A Participatory Design Framework: Incorporating Public Views into the Design of Nuclear Power Plants

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Abstract

This thesis presents a participatory systems design framework for the design of a nuclear power plant. The work begins with a review of the so-called ‘nuclear renaissance’, the risks posed by nuclear power as calculated by experts, how the lay-person perceives such risks and how participatory approaches have been used to reduce opposition to new developments in other industries. The review identifies two key questions; firstly, can the public be engaged on the topic of aspects of nuclear plant design and provide meaningful responses? Secondly, can these responses be integrated into the design process of a nuclear power plant in a meaningful and practicable way?

A representative sample of UK citizens (n=1304) were asked 10 questions on their underlying view of nuclear power and then 12 questions covering different aspects of nuclear design in a questionnaire. This data provides a first understanding of what the UK public might desire from the design of a nuclear power plant. Statistical analysis using asymmetric Somer’s D suggests that whilst design preferences relating to nuclear fuel and waste are driven to some extent by underlying views, design preferences relating to reactor design are not. Further research is required to explore and validate this finding.

A new framework for the design of a nuclear plant is documented. A modified Quality Function Deployment (QFD) method is used to combine sets of requirements from different stakeholders and produce a system level specification of a nuclear power plant. The modified method allows requirements from different stakeholders to be individually weighted, resulting in a graphical output showing how different stakeholders have influenced the design specifications. An example set of stakeholders requirements, including those gathered from the UK public as described above, are developed in a case study that demonstrates how the framework can be used to develop plant designs.

An analysis of how this work might impact both Rolls-Royce and the broader nuclear industry is presented and themes relating to lean manufacturing and the combination of standardised modules into customised systems (Standardised Customisation) is proposed. Finally, an overview of opportunities for future research is presented.

Declaration

The author hereby declares that no portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification at this or any other university or other institute of learning.

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Dedication

This thesis is dedicated to the memory of John and Annie, Keith and Jean, without whom I would not be here.

Acknowledgements

The content of this thesis is the product of over four years of work, comprising over 7500 man hours of effort. Over 600 pages of written working notes were made during this time and over a gigabyte of computer storage space used for project files.

None of this would have been possible without the contribution of a significant number of people. Firstly, thanks to my parents David and Mabyn Goodfellow, whose support has been unreserved and essential. Also thanks to my sister Rachel Goodfellow and latterly my partner Jane Krause. My supervisors, Adisa Azapagic, Jonathan Wortley, Hugo Williams and Kris Bradshaw all of whom helped ensure that I considered every project decision fully and that I planned my work appropriately. Without these supervisors, I would not have developed academically to the point where I could produce a thesis such as this. Thanks must also go to Christine Robinson and Paul Dewick of the University of Manchester and the members of the Rolls-Royce Civil Nuclear Advanced Concepts Team, in particular Tony Donaldson and Dan Robertson.

It is also important to recognise my sources of funding, thanks must go to the Engineering and Physical Sciences Research Council (EPSRC) and Rolls-Royce Plc for funding this Engineering Doctorate.

There are many others who deserve mention if there was only the space. They know who are they are and I am thankful for their support.

The Author

Martin J. Goodfellow completed a Bachelor of Science with Honours (BSc(Hons)) in Physics with Astrophysics at the University of York in 2004. He is an elected Member of the Institute of Engineering and Technology (MIET), an Associate Member of the Institute of Physics (AMInstP) and a student member of the Nuclear Institute. His first-hand experience of IT start-ups, global corporations, laser optic design and manufacturing, and long working hours, gained between 2004 and 2008, proved to be valuable preparation for carrying out a doctoral research project. During the course of this research project, Martin spent three months working for the Parliamentary Office of Science and Technology on an Engineering and Physical Sciences (EPSRC) Fellowship. Martin was also part of the joint University of Manchester/Sheffield team that won the 2011 UK Engineering Young Entrepreneurship Scheme (YES) competition.

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Veni, vidi, dedici.

List of Abbreviations

ABWR	Advanced Boiling Water Reactor
ACT	Advanced Concepts Team
AGR	Advanced Gas-Cooled Reactor
ALARP	As Low As Reasonably Practicable
APM	Adaptive Phased Management
ASME	American Society of Mechanical Engineers
BSL	Basic Safety Level
BSO	Basic Safety Objective
BWR	Boiling Water Reactor
CCS	Carbon-capture and Storage
CDF	Core Damage Frequency
CEng	Chartered Engineer
CORDEL	Cooperation on Reactor Design Evaluation and Licensing
CPD	Continuing Professional Development
CRDM	Control Rod Drive Mechanism
DBA	Design Basis Accident
EAB	Environmental Advisory Board
EngD	Engineering Doctorate
EPR	Evolutionary Pressurised Water Reactor
EPSRC	Engineering and Physical Sciences Research Council
EUR	European Utility Requirements
FOAK	First of a kind
GDA	Generic Design Assessment
GMA	General Morphological Analysis
GWe	Giga-Watts electric
GWh	Giga-Watt Hours
HSE	Health & Safety Executive
I&C	Instrumentation and Control
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IET	Institute of Engineering and Technology
IMechE	Institute of Mechanical Engineers
IRWST	In-containment refuelling water storage tank
IT	Information Technology
kW	Kilo-Watts
LOCA	Loss of Coolant Accident
LOOP	Loss of Offsite Power
LWR	Light Water Reactor
MDEP	Multinational Design Evaluation Programme
MIT	Massachusetts Institute of Technology
MOX	Mixed Oxide Fuel
MRWS	Managing Radioactive Waste Safely
MW	Mega-Watts
MWe	Mega-Watts electric

MWth	Mega-Watts thermal
NBD	New-build Delivery
NDA	Nuclear Decommissioning Authority
NGO	Non-governmental Organisation
NIMBY	Not In My Backyard
NRC	Nuclear Regulatory Commission
NSSS	Nuclear Steam Supply System
OECD	Organisation for Economic Cooperation and Development
ONR	Office for Nuclear Regulation
PD	Participatory Design
PGDip	Post-graduate Diploma
PRA	Probabilistic Risk Assessment
PWR	Pressurised Water Reactor
QFD	Quality Function Deployment
RCC-M	Regulations for Conception and Construction - Mechanical
RCF	Rock-Characterisation Facility
RPV	Reactor Pressure Vessel
RRF	Radiation Release Frequency
SARF	Social Amplification of Risk Framework
SMR	Small Modular Reactor
SOARCA	State of the art Reactor Consequences Analysis
SQEP	Suitably Qualified and Experienced Personnel
UCS	Union of Concerned Scientists
UHS	Ultimate Heat Sink
UTC	University Technology Centre

1. Introduction

1.1. Nuclear power, risk and perception

Increasing concerns about energy security, carbon emissions and the impending closure of existing power plants has led the UK to consider nuclear power in order to fulfil a share of its future energy needs (Greenhalgh and Azapagic, 2009). The UK currently has a fleet of 14 Advanced Gas-cooled Reactors (AGR) spread across 6 sites, augmented by one remaining Magnox reactor (scheduled to close in 2014) and a single Pressurised Water Reactor (PWR) (WNA, 2012). A number of new plants are proposed with construction intended to take place between 2018 and 2025. This includes the construction of several Areva Evolutionary Pressurised Water Reactors (EPR) and several Hitachi Advanced Boiling Water Reactors (ABWR) (WNA, 2012). Construction of these plants is contingent on both continued governmental support for nuclear power as part of the UK's energy generation mix and electricity price guarantees. The latter is particularly important in ensuring that new plant projects receive the level of private capital investment required for completion of construction and commissioning. Continued government support depends on nuclear power remaining politically palatable, which in turn is largely dependent on public support for new nuclear build. Public support and opposition to new build has varied significantly in recent times (Goodfellow et al., 2013a) but at present remains relatively strong. Key issues with the potential to limit public support of nuclear power include the perceived safety of nuclear plants and the cost of nuclear energy in terms of both the cost of construction of nuclear plants and of the electricity produced (Goodfellow et al., 2011).

Nuclear power plants are considered by the public to be a risk to people (Pidgeon et al., 2008). The 1986 Chernobyl accident, and to a lesser extent the 2011 Fukushima accident, demonstrated the negative consequences of a hazardous nuclear event. Few other 'everyday' technologies exist with the potential to cause such widespread damage. Importantly, the probability for such hazardous events to occur is relatively low (US NRC, 1990). As of the time of writing (November 2012), over 14700 reactor years (one reactor running for one year is equal to one reactor year) of nuclear operating experience had been gained worldwide (WNA, 2013). In this time, three reactor accidents have occurred with significant wide-scale consequences; Windscale, 1957, Chernobyl, 1986 and Fukushima, 2011 (Fremlin, 1989, Morse, 2011). One other incident, at Three-Mile Island in 1979, also had wide-scale public panic implications; although negligible amounts of radiation were released into the environment (US EPA, 2012). These accidents have clearly demonstrated the potential for nuclear power plants to affect the lives of millions of people.

The level of risk associated with a hazardous event is often estimated as the product of the probability of occurrence and the magnitude of the consequences (Lamarsh and Baratta, 2001). The magnitude of a large-scale nuclear accident is large, therefore significant amounts of time, effort and money have been spent in attempting to reduce the probability that such an event could occur. By applying key principles such as ‘Defence in depth’ and ‘Diversity of Design’, along with ensuring that work is carried out by suitably qualified and experienced people (SQEP) and to appropriate industry codes and standards of practice, the calculated probabilities for large scale radiation releases have been reduced to very low levels; in the region of $1x10^{-8}$ per year (Goodfellow et al., 2011). However, figures like this contrast with the public’s perception of nuclear risk which remains high, with 46% of people in 2011 believing that nuclear power plants in the UK posed a ‘great deal’ or ‘quite a bit’ of risk (Goodfellow et al., 2013a). This disparity between calculated and perceived risk has been explained in part by psychological and sociological theories of risk perception such as Psychometric Paradigm, Cultural Theory and the Social Amplification of Risk Framework (Fischhoff et al., 1978; Douglas and Wildavsky, 1982; Pidgeon et al., 2003). These theories suggest that factors such as dread, control and cultural stigmatisation also play a role in how the public perceives risk.

In spite of this improved understanding, many unknowns remain. Theories of risk perception are only able to account for about 30-40% of the perceptions observed through views expressed by the public, an observation documented by Sjoberg (2000).

Sjoberg also describes how the theories noted above also break down when considering the perceptions of individuals. During the early stages of this research it was discovered that although the public had previously been asked about their general opinion of nuclear power, little or no research had been carried out to understand the effect that specific parts of the design of a nuclear plant have on how the public perceives it (Goodfellow et al., 2011). Krieg (1993) had hypothesized that the public's perception of nuclear plants might change based on modifying plant design in particular ways.

