gas-cooled Reactor
ALARP	As Low As Reasonably Practicable
ASN	Autorité de sûreté nucléaire [Nuclear Safety Authority]
BSL	Basic Safety Limit
BSO	Basic Safety Objective
BWR	Boiling Water Reactor
CCTV	Closed Circuit Television
COMARE	Committee on the Medical Aspects of Radiation in the Environment
CRE	Collective Radiation Exposure
DBA	Design Basis Accident
EA	Environment Agency
EdF	Électricité de France
EIA	Environmental Impact Assessment
EPR	European Pressurised [water] Reactor
EPRI	Electricity Power Research Institute
EU	European Union
GCR	Gas-Cooled Reactor
HSE	Health and Safety Executive
HSW	Health and Safety at Work [Act]
IAEA	International Atomic Energy Agency
ICRP	International Commission for Radiological Protection
INES	International Nuclear Event Scale
LNT	Linear no-threshold [hypothesis]
LWR	Light Water Reactor (i.e. BWR or PWR)
MOX	mixed oxide (i.e. uranium dioxide and plutonium dioxide)
MUF	Materials Unaccounted For
NII	Nuclear Installations Inspectorate
NPP	Nuclear Power Plant
NPT	Treaty on the Non-Proliferation of Nuclear Weapons
NNWS	Non-nuclear Weapons State
NSC	Nuclear Safety Committee
NWS	Nuclear Weapons State
OCNS	Office for Civil Nuclear Security
OSPAR	Oslo-Paris [Convention]
PORV	Pilot-operated relief valve
PWR	Pressurised Water Reactor
RBMK	Reactor Bolshoy Moshchnosty Kanalny (high-power channel reactor)
SAP	Safety Assessment Principle
SDC	Sustainable Development Commission
SEPA	Scottish Environment Protection Agency
SLC	Site Licence Condition
UK	United Kingdom
UNGG	Uranium naturel graphite-gaz (natural uranium/graphite/gas) (similar to Magnox)
USA	United States of America
USSR	Union of Soviet Socialist Republics
WANO	World Association of Nuclear Operators

9 TABLES AND FIGURES

Table 1: The international nuclear event scale

Event type	INES level	Description
Deviation	0	Event with no safety significance
Incident	1	*Anomaly* On- and off-site impact: nil Defence-in-depth degradation: beyond the authorised operating regime
	2	*Incident* Off-site impact: nil On-site impact: significant spread of contamination, *or* over-exposure of worker Defence-in-depth degradation: significant failures in safety provisions
	3	*Serious incident* Off-site impact: very small release - public exposure at a fraction of prescribed limits On-site impact: Major contamination, *or* acute health effects to a worker Defence-in-depth degradation: near-accident - no safety layers remaining
Accident	4	*Accident without significant off-site risk* Off-site impact: minor release - public exposure of the order of prescribed limits On-site impact: significant damage to reactor core or radiological barriers, *or* worker fatality
	5	*Accident with off-site risk* Off-site impact: limited release - partial implementation of local emergency plans On-site impact: severe damage to reactor core or radiological barriers
	6	*Serious accident* Off-site impact: significant release - full implementation of local emergency plans
	7	*Major accident* Off site impact: major release, widespread health and environmental effects

Table 2: Examples of events rated INES 3 and above

Level	Date	Place	Characteristics
7	1986	Chernobyl, USSR (power station)	Widespread environmental and human health consequences
6	1957	Kyshtym, USSR (reprocessing plant)	Large off-site release and evacuation of local population
5	1957	Windscale (military reactor)	Off-site release and restrictions on consuming food produced locally
5	1979	Three Mile Island, USA (power station)	Severe core damage and reactor written off (very limited off-site releases)
4	1973	Windscale (reprocessing plant)	Release of radioactive material into a plant operating area
4	1977	Bohunice A1, Czechoslovakia (power station)	Accident during fuel loading resulted in corrosion damage to fuel and activity release into plant area. Reactor shut down and decommissioned.
4	1980	Saint-Laurent, France (power station)	Partial damage to reactor core: no off-site release (reactor repaired and operated until 1992)
4	1983	Buenos Aires, Argentina (research reactor)	Power excursion due to not observing safety rules while modifying core: caused death of operator
4	1999	Tokai Mura, Japan (reprocessing plant)	Criticality event resulting in two deaths: violation of safety procedures, lax safety management
3	1989	Vandellos, Spain (power station)	Turbine fire degraded plant's safety systems. No core damage or off-site release
3	2005	Sellafield (reprocessing plant)	Leakage of highly active liquid into secondary containment: undetected for several months