The public are just one of a diverse group of stakeholders involved in the lifecycle of a nuclear power plant. Other major stakeholders include the reactor vendor, the energy utility company (often the 'customer') and local and national government as well as a variety of independent pro and anti-nuclear organisations. The public's relationship with the nuclear industry is complex, as discussed by Nuttall (2006). Although the public is an important end-user of the electricity produced at power plants they are given only limited opportunities to comment on new build proposals and have almost no say at all in specifically what plant will be constructed and how it will look once complete. This lack of opportunity to control what will become a significant part of the local landscape for perhaps over 100 years, can lead to strong feelings of disenfranchisement from the public. Any resolution to this situation would require a means to incorporate a public view alongside the views of other major stakeholders. In order to achieve this in an economically viable way, any intervention on the design of a plant would need to occur early in its design lifecycle at the system level.

A more in depth discussion of the issues raised in this section is presented in Section 2 of this thesis in a review paper on "Nuclear Renaissance, public perception and design criteria: An exploratory review" (Goodfellow et al., 2011).

1.2. Research Aims

The original research proposal for this doctoral research proposed an investigation into how (and if) different parts of a nuclear plant might affect the public's perception of the safety of that plant. Based on a comprehensive review of existing literature, this goal was modified into developing a design framework that would allow for the incorporation of a wider range of stakeholders' views (including those of the lay-public) into the design of new nuclear plants (see Section 2). It was intended that this new design framework would provide a transparent and equitable basis for nuclear designers to engage with the lay-public during the early phases of plant design. Achieving this could lead to improved levels of trust between the nuclear industry and the public and superior plant designs with improved levels of social acceptability.

In order to achieve this new type of participatory design process two key questions must be answered:

1. Firstly, can the public provide meaningful responses to questions about nuclear plant design? and
2. Secondly, if these public preferences can be elicited in a meaningful way, how can they be integrated into the system level design process for a nuclear plant in a transparent and practicable way?

Section 3 of this thesis, Public Perceptions of Design Options for New Nuclear Plants in the UK (Goodfellow et al., 2013a), discusses the research undertaken to answer the first question. This research consisted of the design of a research questionnaire and associated analysis of a survey of a representative sample of the UK population (n=1304) who were asked a series of questions relating to nuclear plant design preferences. Ten questions on the public's existing views on nuclear power were followed by 12 questions on different options for a variety of design features of a nuclear plant and finally a section on the respondents' demographic details.

Section 4, A Systems Design Framework for the Integration of Public Preferences into the Design of a Nuclear Power Plant (Goodfellow et al., 2013b), then covers the novel framework and design tools proposed to answer the second question given above. A new system-level design framework is detailed showing how public engagement and public requirements can be integrated into the design process. A modified Quality Function Deployment (QFD) (Hauser and Clausing, 1988) process is suggested as a means to integrate these alongside existing requirements provided via the European Utility Requirements (EUR) documents. Finally, an example case study is presented that illustrates how the framework can be applied from capturing the initial requirements through to the generation of a system-level concept design. The example concept design is then technically benchmarked against the Areva EPR and Westinghouse AP1000 reactors.

Section 5 of the thesis described the technical steps taken to develop the output from the system level QFD described in Section 4 and turn this into a concept design for a new nuclear power plant. An overview of primary circuit components, secondary circuit thermodynamics and basic safety systems is presented.

The thesis then moves on to discuss the implications of this work for both Rolls-Royce Civil Nuclear and also on the wider nuclear industry in Section 6. A brief introduction to Rolls-Royce Civil Nuclear is provided, and is followed by a discussion of instances where the output resulting from the research documented in this thesis has been applied to on-going Rolls-Royce work. The discussion then considers how the nuclear industry might adapt to the challenge of integrating public views on design and what barriers remain in order to achieve this. In particular, the tension between standardisation of nuclear plants and the additional customisation required for publicly-informed designs is discussed.

In Section 7 potential topics for further research are proposed. Future research themes are divided into three areas; method, deployment and impact. Finally, the concluding remarks are given in Section 7.

1.3. A Brief Introduction to the Engineering Doctorate (EngD) Programme

The Engineering and Physical Sciences Research Council (EPSRC) set up its Engineering Doctorate (EngD) programme in 1992 in response to industry calls for doctoral research projects and training which was more useful to industry. The nuclear EngD programme at the Dalton Nuclear Institute (hosted by the University of Manchester) was established in 2006, coinciding with resurgence in interest (and funding) for nuclear research and development in the UK. Students participating in an EngD programme are referred to as Research Engineers and carry out taught business and technical modules as well as their doctoral research project. The overall aim of the doctoral research in an EngD is the same as that for a PhD; an original contribution to knowledge. However, projects are often focussed on issues of interest to the industrial sponsor company. The intention of the EngD is that the Research Engineer spends a significant portion of their time working at, or with, the industrial sponsor company. In the case of this project, around 75% of the time has been spent based with the industrial sponsor, Rolls-Royce.

Alongside the research component of the EngD are three other professional development and taught elements;

- A continuing professional development programme (CPD) accredited by the likes of the Institute of Mechanical Engineers (IMechE) and Institute of Engineering and Technology (IET).
- A Post-graduate Diploma in Enterprise Management (PGDip). A grade of ‘Distinction’ was awarded.
- Three technical modules (at Masters level).
    - N02 – Nuclear Fuel Cycle (15 credits)
    - N14 – Risk Management (15 credits)
    - SOCY61041 – Protest and Progress (15 credits)

These elements were completed on time and are a compulsory part of the EngD programme. Combined, they are designed to ensure that those undergoing the EngD programme are able to improve a wide range of skills, in both technical and commercial areas. The accreditation of the professional development programme (which includes, but is not limited to, courses on management, industrial law, negotiation, communication and ethics) is designed to assist Research Engineers in progressing towards Chartered

Engineer (CEng) status. It is common for CEng status to be attained shortly after the completion of the EngD.

In addition to the activities already mentioned, the author has attended and presented at both the 2010 Universities Nuclear Technology Forum held at the University of Salford, UK and the 2012 American Nuclear Society Winter Meeting (held in San Diego, USA, from 11th-15th November).

1.4. Justification for Submission as an 'Alternative Format' thesis

The alternative format thesis has several different guises. In this instance, the format in question is one that is conducive to the presentation of a single-coherent project, which for the purposes of academic publication, has been split into distinct sections. In the case of this thesis the main body of work presented herein is split into four sections, three of which are either already published or intended for publication in peer-reviewed journals. The fourth and final section of this thesis comprises the author's assessment of the commercial and industrial impact of the work carried out and potential topics for future research; this is not intended for journal publication.

With such a high percentage of the work being written in the journal article format it made logical sense to apply for permission to submit the thesis in the alternative format. The author of this thesis is the lead author on each of the papers presented. Before each paper is presented a brief overview of the contributions of the other authors is provided; including brief details on their background and, where appropriate, their overall involvement in the project.

Because this thesis is presented in the alternative format, certain information is presented multiple times (this is particularly the case with the various 'Introduction' sections included). This is unavoidable, and will hopefully not detract too significantly from the overall narrative flow of the thesis. References are also included at the end of each paper and each chapter, rather than at the end of the overall thesis. Great care was taken to ensure that all sections of the thesis are properly referenced in a manner befitting such work. Tables and Figures are numbered continuously throughout this document as would be the case in a standard thesis, with the exception of Section 2 which is included in the published journal format. Software limitations prevent headings, tables and figures in Section 2 from being included in the main contents listings.

The appendices associated with the research questionnaire paper (Section 3) are presented with the paper as they would be submitted to a journal as supporting material. All other appendices are presented at the end of the thesis as per standard practice.

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2. Nuclear Renaissance, Public Perception and Design Criteria: An Exploratory Review

2.1. Introduction

The following paper was submitted to the journal Energy Policy on 20th September 2010. It was revised following a double peer review and re-submitted in its final form on 20th June 2011. The paper was published in Energy Policy in October 2011; Volume 39, Issue 10, Pages 6199-6210.

The author of this thesis was the primary author of the paper, and the content of the paper reflects research carried out solely by the primary author under the supervision of the doctoral research supervisors. The paper was co-authored by Dr Hugo Williams (at the time of Rolls-Royce now of the University of Leicester) and Prof. Adisa Azapagic of the University of Manchester. At the time of writing Williams and Azapagic were the Industrial and Academic supervisors (respectively) for this doctoral research project. They contributed by providing comments on draft versions of the paper, guidance on language and writing style appropriate for a peer reviewed journal and contributed to discussions to generate ideas, concepts and topics for research.

The content of the paper included in this thesis corresponds to the final version of the paper as published in the journal. However, the paper was reformatted for publication here with table and figure numbers amended to fit into the structure of this document.

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Nuclear renaissance, public perception and design criteria: An exploratory review

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ABSTRACT

There is currently an international drive to build new nuclear power plants, bringing about what is being termed a "nuclear renaissance". However, the public perception of nuclear energy has historically been, and continues to be, a key issue, particularly in light of the Fukushima nuclear incident. This paper discusses the disparity between perceived and calculated risks based on the last four decades of research into risk perception. The leading psychological and sociological theories, Psychometric Paradigm and Cultural Theory, respectively, are critically reviewed. The authors then argue that a new nuclear-build policy that promotes a broader approach to design incorporating a wider range of stakeholder inputs, including that of the lay public, may provide a means for reducing the perceived risk of a nuclear plant. Further research towards such a new approach to design is proposed, based on integrating expert and lay stakeholder inputs and taking into account broader socio-cultural factors whilst maintaining the necessary emphasis on safety, technological development, economics and environmental sustainability.

1. Introduction

Around the world, a number of countries are investing in or considering building new nuclear power plants. This new-build activity, the so-called "nuclear renaissance", is in stark contrast to muted nuclear build activity over the last 20 years.

The main drivers for this renaissance include climate change, an impending electricity generation gap and security of fossil fuel supply; however, a number of barriers to constructing new nuclear power plants also exist, with one of the most significant being public perception (Greenhalgh and Azapagic, 2009).

Public perception of nuclear power has been an active research topic for decades, with numerous studies reporting on the level of public support for, or opposition to, nuclear power (Eurobarometer, 2010; Poortinga et al., 2005) and how this support has varied over time (MORI, 2009). Investigations into the underlying psychological (Fischhoff et al., 1978; Slovic, 1987) and sociological (Douglas and Wildavsky, 1982; Wildavsky and Dake, 1990) factors that govern these attitudes have also been carried out.

The recent events at the Fukushima Daiichi nuclear power plant in Japan have resulted in a renewed focus on understanding both the safety of nuclear power and the public understanding and level of acceptance of nuclear power. Whilst it may be some time before the full impact of the Fukushima incident on the public perceptions of nuclear power become clear, research carried out shortly after the event suggests that there has been a slight negative impact (FoE and GfK NOP, 2011). The potential causes of such shifts are described in Section 3 of this paper.

Negative public attitude toward nuclear power has often had far-reaching consequences for the nuclear industry. For example, the previous proposals for construction of new nuclear power plants at Sizewell B (O'Riordan, 1984; O'Riordan et al., 1985) and Druridge Bay (Baggott, 1998) in the UK have led to significant delays and cancellation of the whole project, respectively. These and other similar examples around the world highlight the importance of understanding why the public objects to nuclear plants to help address these objections in a more informed and strategic way.

In an attempt to contribute to this aim, this paper focuses on new nuclear build, using the UK case as an example. It first compares and contrasts the *calculated* versus *perceived* risks from nuclear plants. The paper then proposes how the current body of knowledge on calculated and perceived risks could be integrated within a novel decision-support framework to influence changes to the design, or design process, of nuclear power plants. It is

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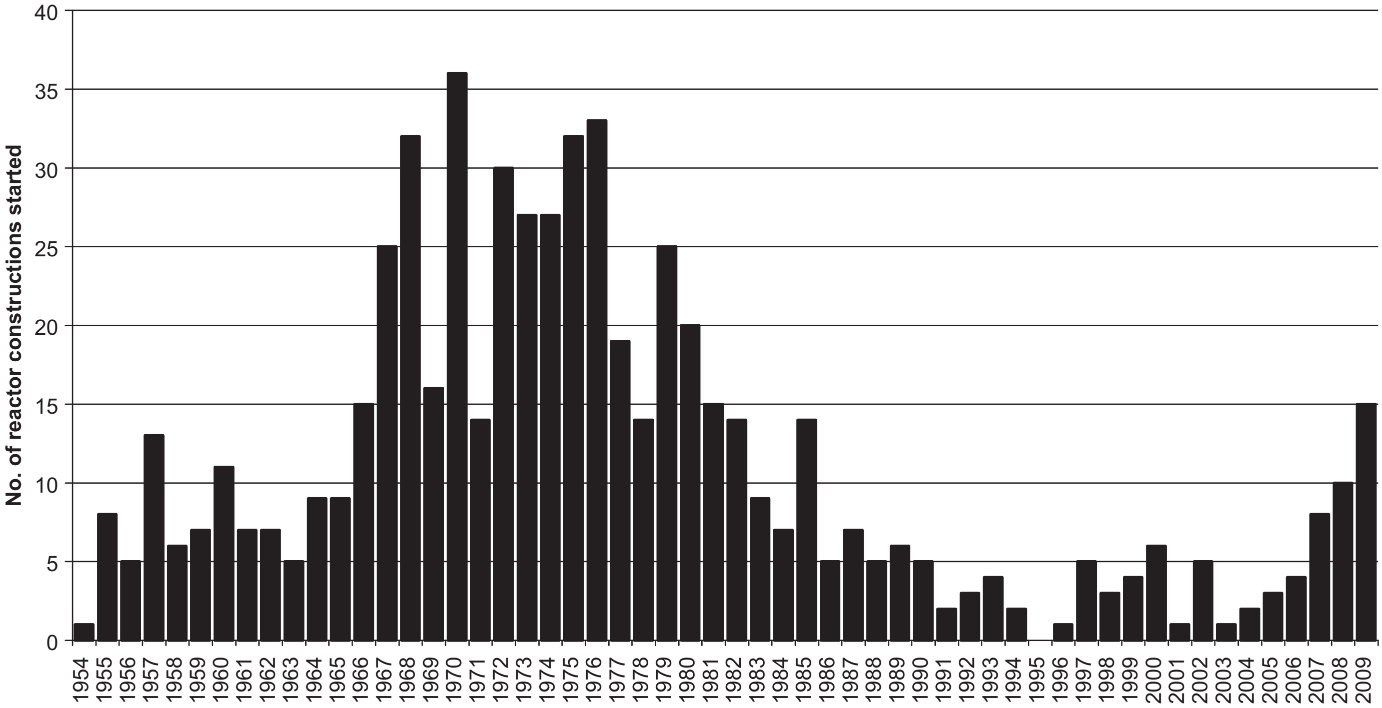

Fig. 1. Nuclear new build from 1954 to 2009 (based on the data from IAEA (2009)).

intended to go beyond simply proposing better communication or education programmes, aiming instead to provide a socially informed approach to design that could potentially help towards addressing social concerns about nuclear power plants. However, to understand better some of the social concerns related to new nuclear build, it is important first to appreciate the influence of the previous nuclear build. This is discussed in the following section.

2. The nuclear renaissance

2.1. Drivers for new nuclear power plants

The historical rate of nuclear plant construction around the world is shown in Fig. 1. The pronounced drop in new build activity during the 1980s may, at least partially, be attributed to various national government policy shifts following the Three Mile Island and Chernobyl incidents in 1979 and 1986, respectively. The legacy of these events may be seen continuing throughout the 1990s and early 2000s with only a small number of new power plants. However, predictions by the nuclear industry foresee an increase in nuclear capacity from the current level of 373 $\mathrm{GW_e}$ up to between 1100 and 3500 $\mathrm{GW_e}$ in 2060, depending on the level of priority and political commitment given to new nuclear power (WNA, 2010d).

The countries in Europe with current significant nuclear power capacity are France, Germany, Russia and the UK. Several Scandinavian and Eastern European countries such as Sweden, Finland, Ukraine and Hungary also have nuclear programmes. The UK and a majority of the European countries that currently have nuclear energy programmes have announced their intention to expand, or at least extend, current operations. This is with the notable exception of Germany, which has declared that it will phase out all nuclear power generation over the coming decades (von Weizsacker, 2005), although more recently there have been some indications that the existing power plants may see a life extension (Nolan, 2009). However, following the recent events at Fukushima, this decision has been called into question (Harding, 2011).

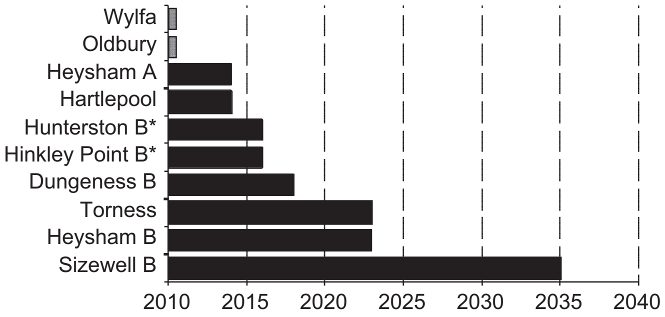

Fig. 2. Predicted UK nuclear plant lifetimes (DTI, 2006) (* denotes life extensions are already in place (WNA, 2010c)).

Looking at the new build situation in the UK, for example, one key driver for new nuclear power is the shutdown timescale associated with the existing fleet of nuclear power plants (Greenhalgh and Azapagic, 2009). The timescale for the shutdown of the present generation of nuclear reactors in the UK is shown in Fig. 2. The decision to decommission these plants largely relates to technology lifespan. Where technically and economically viable, life extensions for some of these plants will be sought, but the Oldbury and Wylfa plants are scheduled to shutdown in 2012 (NDA, 2011a, b). Both plants use Magnox[1] fuel, which is no longer in production (Tynan, 2010).

A second driver for new nuclear build to consider in the UK is the Government's commitment to reduce national carbon emissions in an effort to address climate change. The Climate Change Act 2008 (DECC, 2008) legally commits the Government to reducing the UK's carbon emissions by 35% by 2020 and by 80% before 2050. Meeting these ambitious targets will require low-carbon technologies across all sectors, but particularly in the

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[1] MAGnesium Non-OXidising alloy clad assemblies containing natural (non-enriched) metallic uranium fuel.

power industry. Fossil fuel plants have historically provided the majority of UK electricity generation and whilst Carbon Capture and Storage (CCS) retrofits to these plants have been proposed, CCS remains unproven on a commercial scale (DTI, 2007). Nuclear power on the other hand is already part of the UK energy mix and its increased generation could help towards meeting the climate change targets in the medium term.

A third factor relates to energy security. During the 1990s, the UK Government de-regulated national electricity generation which led to the so-called ‘‘dash for gas’’. Between 2003 and 2007, UK changed from exporting 91,000 GWh of gas to now importing 215,000 GWh (BERR, 2009). This has left the UK highly reliant on foreign gas supplies, reducing the nation’s energy security. Besides, stability of gas supply depends heavily on the source and any fluctuations in supply can rapidly affect the price and availability of gas-generated electricity (Watson, 2010).

With plant lifetimes, greenhouse emissions and energy security in mind, the UK Government presented a review of the energy situation in its 2007 white paper, ‘‘*Meeting the Energy Challenge*’’ (DTI, 2007). This was followed by a white paper on nuclear power (BERR, 2008) which laid out the Government’s plan to include new nuclear power stations in the future energy mix. In these documents the Government also laid out how it intended to make the process of building new nuclear power plants more streamlined, by having a single national consultation on nuclear power, and then narrowing the remit of the local planning procedures to include only local issues. This streamlining was intended to establish industry support for new build right at the outset of the new build programme with the aim of making investment in nuclear power less prone to risk, and therefore more attractive to industry. The Government also stated in the above white paper that it believed that any new nuclear power plants must be built, managed and decommissioned by the private sector and that no subsidies for such activities would be made available (BERR, 2008). This in turn means that a lack of subsidies or financial guarantees places the burden of financial risk on the private sector, potentially raising a significant barrier to new build.

The May 2010 UK General Election saw a Conservative/Liberal Democrat coalition take power. The coalition government has stated that it supports the previous policy of removing ‘unnecessary’ barriers to new nuclear plant construction in the UK, while emphasising that there will be no public subsidy for any new nuclear build (Hendry, 2010). It remains to be seen if the influence of the historically anti-nuclear Liberal Democrats will change this stance over time.

The nuclear plant licensing process is key to nuclear new build. This process involves an in-depth justification of the safety of the nuclear plant to satisfy regulatory bodies. An overview of licensing is covered in the following section, as an introduction to risk discussed later in the paper.

2.2. Licensing nuclear plants

Responsibility for nuclear plant licensing rests with national regulatory agencies. The International Atomic Energy Agency (IAEA) publishes a variety of safety requirements, standards and guidelines that can be applied by national regulators. The IAEA does not function as an overarching international regulator but does foster international cooperation on safe application of nuclear energy (IAEA, 1956). There is no single international design standard for nuclear plants and different national regulators require reactor designers to demonstrate the safety of their designs via different approaches.