Table 3: INES level 0 to 3 incidents in the UK since 1996

Key: DEC Facility being decommissioned
NPS Nuclear power station
REP Reprocessing plant
RES Research facility

Date	Location	Facility	INES level	Brief details
27/8/96	Sellafield	REP	2	Process worker contaminated due to protective clothing being damaged - dose above statutory limits
11/11/96	Hartlepool	NPS	1	Unexpected movement of cold reheat pipework due to condensate build-up
--/2/97	Sellafield	REP	2	Activity-in-air levels increased due to dust being disturbed (collision of shielded container with girder) - doses well within statutory limits
--/2/97	Sellafield	REP	2	Leak from steam supply allowed radioactive liquor to drip onto roof - then washed into surface water drains and road surfaces by rain. No significant doses.
3/3/97	Hunterston B	NPS	0	Reactor gas delivered to clean CO_2 storage tanks with potential to contaminate road tankers
--/3/97	Hartlepool	NPS	0	Sub-surface defect detected during ultrasonic inspection of superheater header
16/4/97	Trawsfynydd (similar event at Berkeley)	DEC	0	Surface dose rates on container for Drigg higher than stated on despatch note and slghtly above permitted level
--/6/97	Chapelcross	NPS	0	Defect identified in heat exchanger bracket
2/10/97	Hartlepool / Heysham 1	NPS	1	Difficulty in determining defect sizes for reactor standpipes from historical records of non-destructive examinations
1/11/97	Windscale (UKAEA)	RES	0	Fire occurred during removal of old Magnox fuel element from container - no release of activity
9/11/97	Sellafield	REP	1	Release of ruthenium-106 from waste vitrification plant
23/1/98	Sellafield	REP	1	Leak of contaminated nitric acid into operating area - no external release
--/3/98	Dungeness B Hartlepool Heysham 1/2 Hinkley Pt B Hunterston B	NPS	1	Incorrectly-set safety relief valves
15/4/98	Hartlepool	NPS	1	Small leak from weld in reheat pipework
21/4/98	Sizewell B	NPS	2	Wiring error during modification - redundancy provisions reduced but plant would have operated correctly on demand
--/--/98	Sellafield	REP	1	Leakage of contaminated water through a defective seal - original drain point blocked
8/7/98	Sizewell A	NPS	0	Cracking of guide tube assembly welds found to be greater than allowed in Safety Case

3/8/98	Sellafield	REP	0	Release of alpha activity from glovebox in MOX demonstration plant - confined to building
17/11/98	Bradwell	NPS	1	Failure of all electrical supplies to Reactor 2 essential supplies board and of some supplies to station emergency board - Operating Rule contravened
27/12/98	Hunterston B	NPS	2	Loss of grid connection due to bad weather leading to double reactor trip - automatic protection systems not reset and subsequent supply problems after second loss of grid. Fault on one back-up generator caused problems in maintaining cooling to one reactor. Reactor conditions remained stable throughout incident.
9/10/00	Sellafield	REP	1	Loss of electrical supplies to large part of plant due to defective component in new 11 kV switchgear - power restored within Safety Case time limit
--/--/01	Hunterston B	NPS	1	Radioactivity discovered in ground water
6/3/01	Sellafield	REP	1	Release of plutonium contamination while changing gloves on glovebox - contained within facility
--/--/01	Chapelcross	NPS	1	Irradiated fuel element failed to release from grab and was lifted out of shielding
5/7/01	Chapelcross	NPS	1	Basket containing irradiated fuel elements dropped during routine operations - 12 elements fell into discharge shaft and remainder were contained within discharge machine.
6/7/01	Sellafield	DEC	1	Localised flooding during rain storm released historic plutonium contamination in laboratory being decommissioned
--/9/01	Heysham 1	NPS	1	Discovery of cracked core bricks during periodic shutdown
--/--/01	Sellafield	REP	0	Discovery of Technetium-99 in borehole
11/3/02	Heysham 1	NPS	2	Failure of short shield plug to disconnect from fuelling machine - plug severed when fuelling machine moved. Lower part fell into storage tube - could have been more serious if operations had occurred over a reactor
12/11/02	Dounreay	DEC	0	Leakage of contaminated zinc bromide into working area - 18 workers received contamination to shoes and/or hands and face. No release to environment
20/4/05	Sellafield	REP	3	Leak of active liquor from THORP pipework into shielded containment sump - no loss to environment. No leak detection equipment fitted and pipe may have been leaking for several months.