In the UK, for example, the nuclear regulator is the Office for Nuclear Regulation (ONR) (Podger, 2011). Under the UK regime, the onus is on the plant designer and operating utility to demonstrate a thorough analysis of the design against a series of high-level safety objectives and a limited number of numerical targets. This is a direct influence of the UK health and safety law and the As Low As Reasonably Practicable (ALARP)[2] principle. First, the risk of death or radiation dose is calculated and compared against numerical target Basic Safety Levels (BSL) (HSE, 2006). If unacceptable, this risk is further reduced by design to be as low as reasonably practicable (HSE, 1992). The regulator will expect the designer to make significant improvements against the BSL, justified by some form of cost-benefit analysis. A target termed the Basic Safety Objective (BSO) defines a risk that could be considered ”broadly acceptable”—providing it had been shown that further improvements incurred ”grossly disproportionate” cost (HSE, 2009).

In the United States, the Nuclear Regulatory Commission (NRC) issues explicit numerical and design standards for aspects of nuclear plant design, from individual sub-systems to overall calculated probabilistic safety goals. Reactor designers and operators must demonstrate via analysis and/or test that these prescribed targets are met.

In general, the differing philosophies of the UK and US regulatory approaches can be considered as the cases at the opposite ends of the spectrum, with the majority of other countries following a prescriptive regulatory format closer to the US approach. It is unusual though for a nuclear plant design approved by a regulator in one country to be accepted in another country without some modification being required. Harmonisation of design standards is being pursued (WNA, 2010a) but is still some way from being realised.

Two nuclear plant designs are currently undergoing assessment by the ONR for suitability for new build in the UK: Westinghouse’s Advanced Passive 1000 MW_e plant (AP1000) (WEC, 2008) and Areva’s Evolutionary Pressurised Reactor (EPR) (AREVA, 2008). Both designs have already been approved in their countries of origin (US and France, respectively) and are currently in the Generic Design Assessment (GDA) phase. GDA consists of a safety and environmental impact assessment of the nuclear plant design; site-specific assessment will form part of the next phase. Technical reports and comprehensive descriptions of plant features are available via the HSE website (HSE, 2010), and the public are invited to comment on the designs via the internet.

Much of the evidence provided in the licensing process is presented in the form of calculated risk. As shown in the following section, calculated risk is a highly technical subject used in engineering and there is much evidence that suggests that the lay person is unable to comprehend its meaning (Carlisle, 1997; Kahneman and Tversky, 1974, 1979; Slovic, 1987; Tversky and Kahneman, 1992). This is arguably one of the reasons why the public continue to object to nuclear power despite the very low calculated risks. This disparity between the *calculated* and *perceived* risk is discussed in the next section, with the aim of understanding better the way in which the nuclear design process could be changed to take into account lay-public views and perceptions of risk.

3. Calculated and perceived risks from nuclear plants

There is no simple way to define the difference between calculated and perceived risk, as perceived risk is difficult to define. However, the main difference is that calculated risk represents an attempt to define risk ‘objectively’ using various mathematical approaches (as, for example, expressed by Eq. (1) in

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[2] ALARP is a legal regulatory test which is applied under UK law to matters of health and safety. In short, operators and designers must be able to demonstrate that risk levels have been reduced to a level ‘‘as low as reasonably practicable’’, where ‘‘practicable’’ may be considered in terms of the amount of time, money or ‘‘effort’’ expended to reduce risk levels further.

Table 1
Probabilistic risk application levels (US NRC, 2007).

PRA level	Description	Typical outputs
1	Considers individual reliabilities of components and sub-systems of plant in a fault or event tree format to determine what events might result in damage to the reactor core, usually due to overheating.	Core Damage Frequency (CDF) [a]
2	Using events leading to core damage (Level 1 PRA) as a basis, the probability, magnitude and timing of a significant release of radiation to the environment is determined. This is usually the combination of core damage and a failure of the containment summarised into a large (or 'early') release frequency. Essentially this is a radiation release that requires an off-site emergency response.	Radiation Release Frequency [b]
3	Taking the radiation release frequency and characteristics as an input, environmental dispersal and public exposure is used to determine the health or economic consequences. This can be expressed in a number of ways, but commonly as the frequency of death caused in the first few hours after a radiation release (short-term health effects) or by considering longer term health effects such as increased incidences and mortalities of various types of cancer.	Early death frequency (Short-term) or Excess Mortality rate/Latent Cancer fatality (Long term effects)

[a] Core Damage Frequency (CDF) is the frequency expected for an accident or event occurring that damages the reactor core. It is often expressed as a probability per year, e.g. 1×10^{-5} (or 1 in 100,000 years).

[b] Radiation Release Frequency (RRF) is the frequency expected for an accident or event that leads to radiation being released from the containment structures of a nuclear plant. This often follows a CDF event and is often expressed as a probability per year, e.g. 1×10^{-6} (or 1 in 1,000,000 years).

Table 2
Summary of results from PRA studies on nuclear reactor plants (*all values represent probability per reactor per year).*

	Safety goals		***PRA of operating plants***		**PRA used in New Nuclear Plant Designs**	
	US NRC	**UK HSE**	**Wash-1400**	**Nureg-1150**	**Areva EPR**	**WEC AP1000**
	(US NRC, 1990)	*(HSE, 2006)*	*(US NRC, 1975)*	*(US NRC, 1990)*	(HSE, 2007)	(WEC, 2009)
Date	***1991***	**2006**	**1975**	**1991**	***2007***	***2007***
Core Damage Frequency (CDF) (Level 1)	N/A		$\sim 1 \times 10^{-4}$	$\sim 5 \times 10^{-5}$	6.1×10^{-7}	2.41×10^{-7}
Radiation Release Frequency (Level 2)	N/A		$\sim 5 \times 10^{-4}$	$\sim 5 \times 10^{-5}$	3.9×10^{-8}	1.95×10^{-8}
Early Death Frequency (Level 3)	5×10^{-7}	ALARP	$\sim 10^{-5}$	$< 10^{-7}$ [a]		
Excess Mortality or Latent Cancer Fatality (Level 3)	2×10^{-6}	BSL 10^{-4} BSO 10^{-6} [c]		$< 10^{-7}$ [b]		

[a] Typical mean probability between 5×10^{-11} and 2×10^{-8} but report suggests all results below 10^{-7} should be viewed with caution.

[b] Typical mean probability between 1×10^{-8} and 4×10^{-10} but report suggests all results below 10^{-7} should be viewed with caution.

[c] Basic Safety Level and Basic Safety Objective define limits on 'tolerable' and 'broadly acceptable' risk. PRA results must be supplemented to show risks are ALARP.

Section 3.1) while the perceived risk tries to account for subjective factors of psychological and sociological nature calculated risk does not include. This is discussed in more detail below.

3.1. *Calculated risk*

Nuclear plants consist of complex sub-systems with many components, often with various layers of 'redundancy' in an effort to increase safety. Components or sub-systems may function continuously, intermittently or only in an emergency situation. In normal operation, components or sub-systems are almost certain to be taken off-line for maintenance periodically. Components may fail in service by a number of different modes, for example a pump may cease to function, may fail to switch off or may leak even when not required to run. Whilst not mathematically infinite, it is easy to see that the combinations of failure modes in different operating regimes make obtaining a single numerical risk figure extremely challenging.

Probabilistic Risk Assessment (PRA) is one of the methods most often used to calculate risk from nuclear plants. In PRA, risk is characterised by the probability or likelihood of occurrence of an adverse event and the severity or magnitude of the possible adverse consequences of that event. It is calculated as

$$R = \sum_{i=1}^{n} p_i \bullet C_i \tag{1}$$

The above equation states that the level of calculated risk R associated with an event is the product of the probability p_i of a risk event occurring and the magnitude of the consequences C_i of such an event, summed over all occurrences of the event. For the purposes of this paper, this is termed "calculated risk" to differentiate it from "perceived risk" discussed further below. The implication of this definition is that a simple probability is not a risk, since it does not take account of a consequence. In the nuclear context, the magnitude of consequences might relate, for example, to fatalities or a reduction in life expectancy associated with a given radiation dose.

Applying Eq. (1) to each component in a nuclear plant is difficult due to the amount of data required to understand the probability of every potential component failure. The level of redundancy and diversity in components means a sequence of events must occur for an event causing measurable consequence to occur. Two most common methods for PRA are fault- and event-tree analysis (Bedford and Cooke, 2001) which provide a calculated risk, often expressed as a probability but implicitly incorporating increasing levels of consequence as described in Table 1.

A selection of PRA results for some nuclear plants is presented in Table 2. One of the first probabilistic risk analyses of a nuclear plant was carried out in the USA and is commonly known by its document name, WASH-1400[3] (US NRC, 1975). The report focused on the risks associated with commercial Pressurised Water Reactors (PWR) and Boiling Water Reactors (BWR) in the USA. WASH-1400 stated that the frequency of deaths caused by nuclear power in a country the size of the USA, with 100 operational reactors, would be around 100,000 times lower than the total frequency of deaths caused by all natural disasters in the USA per year. The report was criticised by non-governmental organisations (NGO) such as the Union of Concerned Scientists (UCS) who accused it of lacking clarity

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[3] Now NUREG-75/014, or commonly known as the Rasmussen Report.

and presenting long-term fatality predictions in a misleading manner (UCS, 1977).

In 1991 a new report, NUREG-1150 (US NRC, 1990), was published as an update of WASH-1400. NUREG-1150 compared its results to WASH-1400 and demonstrated that in many ways nuclear safety had improved and concluded that this was a direct result of improvements in both the design of the plants and the operating procedures in place at the plants studied.

The Level 3[4] calculated risk of around $\sim 10^{-7}$ fatalities per plant per year published in NUREG-1150 (US NRC, 1990) is broadly in agreement with results determined for similar plants in Europe (Slaper and Blaauboer, 1998), although the later study focused solely on long-term health effects. For reference, this level of calculated risk is similar to the probability of death caused by other "rare" events, such as being struck by lightning, which was calculated (for the USA) to be 4.2×10^{-7} per person per year (Curran et al., 2000). The UCS (and others) again raised serious concerns about the validity of the NUREG-1150 study, criticising assumptions made such as "zero violations of safety regulations" as unrealistic (Lochbaum, 2000).

Based on the criticisms of NUREG-1150, the NRC has instigated a further study, State of the Art Reactor Consequence Analyses (SOARCA), which aims to take into account for a much wider range of accident initiation factors in order to provide an improved assessment of the risks (US NRC, 2009).

The above-described PRA studies were conducted retrospectively, whereas the PRA process is now integral to the design of new plants. Levels 1 and 2 PRA can be conducted at the generic design stage and the full Level 3 PRA becomes more appropriate once a specific site is chosen. For example, Table 1 shows the Level 1 and 2 PRA results for the AP1000 and EPR presented in the manufacturers' safety documentation during the GDA phase. These data indicate a further fall in calculated risks that can be attributed to a variety of factors including the PRA method being used and the incorporation of plant operating experience into the designs.

The key conclusion of this section is that integrating operational experience and improved PRA methods with plant design has resulted in significant reductions in calculated risk levels (three to four orders of magnitude over a period of 30 years as shown in Table 2). However, as with any analytical method, there is always uncertainty as to the accuracy and completeness of the models used, especially for events of very low probability. In spite of the many safety improvements made and the fact that nuclear power is calculated to be significantly safer than many other everyday activities, the following section shows that the public still perceives nuclear power as a high-risk activity.

3.2. Perceived risk

3.2.1. Public support for, and opposition to, nuclear power

A great deal of research has been undertaken into the public perception of nuclear power, in part because the controversy of nuclear power has been present since the inception of the technology (Kasperson et al., 1980). Of recent surveys, the pan-European *Eurobarometer 324 – Europeans and Nuclear Safety* (Eurobarometer, 2010), and its predecessor Eurobarometer 271 (Eurobarometer, 2007), are significant owing to the size of the samples used. In both surveys, around 27,000 individuals across 27 European countries were questioned face-to-face on a wide variety of nuclear issues.

Eurobarometer identified a spectrum of beliefs relating to the advantages and disadvantages of nuclear power. People were asked to state what first came to mind when they thought of nuclear power—that the advantages outweigh the risks, or the risks outweigh the advantages. People living in countries that have existing nuclear power generation capacity tended to be more positive about nuclear power than those from countries without existing capacity, stating that the advantages outweigh the risks. People in France, Germany and Spain were the exception to this result, displaying a more negative viewpoint (risks outweigh advantages), in spite of the presence of current nuclear power plants. Since France generates over 75% of its electrical power from nuclear plants (WNA, 2010b), it is perhaps surprising that 53% of the country's population believes that the risks of nuclear power outweigh the advantages (Eurobarometer, 2010). Research into cross-cultural risk perceptions has identified a number of underlying reasons that might explain such disparity, such as cultural collectivism, or the bias between individual and societal influence in determining values and goals (Weber and Hsee, 1998).

Eurobarometer also found that a substantial proportion of people (74%) in the EU felt they were not well informed in relation to nuclear plant safety. Additionally, 46% of people in the UK believed that construction of new nuclear plants was already underway in the UK; in reality, it is likely to be at least two or three years before any construction work begins.

Results obtained in the UK by Ipsos MORI (MORI, 2007, 2008, 2009) using samples of approximately 2000 people showed a downward trend in how well the public felt they knew the nuclear industry—down from 27% of "know very well/a fair amount" in 2007 to just 17% in 2009. However, in a wider context, it appears that nuclear issues are not of great concern to the British public, with a consistently low proportion, $\sim$3% or less, of respondents mentioning nuclear issues as a concern when asked (MORI, 2007, 2008, 2009).

In the UK, the number of people supportive of nuclear power has grown steadily, from around 20% in 2001 to around 33% in 2009 (MORI, 2009). What is more notable according to the same survey is that the number of people opposed to nuclear power has significantly decreased, from nearly 50% in 2001 to around 20% in 2009. It should also be noted that 2001 represented a peak in opposition to nuclear power, with the historical level being much closer to a figure of around 25% (de Boer and Catsburg, 1988).

This swing in opinion requires some explanation, and research carried out by Poortinga et al. (2005) and Pidgeon et al. (2008), may help to provide it. The authors explored the public perception of nuclear power placed in the context of climate change. The research took the form of a survey of a randomly selected stratified sample of around 1500 people in the UK and it found that there was a reluctant acceptance of nuclear power as a method to reduce the level of greenhouse gas emissions, but that other, non-nuclear options would be preferable if possible. It is possible that the re-framing of nuclear power as a "green" technology has led to the steady growth in support and reduction in opposition to the technology seen by the annual Ipsos MORI polls.

In seeking to understand the underlying causes of the trends observed in quantitative research by Eurobarometer and Ipsos MORI it is important not to ignore qualitative research. This is particularly true for communities that are close to nuclear plants where qualitative research has observed deeper, subtler trends in risk perception (Wynne et al., 2007). The researchers discovered that people living close to nuclear plants do have a tendency to be supportive of nuclear power, but with several caveats attached. Observed local issues ranged from feelings of a lack of empowerment to influence nuclear issues (this also seemed to be synonymous with social class with lower class people feeling less powerful), to a sense that local people were being stigmatised for living near nuclear facilities (Slovic et al., 1991). Wynne et al. (2007)

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[4] Early death frequency is defined as deaths that occur instantly or within a period of a few weeks of the event or accident.

also found that there was a feeling amongst local people that they deserved more back from the nuclear companies and the government in exchange for their tolerance of the nuclear plant and a concern that they were perceived as gullible or mercenary by wider society for accepting nuclear installations into their communities. One conclusion in particular stands out from the rest:

> [Local] "People are much more realistic about risk and uncertainty than the industry and regulatory authorities seem to realise. Communications based on the assumption that the public is seeking 'zero risk' are misguided, and are undermining the credibility of the institutions involved." (Wynne et al., 2007)

A further exposition on risk perception by communities close to nuclear plants can be found, for example, in Azapagic and Perdan (2011).

The Eurobarometer and Ipsos MORI surveys discussed above attempted to explore the particular aspects of nuclear power that cause people the greatest concern. Although these studies provide a wealth of data on a range of nuclear issues, it is important to note that expressed preference studies of this type are only one experimental tool that can be used to understand public opinion. One drawback of using an expressed preference methodology is that the norm is for only around 3% of people to worry about nuclear power (MORI, 2009), which suggests that issues relating to nuclear power may not be particularly important to the lay public in general. A second drawback is that nuclear design is a complex area and the majority of the public are not qualified to assess plant safety levels on a technical level. The combination of these factors may reduce the usefulness of using expressed preference studies to survey public opinion of nuclear safety.

Early work by Kahneman and Tversky (1974) details tests whereby people without sufficient information or understanding of a subject would rely on various heuristic[5] judgement mechanisms to provide an answer. It is possible that in asking the lay public for their opinion on the nuclear hazards of greatest concern researchers may invoke these heuristic judgements, essentially leading to people 'guesstimating' an answer based on their previous experiences; this may not provide an appropriate background to the specialist nuclear issues in question.

It is important to recognise that despite such 'failings' the public perception of technical risk is informed both by what they *do* and by what they *do not* understand. Understanding the psychological and sociological processes that occur in rationalising aspects of risk that are not understood is key to understanding how risk perceptions are formed. This is explored in the next section.

3.3. *Psychometric paradigm and cultural theory*

A great deal of work has been carried out in an attempt to explain observations such as those discussed in the previous section. Two leading theories have emerged:

a) Psychometric paradigm,[6] which developed from the psychological perspective of how an individual responds to perceived risk, building on the work by (Starr, 1969); and
b) Cultural theory, which developed from the sociological perspective of how group behaviour responds to perceived risk.

3.3.1. *Psychometric paradigm*

This is a psychological model that attempts to explain risk perception by using an expressed preferences method (as for example, used by Eurobarometer discussed previously). The answers provided by people allow profiles to be constructed for different risks; these profiles are based on a number of dimensions that are said to be evaluated cognitively when a person attempts to evaluate a risk.

The psychometric paradigm developed from the early work on risk perception by Starr (1969) which used 'revealed preferences' to explore behavioural patterns across a diverse range of activities. Revealed preference studies rely on observing behaviour in an effort to uncover patterns that may suggest the presence of underlying factors driving the behaviour in question. Starr's work established four basic rules of risk perception:

- voluntary risk levels can be roughly 1000 times greater than involuntary risk levels and still be acceptable to the public;
- the underlying risk posed by death from disease appears to act as a baseline that other risk levels are compared to;
- acceptable risk levels appear to be roughly proportionate to the [mathematical] cube of the benefits of an activity; and
- public acceptance of risks appears to be directly influenced by the public understanding of the benefits of the activity in question.

These conclusions have been found to hold across a wide range of cases despite criticisms of the potential shortcomings of the revealed-preferences approach (Otway and Cohen, 1975). As a result of his work, Starr recognised that nuclear power is not positioned favourably against these conclusions: it is largely involuntary, it is generally perceived as potentially harmful and the benefits of nuclear energy have been debated since its conception in the 1950s.

Starr also arrived at a fifth conclusion, suggesting that the economic drivers for nuclear safety would lead to a higher level of safety and reliability than the drivers based on perceived risk. This is driven by the large capital cost of nuclear power which must be amortised by maximising plant availability and service life as much as is technically and safely viable in order to maximise their return on investment. Whether a plant makes a profit or not is particularly sensitive to events that curtail operating lifetime or reduces plant availability, such as a period of unscheduled maintenance (BERR, 2007).

The dimensions analysed in the initial model for the psychometric paradigm (Fischhoff et al., 1978) are shown in Table 3. This initial model was tested against a relatively small sample of 76 individuals, who were asked to rate 30 different activities and technologies that were deliberately diverse in an effort to obtain as broad a view as possible.

Statistical analysis of the results determined that two overarching meta-dimensions, which combine the effects of several dimensions, could be distilled from the answers provided. The first meta-dimension relates to dimensions 1–6 and is often termed "unknowness". The second incorporates dimensions 7–9 and is known as "dread consequences". Repeated empirical research has corroborated these findings (Slovic, 1987) as has the application of additional analytical techniques, such as three-way principal component analysis (Siegrist et al., 2005). Nuclear energy was shown to be highly dreaded and highly unknown by these studies. Nuclear energy also scores significantly higher in the dimensional terms than any other activity or technology surveyed, suggesting that it occupies an extreme position psychologically—almost a worst case combination of an unknown technology with fearful effects if something goes wrong.

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[5] A heuristic judgment is based on a person's previous experiences. Such judgments may often differ significantly from a judgment made based on 'knowing all the facts', particularly in situations which are new or challenging to the person making the judgment.

[6] The psychometric paradigm is also often referred to as the psychometric model.

Table 3
Dimensions of risk as per psychometric paradigm (based on Fischhoff et al. (1978)).