Table 4: Summary of the CRE performance indicator (WANO data) ’

	CRE (man-Sv/y) per unit			No. of units		
	PWR	BWR	GCR	PWR	BWR	GCR
1990	1.74	2.76	0.57	218	81	37
1992	1.66	2.66	0.21	227	83	35
1994	1.27	2.56	0.23	234	88	35
1996	1.16	2.24	0.19	246	92	35
1998	0.93	1.75	0.20	247	91	34
2000	0.85	1.26	0.10	250	90	32
2002	0.78	1.23	0.15	255	90	16
2004	0.61	1.22	0.03	259	91	22

Table 5: Average CRE for PWRs by country, 2000-2004[51,52]

	Average collective dose per reactor (man-Sv/y)				
	2000	2001	2002	2003	2004
Belgium	0.35	0.54	0.42	0.38	0.39
France	1.09	1.02	0.97	0.89	0.79
Germany	1.13	0.89	1.23	1.04	0.90
Netherlands	0.56	0.52	0.34	0.26	0.79
Slovenia	-	-	0.58	0.80	0.69
Spain	0.59	0.43	0.49	0.43	0.30
Sweden	0.43	0.35	0.51	0.54	0.58
Switzerland	0.69	0.48	0.51	0.34	0.48
United Kingdom	0.46	0.19	0.30	0.35	0.03
All countries	0.91	0.87	0.88	0.80	0.71

Table 6: Average occupational doses across UK industries (from NPRB ‘At-a-glance’ leaflet *Maps and Magnitudes*)

Occupational group	Average annual dose (mSv)
Medical, dental and veterinary	0.1
Industrial radiography	0.8
Nuclear industry	1.0
Air crew	2.0
Workers in radon-prone areas	5.3

Table 7: Breakdown of annual average dose to the UK population (from NPRB ‘At-a-glance’ leaflet *Maps and Magnitudes*)

Source	Average dose (mSv)
Radon gas	1.3
Food and drink	0.3
Gamma rays (construction materials, etc)	0.35
Cosmic radiation	0.26
Medical	0.37
Work	0.007
Fall-out	0.005
Radioactive discharges	0.0004
Consumer products	0.0004
Total	2.6

Table 8: Estimates of radiation exposure to a one year old child from radionuclides in the diet[57]

Nuclide	Exposure (mSv) to a 1 year old child	Notes
Man-made radionuclides		
Tritium Sulphur-35 Strontium-90 Caesium-137 Plutonium-238 Plutonium (239 + 240) Americium-241	0.0001 0.0004 0.02 0.0002 0.0001 0.0001 0.0003	Also produced by natural means Derived from weapons test fall-out
Sub-total	0.023	
Natural radionuclides (excluding Potassium-40)		
Carbon-14 Lead-210 Polonium-210 Radium-226 Uranium Thorium-232	0.01 0.04 0.08 0.008 0.001 0.0004	Also produced by man
Sub-total	0.14	
Potassium-40	0.17	Levels of potassium in the body are homeostatically controlled[xx] and so exposures do not vary according to the potassium-40 content of food. The average annual dose from potassium-40 in the general diet is 0.17 mSv.
Total	**0.333**	

[xx] This means that the body itself controls the potassium level to an ideal value. An example of homeostatic control is the regulation of body temperature at around 37°C, using mechanisms such as sweating or shivering to correct any imbalance.

Table 9: Estimated individual radiation exposures to critical groups around nuclear power station sites (2003 data)