	Scale (1–7)	Description
1. Voluntariness	1 = Voluntary 7 = Involuntary	Can the affected choose to participate in the risky activity/event?
2. Immediacy	1 = Immediate 7 = Latent	How immediate are the effects?
3. Known to exposed	1 = Precisely 7 = Not known	How well does the participant understand the risk?
4. Known to science	1 = Precisely 7 = Not known	How well does science understand the risk?
5. Controllability	1 = Cannot be controlled 7 = Complete control	How much control does the affected have over exposure, can exposure be avoided using individual skill?
6. Newness	1 = New 7 = Old	Is the risk new or old and familiar?
7. Chronic/Catastrophic	1 = Chronic 7 = Catastrophic	Do the consequences affect an individual (chronic), or many others?
8. Common/Dread	1 = Common 7 = Dreaded (unusual)	Is the risk "everyday" or something feared and dreaded?
9. Severity of Consequences	1 = Certain not to be fatal 7 = Fatal	If the consequences occur, what is the chance that death will result?

3.3.2. Cultural theory

The cultural theory is the sociologically based alternative to the psychometric paradigm (Douglas and Wildavsky, 1982; Wildavsky and Dake, 1990). It begins by making two suppositions:

- people adhere to specific codes of social relationships and these relationships influence how the people involved view the rest of the world; and
- there are four basic modes of living within society corresponding to different levels of collective identity (group) and levels of personal freedom (grid).

Collective identity (group rating) is the extent to which a person identifies themselves as an individual or as part of a group. A high group rating means that a person not only feels part of a larger whole, but is also willing to make decisions based on group priorities rather than individual priorities. Conversely, a low group rating means that a person perceives themselves as an individual with no group identity and makes decisions based on their own, individual, priorities.

Personal freedom (grid rating) is the extent to which an individual can differ from an established norm and how much power an individual has to choose their own path, independent of others. A low grid rating means that they are only loosely constrained by wider society and are allowed a wide range of personal freedoms. A high grid rating means that an individual is constrained within society and has less personal freedom or control over his or her own fate. The four resulting archetypes can be seen in Table 4.

Broadly speaking, egalitarians believe in a high level of freedom for all, but with an emphasis on societal well-being. Hierarchists share this view of societal well-being but are willing to restrict freedoms to achieve it. Individualists believe in freedom but with an emphasis on individual well-being, whilst fatalists believe that freedom is largely illusionary and that an individual's destiny is largely uncontrollable and is instead determined by fate.

The four different archetypes perceive and rank the same risks differently, based on the wider cultural influences that have shaped their outlook on the world and the beliefs that they then hold. Determining which archetype people belong to is generally achieved via the use of a questionnaire.

People belonging to different archetypes view nuclear power differently. Exactly who falls in to what category is complicated, based on the many different relationships that any individual possesses within the culture and society that surrounds them. However, some general trends have been drawn. From the basic criteria that underpin each archetype, arguably, nuclear power is likely to sit more favourably with hierarchists (it is ordered, structured and centralised) and less favourably with egalitarians (it is inequitable as it presents risks to the minority who live close to a plant and the technology itself is often imposed on them) and individualists (there is little personal freedom to choose nuclear power).

Table 4
Archetypes of cultural theory.

	Low grid	High grid
High group	Egalitarianism	Hierarchy
Low group	Individualism	Fatalism

3.4. Critique of psychometric paradigm and cultural theory

Despite some apparent success, neither theory can explain perception of risk completely. Numerous reviews of the literature have identified a range of issues and aspects that the psychometric paradigm fails to explain. These include, but are not limited to:

- trust in regulators, operators, designers and scientists (Lidskog, 1996; Slovic, 1987);
- stigma effects associated with the history of nuclear energy (Gregory et al., 1995);
- expert versus lay judgements in matters of risk assessment (Fischhoff et al., 1982; Rowe and Wright, 2001);
- origin—natural versus man-made effects (Sjoberg, 2000b);
- demographic effects such as sex, education and racial background (Savage, 1993); and
- sample sizes and the representativeness of various surveys (Gardner and Gould, 1989; Sjoberg, 1996).

In response to these criticisms, Sjoberg has offered an improvement on the psychometric paradigm with the extended psychometric model (Sjoberg, 2000a, 2002). The model incorporates additional dimensions such as origin and attempts to analyse results at an individual level, rather than averaged across groups of people, as is generally the case with the classical psychometric paradigm. Whilst this had led to a slight improvement in the accuracy of the model, many of the previously mentioned problems with a psychometric approach remain.

The cultural theory has also been subject to criticism. In particular, the basic postulate that our perception of risk is informed by the imposition of wider cultural values on the individual is questioned by Boholm (1998). Additionally, several experiments into the ability of cultural theory to explain perceived risk have found that the theory correlates poorly with empirical results (Sjoberg, 1996) with only around 5% of observed results showing statistically significant correlations with theoretical predictions. A serious weakness of the cultural theory is that questionnaires have a tendency to show that the majority of people do not conform to one particular archetype. This leaves a 'silent majority' of people at the centre of Table 4 who are characterised by a blend of archetypes meaning their expressed preferences are difficult or impossible to analyse.

An empirical comparison of the psychometric paradigm and the cultural theory was presented by Marris et al. (1998), which suggested that whilst both approaches shed light on the mechanisms of risk perception, further work is required to mitigate disagreements between the different methods of analysis and to improve the ability of the two theories to deal with both groups and individuals. A number of reviews of risk perception research also call for more integration of individual (psychological) and group (sociological) factors (Boholm, 1998; Renn, 1998; Taylor-Gooby, 2002).

The Social Amplification of Risk Framework (SARF), first discussed by Kasperson et al. (1988) and discussed in more depth by Pidgeon et al. (2003), is an attempt to provide an integrating framework combining psychological, sociological, organisational response and risk communication theories to form an overall view of risk perception. A risk event is viewed by SARF as causing a risk signal. The signal is analogous to ripples on a pond, reaching and informing those closest to the hazard first and then spreading out. As the ripples spread out and move through society further from the source, it is likely that they will become distorted, amplified or attenuated. In SARF, it is the amplification of these risk signals, combined with other effects such as historical stigma which leads to the perception of risk of technologies like nuclear power becoming so different to the expertly calculated risk. The experts are located near the centre of the ripples, whereas the public is located very far away. Critics of SARF point out that, much like the psychometric paradigm, it is not a fully developed theory and that much more work is required before it can begin to predict the risk perception outcomes of risk events (Wahlberg, 2001).

In conclusion, the psychometric paradigm has demonstrated that there are specific themes underlying the perception of risks, with the meta-dimensions of dread-consequences and unknowness predominating. Nuclear power is found to rate highly on both these scales and this may go some way towards explaining its controversial history. The cultural theory expands on this by suggesting that within our society there will be pockets of more "extreme" groups with ideals that align positively or negatively with an activity such as nuclear power. This provides a theoretical background that places pro-nuclear industry and their diametric opposites in anti-nuclear NGO such as Greenpeace and the Union of Concerned Scientists. In particular, the work of Fischhoff et al. (1982, 1978), Slovic (1987, 1996) and Sjoberg (1999, 2002, 2004) on the psychometric paradigm has demonstrated that whilst further work is required, the current theories do allow us to understand the underlying themes and dimensions that drive our perception of risks, even if we cannot be as accurate as we would wish to be when attempting to quantify such underlying drivers.

Overall, there is broad agreement between the two theories that perceived risks increase when people feel their understanding of the topic is inadequate. As mentioned previously, since public awareness of the safety requirements and technical features of nuclear plants is generally low, this could be one reason for the difference between calculated and perceived risks. The following section therefore explores how it may be possible to expand the definition of risk to inform the design of nuclear power plants.

4. Transforming negative perceptions

4.1. Expanding the definition of risk

Current risk analysis procedures could be defined as being technocratically driven, with the absolute authority of science and expertise dominating political decision making (Fischer, 1990). Fischer (1999) challenges this ideal in the context of a democratic society, where all stakeholders, regardless of their "expertise" are, by definition, entitled to contribute at some level. A particular concern is the fact that it is far too easy for experts to simply define the values relating to risk analysis based on PRA without also accounting for the public perception of risk.

Bohnenblust and Slovic (1998) postulated a quantitative approach to expanding the fundamental definition of risk in an effort to provide a broader method for evaluating risk levels:

$$R=\sum_{i=1}^{n} p_i \bullet C_i \bullet \varphi(C_i) \bullet \omega_i \tag{2}$$

As can be seen from Eq. (2), the authors have modified Eq. (1) to incorporate the "risk aversion factor", $\varphi(C_i)$, which is a function of the consequences of the risk occurring, and the marginal cost, ω_i, which is defined as the amount of expenditure that people are willing to make to eliminate the risk. Unfortunately, this risk aversion factor is not fully described, stating only that it should incorporate factors such as "historical precedents" (stigmatisation factors), the "nature of a risk" (hinting at a psychological connection) and other such factors. Whilst marginal cost may shed light on how much money the public is willing to spend on safety, what it does not tell us is if the public has a preference for the method to be used to create that improvement in safety.

The additional factors in Eq. (2) are an attempt to quantify the various factors listed in Tables 3 and 4. Quantifying such factors is difficult, as many are not easily captured by numerical evaluations. The consequences of an event, in whatever way they are evaluated or defined, do seem to be a dominant factor in psychological and sociological terms. This may be due to the fact that in many cases the consequences of an event are much easier to understand at a lay level compared to the complexity of probabilistic evaluations of initiating events and the costs (financial and otherwise) of preventing or mitigating a risk.

Slovic (2001) attempted to redefine risk in terms of a game. He states that risks, just like games, are characterised by sets of differing attributes, in analogy to the situation where a game of Snakes and Ladders is dependent on the layout of the board and how the die falls, whilst Scrabble is dependent on the board, the skill of the player and the letters they are dealt. In essence, one risk might be evaluated predominantly on "voluntariness" and dread, whilst another risk may be more strongly influenced by whether the risk is human-made or natural. In his discussion of the "risk game", Slovic also stresses the importance of developing participatory processes for involving the public in risk analysis activities. He focuses on the issue that all too often the 'official' definition of risk is limited in scope to a pure relationship between probability of occurrence and magnitude of consequences (as calculated by experts), ignoring a great number of psychological, sociological, and cultural factors that have been demonstrated to be important. He goes as far to say that probability and consequence are no different to factors such as perceived dread, novelty and the various other psychometric factors investigated by risk perception researchers (in particular, the exponents of the psychometric paradigm such as Slovic himself).

Both Fischer and Slovic believe that by incorporating lay input into risk analysis decision-making at an early stage many of the problems encountered in later technological development may be avoided entirely. By having the lay-public help to define the rules of the "risk game", they are "bought in" at an early stage and they become part-owner of the game, with the power to influence decision making and so alter the course of any future developments and outcomes. This potentially reduces the possibility that they will oppose the results, as they helped create them.