Site	Exposed group		Total Exposure (mSv/y)
Berkeley (shutdown) and Oldbury	Seafood consumers	adult	0.007
	Inhabitants and consumers of locally grown food	1Yr old child	0.005
Bradwell (shutdown)	Seafood consumers	adult	0.013
	Consumers of locally grown food	1Yr old child	<0.005
Chapelcross (shutdown 2004)	Seafood consumers	adult	0.037
	Inhabitants and consumers of locally grown food	1Yr old child	0.020
Dungeness 'A' and 'B'	Seafood consumers	adult	0.007
	Inhabitants and consumers of locally grown food	1Yr old child	0.11
Hartlepool	Seafood consumers	adult	<0.005
	Consumers of locally grown food	1Yr old child	<0.005
Heysham 1 and 2	Seafood consumers	adult	0.075
	Consumers of locally grown food	1Yr old child	0.006
Hinkley Point 'A' (shutdown) and 'B'	Seafood consumers	adult	0.013
	Consumers of locally grown food	1Yr old child	<0.005
Hunterston 'A' (shutdown) and 'B'	Seafood consumers	adult	<0.005
	Beach occupants	adult	0.007
	Consumers of locally grown food	1Yr old child	0.014
Sizewell 'A' and 'B'	Seafood consumers	adult	<0.005
	Inhabitants and consumers of locally grown food	1Yr old child	0.057
Torness	Seafood consumers	adult	0.005
	Consumers of locally grown food	1Yr old child	0.019
Trawsfynydd (shutdown)	Anglers	adult	0.032
	Consumers of locally grown food	1Yr old child	0.006
Wylfa	Seafood consumers	adult	0.012
	Consumers of locally grown food	1Yr old child	<0.005

Table 10: Annual predicted radiological impact of a proposed PWR station (Hinkley Point C)

	Dose	Radionuclides contributing 5 % or more
Effective dose to the critical group (adult) from liquid discharges	0.006 mSv / y	Cobalt-58 / 60 Caesium-134 / 137 Carbon-14 Iodine-131 Silver-110m
Effective dose to the critical group (1 yr old child) from atmospheric discharges	0.0009 mSv / y	Carbon-14 Xenon-133
Collective dose to the population of Great Britain due to normal operation	0.08 man Sv / y	Carbon-14 Cobalt-60 Cobalt-58

Figure 1: Comparative size of targets (World Trade Center, Pentagon and typical PWR containment)

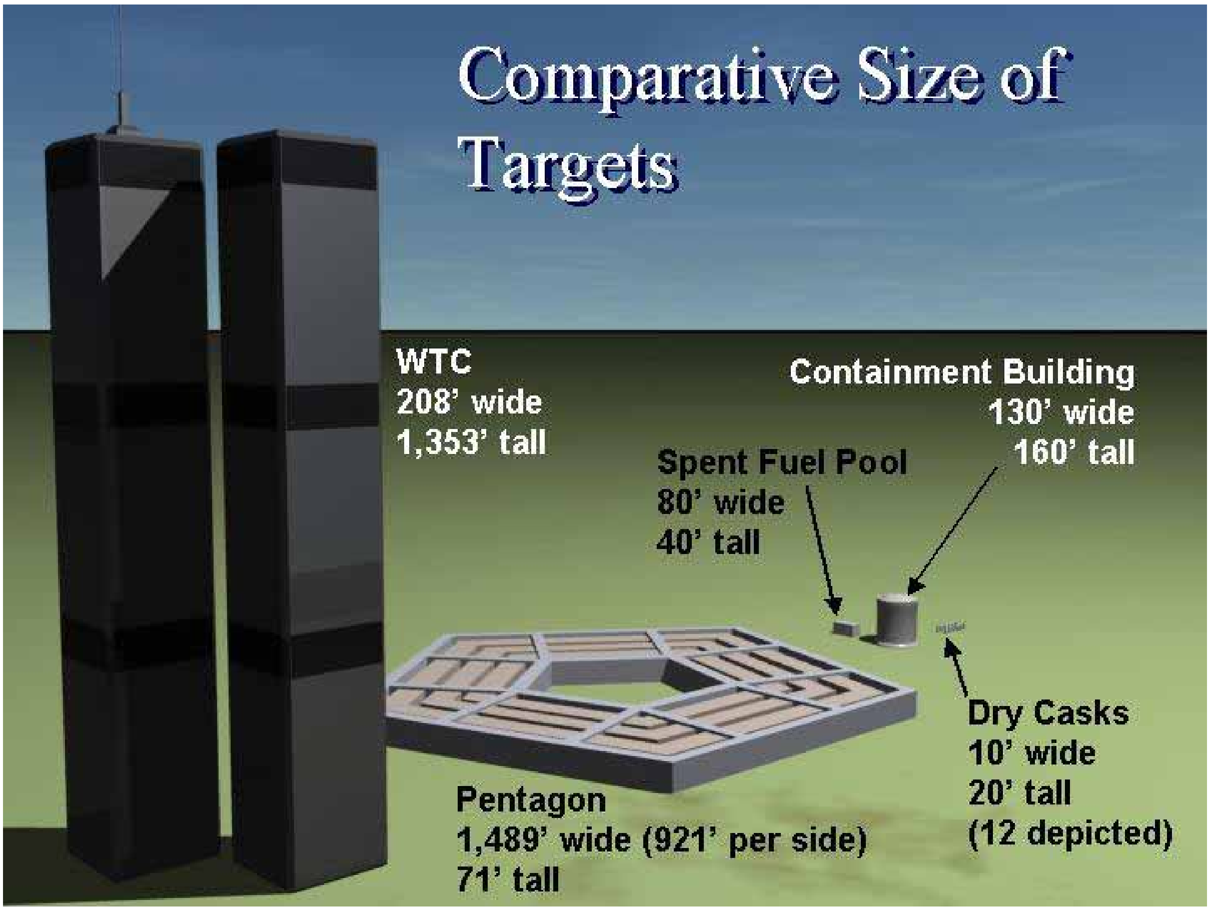
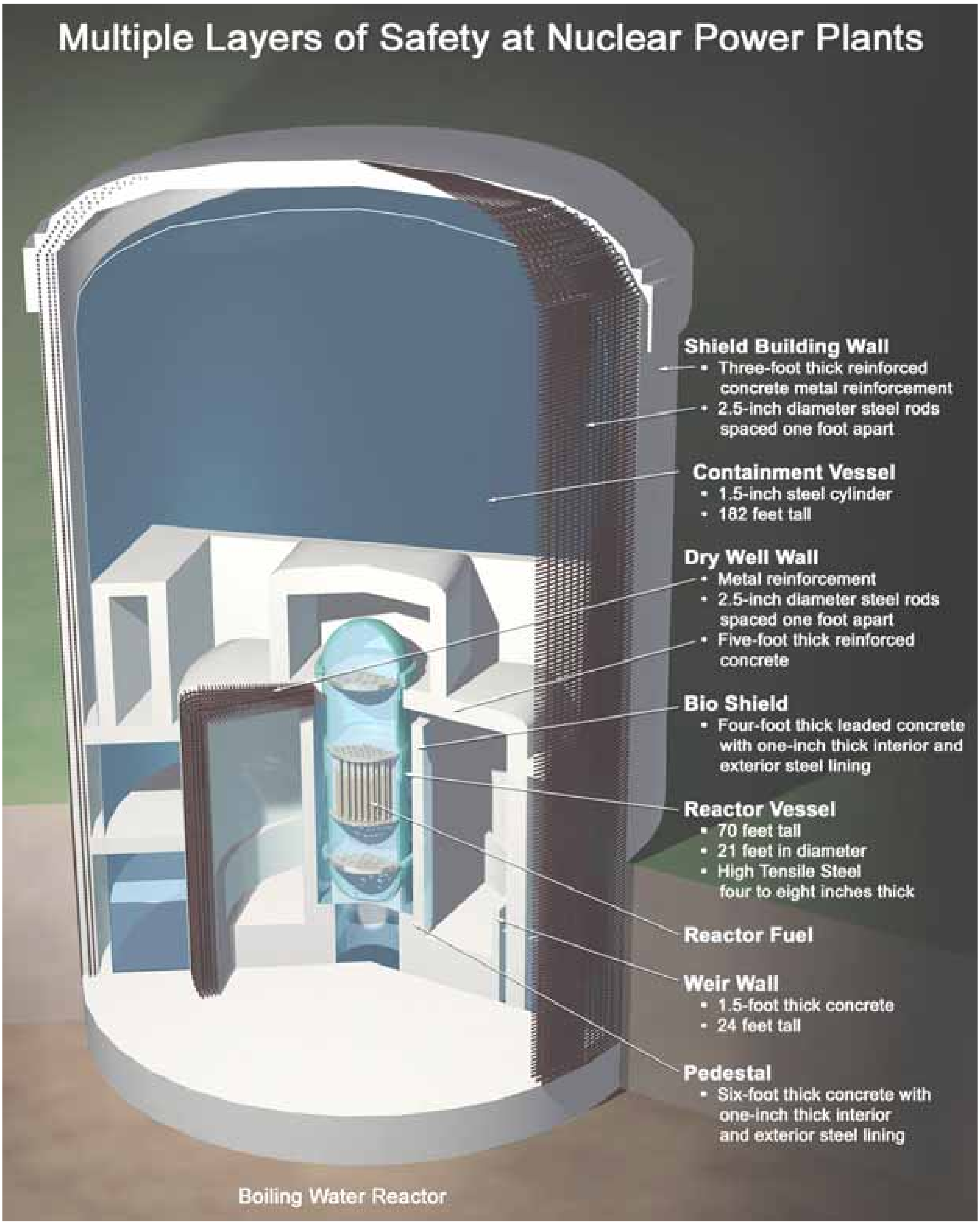