Efforts by the government and industry to transform the public perceptions of an issue often simply revolve around 'getting the right message out', whether that be via press releases and the media, education programmes or public consultations. Whilst these approaches are carried out with the needs of the public in mind, they rarely incorporate public input into their procedures or methodology. An approach to design based on such grounds was suggested by (Krieg, 1993) who discussed the potential for improved acceptance of nuclear reactors by simplifying containment-building designs to assist the public in understanding the design criteria. The author argues that this has the potential to reduce negative perceptions of nuclear plants but also stresses the need for a transparent and balanced communication of risk to minimise misunderstandings. Krieg's approach does not involve full public participation in the design process; it merely champions extending the consideration already given to the public as a minor stakeholder. Unfortunately, very little research has been carried out following on from this work to either determine if the conclusions have merit, or to broaden the scope to deal with other aspects of nuclear plant design (Krieg's work focuses on just one aspect of nuclear plant design—containment).

An alternative approach to design would be to follow the ideology of Fischer, Slovic and others and take a proactive approach to incorporating the lay-public's views at the earliest stages. This proactive approach would result in a plant that is not only designed to the highest engineering and safety standards, but is also based on a wider, socially accepted design that may allow for easier integration of the plant within society.

4.2. Participatory design

Consultative activities are becoming more commonplace within society, with risk communication activities in particular seeking to incorporate lay-public input. However, these consultative processes are yet to influence significantly the design of systems and technologies, with the notable exception of participatory design processes that exist within the Information Technology (IT) sector (Schuler and Namioka, 1993). Participatory Design (PD) in this sector was born out of conflict between workers and managers over the use of IT to automate work functions. Initial efforts to introduce automation were beset with issues relating to stakeholder rejection by blue-collar workers and Trade Unions in particular, who felt that the new technology would threaten their jobs. An overview of the genesis of PD is provided by Kensing and Blomberg (1998). The ethos of PD is that by involving workers from the very early stages, they are woven into the project and are able to define their own rules and goals, much as Slovic suggested with his "risk game" (Slovic, 1998).

Research also points to a number of challenges that any participatory procedure must overcome, including (Hansen, 2006):

- the conflicting agendas of various stakeholders;
- differences in the amount of credence attributed to the input provided by different stakeholders; and
- the lack of a widely accepted standard format for such consultative activities to follow.

The nuclear industry has attempted on several occasions to engage the public at a more fundamental level through consultative processes with varying degrees of success, although it has never gone so far as to incorporate direct public input into nuclear plant design. Green (1973) provides insight into the fact that during its early years the nuclear industry was not successful in consultative efforts. A more recent example of a consultative process in the UK where significant mistakes were made would be the attempts by Nirex to obtain planning permission in West Cumbria for a rock-characterisation facility (RCF) to aid in research into the long-term disposal of radioactive waste (Folger, 1993). The RCF was designed with the public in mind, but not with the public involved, a subtle and ultimately costly mistake. The public, feeling distanced and disenfranchised, rallied against the project resulting in the refusal of the planning permission, an indefinite postponement of the project and a long-term review of the UK's entire nuclear waste-disposal strategy (NDA, 2006).

Lessons continue to be learned from incidents such as the Nirex affair, where a lack of clear communication and consultation had significant consequences (Dalton and Atherton, 2002). Despite this, issues still arise, as seen in similar circumstances in 2007 when the UK Government consultation on new nuclear build, after being challenged by Greenpeace, was ruled unlawful by the High Court (Sullivan, 2007). More effective consultation procedures have been carried out in Canada where extensive public engagement activities were carried out in the early 2000s prior to the adoption of the Adaptive Phased Management (APM) radioactive waste disposal plan (NWMO, 2005). Reinvigorated efforts in the UK by the Nuclear Decommissioning Authority (NDA) to select sites for long-term radioactive waste disposal have begun to adopt similar consultative processes to those used in Canada (NDA, 2006).

4.3. Changing the approach to design

The existing design process for a nuclear plant takes around 10–15 years and strives to optimise the design on safety, performance and costs. Public consultation is only initiated after the design has been completed and it seeks to facilitate a smooth transition between no plant existing and a plant being built, operated and eventually decommissioned. Therefore, existing consultative processes do not encompass nuclear design which means that if any part of the design is of particular concern to the public, it is often too late to take any remedial action without great expense and delays. If on the other hand, the public is consulted prior to the design stage, during the 'requirements analysis',[7] this could be by far the most cost-effective way to incorporate their concerns and alleviate any future problems with the siting and building of new nuclear plants.

Thus, there is a need to explore the potential for combining expert knowledge of plant design and calculated risks with the lay-public's perception of risk to arrive at a novel, socially informed, approach to design. Such an approach to design would be able to provide guidance to the nuclear industry on the potential effects of plant design changes on the public perception of risk from nuclear plants.

However, any changes in the approach to design for nuclear power plants that goes beyond the current practice of combining

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[7] Requirements analysis or requirements capture is the first stage in the life cycle of any engineering system, aimed at helping to determine the requirements for a new product or a plant, taking into account views of various stakeholders, including the public.

calculated risk with technological and economic aspects must adhere to a number of different criteria. For example, it must:

- strive to continuously improve overall safety levels;
- incorporate information from many different stakeholders, both expert and non-expert;
- accept quantitative and qualitative inputs from both engineering and social science disciplines;
- structure these inputs in a clear, logical and unbiased fashion;
- interface with established systems engineering techniques right through the life cycle of nuclear power;
- be robust enough to be modified and updated as our understanding of risk and engineering expertise develop;
- provide a basis for practical designs that are economically, socially, and technically viable; and
- be simple to apply and follow.

This list of criteria is by no means exhaustive, and significant further work is required in order to develop the full set of criteria.

It is conceivable that some aspects of procedure or design will be more dominant than others. An early stage activity should be to evaluate the range of aspects associated with the design of a nuclear plant and attempt to prioritise areas for further study. Research into revealed and expressed-preference could help identify the design features that should be modified. Further research is also required on how to integrate the various results showing how different design aspects influence the overall perception of the nuclear plant.

A potential pitfall of expanding the approach to design is that by incorporating the views of a wide variety of stakeholders may lead to any conclusions becoming at best an approximation of reality and at worst vague and meaningless. In order to avoid this, careful consideration will need to be made in terms of assessing the various stakeholder inputs on an equitable basis. Additional stakeholder requirements will also impose an additional cost, but if incorporated at the requirements analysis stage, this should be much lower than the cost of re-design at a later date.

Ultimately the new, expanded, socially informed approach to design must be evaluated on its ability to generate meaningful and useful system requirements, design features and procedures that can provide measurable benefits to both the nuclear industry and society as a whole. Metrics for measuring such factors may also require development as established methods for evaluating the financial cost of negative public perception and the societal advantages created by a reduction in level of perceived risk do not currently exist.

4.4. Policy implications

The UK Government has carried out several consultations on nuclear power including the role that nuclear power should play in the UK energy mix (BERR, 2007), the suitability of the licensing process (DECC, 2010), the suitability of various sites (DECC, 2010) and the options available for the long-term disposal of nuclear waste (BERR, 2007). Further detail on UK policy on nuclear power can be found in, for example, Azapagic and Perdan (2011) and Greenhalgh and Azapagic (2009).

The UK Government's latest National Policy Statements for Energy Infrastructure recognise that there may be positive and negative effects from the construction of new nuclear plants and that organisations applying for site licenses should identify these effects in their license application (DECC, 2011), although there are no specific comments on mitigating or avoiding these effects. The UK Health and Safety Executive has invited public input into its Generic Design Approval (GDA) process for the assessment of new nuclear reactor designs (HSE, 2009). However, any design changes that are considered now must be balanced and justified against the cost of making the change. As the designs are almost finalised, such changes are potentially very costly and time consuming, and therefore it is perhaps less likely that any changes that are not critical for the safety will be made, even if they might enhance the socio-economic benefit of the plant. Therefore, making changes earlier in the design process would be less costly as the previously mentioned example of Sizewell B (O'Riordan, 1984; O'Riordan et al., 1985) demonstrates clearly.

Furthermore, the case of Fukushima has shown yet again the influence the public can have on nuclear policy. Although at the time of writing it is too early to determine the global long-term consequences for new nuclear build, it is already evident that some countries are changing their policies on nuclear power. A number of countries (such as China, the UK and USA) have instigated safety reviews. Germany, which had recently decided to re-consider new nuclear as a bridge to renewable energy generation, has shown signs of reverting to its previous policy of phasing out nuclear power as quickly as possible (Harding, 2011). This is perhaps as much a socio-political decision as it is one of safety; incumbent Chancellor Angela Merkel faces significant public and political opposition on the issue of German nuclear power (BBC-News, 2011).

5. Concluding remarks

Our understanding of risk, both from a technical and lay perspective, has developed significantly over the last 40 years. There now exists a large body of evidence around the issue of public perception of nuclear energy, in both quantitative and qualitative forms, that continues to expand. Research has shown that there are highly complex factors at work, influencing and shaping the perception of nuclear energy in many different ways. These factors go beyond simple direct interactions with government and industry and incorporate a whole spectrum of interactions within local communities and within wider society.

Policy makers must recognise the importance of public perception of nuclear power as a significant factor within global nuclear new build. This paper suggests that by involving the public at an earlier stage than is currently common, a nuclear plant can be built on a foundation of social consensus. Currently, interactions between the public and nuclear industry start with the licensing process and continue through to decommissioning. By extending this interaction to earlier stages, specifically during requirements analysis and plant design, it ought to be possible to increase public understanding of nuclear power and minimise the probability for disruption to new-build activities caused by misunderstanding and mistrust. It may not be possible to integrate all of the public views into a nuclear plant design, however the process of dialogue involved in such discussions can only reinforce current educational campaigns and help in building mutual trust.

Thus, this paper has argued that implementing approaches and policies which include an increased integration of lay-public risk perceptions into the design process for nuclear plants could result in a broader, socially informed nuclear plant design. The methods for carrying out early-stage design interactions between nuclear engineers and the public are still being investigated by the authors. To this end, further research is ongoing to understand the degree to which different aspects of nuclear plant design affect the overall perception of the risk posed by nuclear plants. It is also proposed that this socially informed approach to design, which retains the technological development and safety emphasis of the current design basis, would provide designs and processes that are more widely accepted by the general public. This in turn has the potential to reduce the capital cost and financial risks of new nuclear build.

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2.2. Updates to this Paper

This section will briefly discuss developments that have occurred since the publication of this paper, and their impact on the rest of the research documented in this thesis. Naturally, some of the impact that these developments had on the research is documented and accounted for in the papers presented in Sections 3 and 4.

The Fukushima accident of 2011 has continued to dominate discussions around nuclear energy in 2012. The full implications of how Fukushima may have affected the public's perception of the risks posed by nuclear power is still unclear, as many affects may take time to materialise and further research is required. Adding to this uncertainty is the challenge of measuring shifts in perception in different parts of the world; as discussed in the previous paper (Goodfellow et al., 2011) locality and culture play important roles in how people perceive risks.