Figure 2: Typical water reactor, showing multiple layers of safety



10 APPENDIX A - SUMMARY DESCRIPTION OF MAJOR NUCLEAR ACCIDENTS

Should we also discuss other nuclear accidents including: NRX, SL-1, FERMI 1, Lucens. Also in the UK the channel fire at Chapelcross (1960s) is of interest and, more recently, the difficulties experienced by HMS Tireless at Gibraltar provide an insight into the British nuclear safety culture.

10.1 Chernobyl (INES 7)

(from [62], adapted)
The accident at Chernobyl Reactor 4 took place shortly after midnight on 26 April 1986. It was intended to carry out an experiment to determine whether, if the reactor was shut down, the turbine would generate enough electrical power (while it was running down) to keep the coolant pumps running before the emergency diesel generator came on line. Since the reactor was due to be shut down for routine maintenance, the test was planned to coincide with the shutdown. To prevent the test from being interrupted, various safety systems were deliberately switched off (including the emergency core cooling system), and the reactor power was to be reduced to 25% of normal. The reactor design is unstable below about 22% power, and the operating computer could be programmed to maintain the reactor above this level. The operators appear not to have done so.

The shutdown started around 0100 the previous day, and by 1400 the reactor had reached 50% power. Because of grid demand, further power reductions were not permitted but, because the shutdown was already in progress, the core was progressively being poisoned by xenon, which is a strong neutron absorber[xxi]. To compensate for this, control rods were progressively withdrawn, leaving only 6-8 in the core rather than the minimum 30. Several automatic reactor trip circuits also had to be disabled, to prevent the reactor from automatically shutting down. The reactor was most unstable at these conditions, and the operators had to make constant adjustments to maintain the power level.

When the turbine was tripped for the start of the test, four of the cooling water pumps were switched off, which would have caused a reactor trip had the protective circuits not been disconnected. The reduced coolant flow caused water to boil rapidly in the pressure tubes which, because of a specific feature of the reactor design, caused a power surge (estimated at 100 times nominal power). This was only made worse when the operators belatedly attempted to insert the control rods. The sudden increase in temperature caused the reactor to overheat, fuel rods burst and the coolant water flashed to steam. The high pressure blew the 1000 ton biological shield off the top of the reactor, rupturing all the pressure tubes and exposing the hot core to the atmosphere. Large quantities of activity were released and contaminated the surrounding countryside, with lesser (but significant) amounts being dispersed over parts of Western Europe.

Thirty one reactor staff and emergency workers died in the accident or shortly afterwards as a result of receiving acute radiation doses. An IAEA report published in 2005 concludes that up to four thousand people could eventually die of radiation exposure from the accident[63]. The Green Party submission to the EAC Inquiry (*Keeping the Lights On*, 2005) quotes Kofi Annan, UN Secretary General as saying (July 2004) that it will be at least 2016 before the full

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[xxi] More technical details can be found by consulting the references by Edwards and Kress, quoted in [62].

number of those likely to develop serious medical conditions as a result of Chernobyl is known.

While the accident can be attributed to the the many violations of safety procedures as the operators were under pressure to perform the experiment at that time. If the test had been aborted, it could not, apparently, have been repeated for another year. The RBMK had a major design fault which led to instability at low power: a similar incident occurred at Ignalina in 1983, with much less severe consequences, but the experience was not passed on to the personnel at Chernobyl. Finally, the communication between the personnel conducting the test and those responsible for operating the reactor seems to have been inadequate.

In the UK, experiments on reactor plant are specifically covered by SLC 22, which requires the licensee to make ‘adequate arrangements to control any modification or experiment ... which may affect safety’ - similar to restraints under the Soviet Gosatomnadzor system. All such modifications or experiments are categorised according to their safety significance, on the basis of the consequences if they were ‘inadequately conceived or executed’. They are subjected to progressively increasing amounts of scrutiny. Those with the highest category, where ‘inadequate conception or execution’ would lead to a ‘serious increase in the risk of a radiological hazard’, must be approved by the NII as well as by the station’s Nuclear Safety Committee (NSC)[xxii]. The NSC includes members that are not employed by the generating company and are therefore less liable to be pressured in any particular direction. Any proposal where ‘inadequate conception or execution’ would lead to a ‘significant but less serious increase in risk’ will at least require the agreement of independent nuclear safety assessors within the company. The experiment would be controlled to strict procedures, and any major deviation (e.g. the requirement to continue generating for longer than envisaged) would have led to the test being aborted. It is extremely unlikely, therefore, that a situation as occurred at Chernobyl would ever have been allowed to develop in the UK.

10.2 Three Mile Island (INES 5)

(adapted from [64])
The accident to Three Mile Island Reactor 2 happened at 0400 on 28 March, 1979, when the reactor was operating at 97% power. A relatively minor malfunction in the secondary cooling circuit caused the temperature in the primary coolant to rise and resulted in the reactor shutting down automatically. Within seconds of the shutdown, the pilot-operated relief valve (PORV) on the reactor cooling system opened, as it was supposed to, to relieve pressure in the circuit. It was supposed to close again after ten seconds but failed to do so. The operators believed that the valve had re-closed, since the instruments showed that a ‘close’ signal had been sent to the valve (there was no instrumentation to show the valve’s actual position).

Since the PORV remained open, water from the primary circuit continued to leak into the reactor coolant drain tank, which resulted in water being pumped into the reactor system to compensate for the loss. As water and steam escaped through the PORV, cooling water surged into the pressuriser (a large pressure vessel that is part of the primary circuit and prevents the primary coolant water from boiling), causing the level to increase. Believing that the system had too much water in it, the operators reduced the flow of make-up water, which had been cooling the reactor core. Eventually they shut down the cooling pumps altogether, due to excessive vibrations. The water then boiled away, partly uncovering the reactor core and causing the fuel to overheat. Most of the fuel core was severely damaged and released radioactive material into the cooling water. A high-temperature reaction took place

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[xxii] The establishment of a Nuclear Safety Committee is itself a Site Licence Condition (SLC 13).

between the fuel pin material (zircaloy) and the water, resulting in the formation of hydrogen.

It was eventually realised that the PORV had stuck open, and measures were taken to isolate it. One cooling pump was re-started, and cooling of the overheated core was restored. The hydrogen gas was periodically vented because of the perceived risk of explosion (a hydrogen burn did occur several hours into the accident, but a more damaging explosion was avoided). A month later, the operators were able to establish natural coolant circulation and were able to shut down the cooling pumps. However, the almost-new reactor was written off and removal of the badly-damaged fuel took until 1991 (about 1% of the fuel and associated debris remains in the vessel, in inaccessible locations).

Measurements taken around the plant at the time of the accident and afterwards showed that radiation releases (those resulting from periodic venting of the containment) were minimal, and the maximum offsite dose was probably 1 mSv (about one-third of the average background received by US residents each year). The average dose to people living within ten miles was 0.08 mSv, equivalent to one chest X-ray. However, inaccurate reporting of plant events (via state and federal agencies) caused a mass exodus of the local population over the weekend of 31 March - 1 April. The only detectable health effect on the local population was psychological stress during and shortly after the accident, and no long-term health effects have been detected.

The accident was caused by the operators misinterpreting a plant malfunction and, as a result, taking measures that only made the situation worse. Plant instrumentation has since been improved considerably, and operator training has been refocussed on maintaining core cooling regardless of the initiating event, following a 'symptom-based' approach. The use of simulators to test the operators on various accident scenarios has become routine.

10.3 The Windscale fire (INES 5)

(although others regard this as INES 7, adapted from [65])
On 7 October, 1957, plutonium pile no.1 at Windscale was shut down for a routine fuel element change. This was a routine operation, but there were plans to modify the moveable atmospheric scanning gear, which was used to detect any failed fuel and was known to jam at high temperatures. This work was to have been done before the reactor next went critical, however the reactor was started up again that evening without the work being done. It was normal practice to establish criticality at low power during shutdown periods, to raise the graphite temperature and release *Wigner Energy*[xxiii]. The pile was again shut down the following morning, but some time afterwards some core temperature instruments indicated a falling temperature. The operators concluded that the Wigner release had not been established, and took the pile critical again for further heating. The rate of temperature increase was clearly excessive, and the operators quickly shut the core down. However, the temperatures failed to stabilise, and the air cooling flow was increased in an attempt to bring them down. On 10 October, a high activity alarm was generated, and further measurements showed that at least one fuel element had failed, causing radioactive particles to be released via the tall ventilation stack. Investigations showed that the fuel elements in one channel were glowing red hot, and had jammed in the channel. The surrounding fuel channels were cleared, and

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[xxiii] Wigner energy is generated when graphite is irradiated and its shape changes. When the distorted material is able to regain its original shape there is a spontaneous release of this energy and an increase in graphite temperature. The only means of heating the graphite to achieve the Wigner release temperature is by operating the pile at an elevated temperature to trigger the release and then, as the Wiger energy is released, progressively closing down the pile's nuclear activity to maintain steady state temperature conditions.

the fire was eventually put out using carbon dioxide and then water.

Radioactivity was released over the surrounding area of west Cumberland, resulting in a ban being imposed on the consumption of milk produced in a 500 km^2 area (this was because enhanced levels of radioactive Iodine-131 were considered excessive for children). The control area was progressively reduced and all restrictions were lifted by 23 November.
The cause of the accident was considered to be the second nuclear heating, which caused the cladding of a considerable number, some of which have never been recovered, to fail. Not all the temperature recordings had shown the temperature to be falling, and some of the instruments were considered to be badly positioned for monitoring Wigner release. The enquiry into the accident recommended, amongst other things, fitting six hundred extra temperature sensors to the undamaged Pile 2 (Pile 1 having been written off) and adopting an alternative method of releasing Wigner energy. In practice, Pile 2, which had been shut down following the accident, was not re-started because the modifications were judged to be either uneconomic or because nobody was prepared to take the risk of another uncontrolled Wigner energy release – the No 2 pile remains today in this 'Wigner charged' condition .

10.4 Saint-Laurent A2 (INES 4)

(from [66], translated into English)
On 13 March 1980, a metal plate inside the reactor dropped onto the graphite core, because of corrosion, and blocked the carbon dioxide coolant flow to twelve fuel channels. The fuel elements in the channels overheated and two of them melted. The reactor was safely shut down and the damaged fuel was removed. Repairs to the reactor took around two and a half years, and the reactor then operated until 1992. There was no off-site release of activity.

10.5 Tokai criticality accident (INES 4)

(from [67])
On 30 September 1999, an accident occurred at the Tokai works of JCO Company Ltd. JCO's main business was the conversion of enriched uranium hexafluoride to uranium dioxide for light water reactor (LWR) fuel, but it also occasionally produced purified uranyl nitrate solution for the Joyo experimental fast reactor. The approved procedure was to dissolve purified uranium oxide powder with nitric acid in a dissolution column, ensuring a batch size below 2.4 kg uranium. However, the procedure had been amended over the years, and JCO staff had for some time dissolved the oxide powder in a bucket, and mixed several batches in a larger storage tank, to ensure a uniform (homogenised) product.[xxiv] On this occasion, a still larger precipitation vessel was used[xxv]. After seven batches of liquid had been added to the tank, with an estimated mass of 16.8 kg uranium, a critical mass was attained and a reaction took place in the tank. The three workers carrying out the process received high doses of radiation. The reaction was terminated some 20 hours later by draining water from the cooling jacket surrounding the tank. In the meantime residents within a 350 m radius of the factory had been evacuated, and those living within 10 km were advised to stay indoors. In practice, doses to workers (except the three involved in the accident) and to local

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[xxiv] The importance of this is that the critical mass (above which a self-sustaining chain reaction will occur) is based not just on the mass of material but on the shape. Neutrons will escape more readily (and therefore be lost to the chain reaction) if the surface area is large, consequently a long, thin shape is better (for a given mass) than a squat one.

[xxv] This met the customer's requirement for 40 litres of solution to be homogenised in one batch. The approved cross-blending method required 10% to be taken from each of ten 4 litre containers, and subdivided into another ten containers. This was clearly more time-consuming, but ensured that all batches remained sub-critical.

inhabitants remained within safe levels. However, two of the workers (one who had been pouring the solution and one who held the funnel) suffered severe radiation sickness, and died about three months and seven months later.

The process amendments had never been authorized, and those processes latterly in place had not been reviewed by a competent authority. Furthermore, JCO had no procedures in place for obtaining approval for process changes. Staff had, in effect, acted on their own initiative. Since the process was only required infrequently, it had not been covered in safety inspections which had taken place when the plant was shut down. There were also licensing deficiencies, in that reviews had focussed mainly on the design integrity of the equipment, rather than on what it was being used for. It was perhaps fortunate that the storage tanks that had been used previously had a favourable (long and thin) geometry, otherwise such an incident might have occurred in previous campaigns where the process had been amended from what had been approved.

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