Within the UK, the largest challenge to new nuclear build has been continuing uncertainty relating to private investors backing the companies intending to build new nuclear plants. A lack of clarity in the UK Government's energy policy has been cited by some as a driver for increasing the risks of investing in new nuclear (London Evening Standard, 2012). The latest energy bill, published on 29th November 2012 (DECC, 2012a) has been hailed by some as finally resolving many of these issues (Chazan, 2012) but it will take time to see if this is the case.

The German government has moved to fully phase out nuclear power by 2022 (Mez, 2012). This put financial pressure on RWe and EoN, owners of Horizon Nuclear in the UK, resulting in them selling Horizon to the Japanese company Hitachi GE. The net result of this transaction is that the generation III Advanced Boiling Water Reactor (ABWR) is now proposed for construction at both the Oldbury and Wylfa sites in the UK. First, the ABWR must pass through the Office for Nuclear Regulation's (ONR) Generic Design Assessment (GDA) process and receive design certification. This marks a significant technology shift for the UK nuclear industry which has not operated boiling water reactors previously. It also remains to be seen how the public will perceive the risks of boiling water reactor technology in the context that these reactors evolved from the technology that was in use at Fukushima.

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3. Public Perceptions of Design Options for New Nuclear Plants in the UK

3.1. Introduction

The following paper is currently being prepared for submission to a peer reviewed academic journal. Leading candidates include Futures (Elsevier) and Technological Forecasting and Social Change (Elsevier).

The author of this thesis was the primary author on the paper, and the content of the paper reflects research carried out solely by the primary author under the supervision of the doctoral research supervisors. The paper was co-authored by Jonathan Wortley of Rolls-Royce, Dr Paul Dewick of the Manchester Business School (The University of Manchester) and Prof. Adisa Azapagic of The University of Manchester. At the time of writing (during 2012) Wortley and Azapagic were the Industrial and Academic supervisors (respectively) for this doctoral research project. The co-authors contributed by providing comments on draft versions of the paper, guidance on language and writing style appropriate for a peer reviewed journal and contributed to discussions to generate ideas, concepts and avenues for research. Table and figure numbers have been amended to fit into the structure of this document.

Public Perceptions of Design Options for New Nuclear Plants in the UK

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ABSTRACT

An important consideration for any new nuclear build programme is an understanding of the public's viewpoint, as in many countries this can influence the direction of future energy markets. This paper presents a first attempt at understanding the UK public's views on the design of new nuclear plants in an attempt to help engineers and policy makers design future facilities in a socially more-acceptable way. A survey of 1304 adults was carried out using a questionnaire developed in this research. The majority of respondents expressed a preference for locating nuclear plants in coastal areas whilst ensuring that they fitted more closely with the local environment. A third of respondents expressed preferences for multiple smaller reactors with alternative reactor design. The majority expressed a preference for recycling reactor fuel and nuclear weapons material to produce electricity. There was no clear preference between on-site versus centralised underground storage of nuclear waste. Pre-existing attitudes towards nuclear power influence the public's views on nuclear waste and transport; expressed preferences related to plant design do not appear to be related to existing attitudes. Further research is required to understand why this is the case, what is driving attitudes towards plant design features and how to integrate the public's view into the nuclear plant design process.

KEYWORDS

Nuclear Power; Public perceptions; Sustainable Design

1. INTRODUCTION

Nuclear power, for years an anathema in many countries, could be poised for a revival. In the UK, a convergence of circumstances including a need for low carbon electricity to combat climate change, an emerging energy gap and increased concerns over security of energy supply, have led policy makers and increasingly the public, to reconsider the use of nuclear power as a part of the UK's energy mix (Greenhalgh and Azapagic, 2009). Planned new nuclear build is on the rise worldwide after two decades of decline (WNA, 2012a). However, planned new build and actual new build are not one and the same and some doubts remain over the 'reality' of nuclear renaissance. Internationally the picture is mixed, with nations such as Germany (Harris & Venables 2011) Japan and Switzerland moving away from nuclear power whilst countries such as the UK, China, USA, India and others continue to see new nuclear build playing a part in future energy policy (Mez, 2012).

The UK government recently released a draft Energy Bill (DECC, 2012b) which details its approach to ensuring that future investment in UK energy infrastructure is low-carbon. In the Bill the Government commits to creating a market that makes it commercially viable for companies to invest in low-carbon technologies such as renewables, coal with carbon capture and storage and nuclear power. The Bill also includes interventionist measures, such as feed-in-tariffs, contradicting previous policy which favoured a free and open energy market (DTI, 2007). In particular, 'contracts-for-difference' will be issued to nuclear energy producers guaranteeing a given price for the energy they produce regardless of the current market price. This may be perceived as a 'stealth' subsidy and the European Commission is currently conducting a preliminary investigation into the issue (The Guardian, 2013). Whilst the Bill may go some way towards reassuring investors that the economics of low-carbon generation, including nuclear power, are viable, other issues relating to nuclear power stations, such as NIMBY-ism (Not In My Backyard) (Welsh, 1993) and risk perception, may influence future nuclear build in the UK.

The recent Fukushima nuclear incident (IAEA, 2011a) has brought nuclear safety issues back into the public spotlight in a way not seen since the late 1980's in the wake of the

Chernobyl accident. In the UK, for example, research carried out shortly before and after the incident showed that support for nuclear power fell by 12% (FoE and GfK NOP, 2011) although it has since started to return to pre-Fukushima levels (Ipsos MORI, 2011).

Within the UK, key issues related to public's views of nuclear power include trust of the nuclear industry, understanding of nuclear technology and confidence in 'expert' views on risk issues such as reactor safety and the long-term solutions for the storage and/or disposal of radioactive waste (Ipsos MORI, 2010). Different theories of risk perception have been used to explain the reasons behind these views (for a review see Goodfellow et al. 2011).

Previous work by the authors has identified a need for research into the possibility of including public input in the design of new nuclear power plants (Goodfellow et al., 2011) to help bridge the gap between limited public support for nuclear power and the growing drive for new nuclear build,. However, this would not be a trivial task and there are at least two key barriers:

- effectively determining the public's view on different nuclear plant design options (and if it is even possible to elicit such information); and
- integrating this largely non-technical or 'soft' information into the design process alongside the 'hard' technical design input and strict regulatory requirements.

This paper focuses on the former barrier, in an attempt to determine if the public can provide an input at the conceptual stage of nuclear plant design and so help design socially more-acceptable nuclear plants.

As discussed in Goodfellow et al. (2011), previous efforts on understanding the public perception of nuclear design have been very limited. An attempt in this respect was made by Krieg (1993) who proposed simplifying containment structures around nuclear plants and using more transparent design methods, in order to assist the public in understanding the safety concepts in use. Krieg's argument was that "Engineered safeguards not only are to prevent damage and injuries to people and the environment, but are to make all these achievements plausible to the public." *(sic).* However, it is not clear if and how this argument has been integrated into the design of nuclear plants that are currently being proposed.

A more recent example of attempting to engage the public on a design issue is found within the nuclear industry through the decision by Horizon Nuclear Power to pursue fan-assisted cooling towers in the new-build developments on the Oldbury site in Gloucestershire, UK. According to Horizon, this decision had been made, in part, through consultation and feedback provided by local communities (Horizon Nuclear Power, 2010). These consultations were carried out when it was anticipated that either an EPR or AP1000 reactor would be constructed at the Oldbury site, it is unclear if they still apply now that the ABWR reactor type is being proposed.

It should be noted that significant efforts have been made to engage the public in the area of nuclear waste disposal in the UK in recent years. In the 1990s an attempt was made in the UK to construct a Rock Characterisation Facility (RCF) to determine if the county of Cumbria was a suitable location for a geological depository for nuclear waste. Nirex Ltd, the company charged with the task of developing the facility employed a 'Decide-Announce-Defend' approach and encountered severe public opposition to the plans (Folger, 1993). This opposition was so strong that the project was cancelled and a period of several years elapsed before a new approach was taken in 2008 with the establishment of the West Cumbria: Managing Radioactive Waste Safely (MRWS) partnership (WC:MRWS, 2013)

The West Cumbria: MRWS partnership active in engaging the public between 2010 and 2013 on the issue of progression towards construction of a geological depository for nuclear waste in the county of Cumbria in the UK. Several rounds of public engagement work were carried out; starting with efforts to disseminate information about the proposed facility with efforts including neighbourhood forums, drop-in events and media exposure. This work was then followed up by a formal public consultation in the form of a statistically representative opinion survey (Copeland Borough Council, 2012). Ultimately it was elected local council leaders who made the final decision on whether to proceed with further stages of the depository project and whilst two local councils backed the plan to proceed the overarching county council rejected the plan. The status of a project to create a final waste depository in the UK remains in limbo following this decision.

In this work, we take a much broader approach to determine the public's views on a variety of possible design options for a new nuclear plant by means of an electronic survey. It is important to recognise that in practice multiple methods of engagement would be required to fully understand the public's view of reactor design. These would include surveys as well as methods such as focus groups, liaison meetings, interviews and formal written responses (Powell and Colin, 2008). The approach documented in this paper is merely a first attempt at eliciting a response on this topic. The reader should therefore consider this to be an introduction to the topic and the first element of a 'proof of concept'; demonstrating that such questions can be asked of the public in an effort to provide a means for two-way engagement between the public and the nuclear designer.

The purpose of this research was to begin to explore the public's perceptions of nuclear design options with the ultimate aim being the integration of such views into the design of new nuclear plants. A method for achieving this integration is proposed in a parallel paper entitled 'A Systems Design Framework for the Integration of Public Preferences into the Design of Nuclear Plants' (Goodfellow et al. 2013). In summary, the framework proposes that engagement activities, such as that documented in this paper, ought to be carried out by reactor designers and energy utilities at the earliest possible stage of a new build project (ideally during the early stages of reactor design). By doing this, the designer can take into account the views of the people who will be living with the reactor during its construction, operation (and possibly decommissioning). This paper proposes that such efforts will help to improve levels of engagement between the nuclear industry and the public, with the potential gain of improving the social sustainability of nuclear power.

As far as we are aware, this is the first time an approach like this has ever been attempted. The paper is structured in the following way: section 2 discusses how and why the various design aspects have been selected and the methods used to explore the public's perception of these design aspects. The results of the study are then presented in section 3, followed by a discussion and policy recommendations in section 4 with the backdrop of new UK nuclear build in mind. Finally, the conclusions of the study are summarised in section 5.

2. RESEARCH METHOD

A survey using an on-line questionnaire and a subsequent statistical analysis have been used for capturing and analysing the public's views on the design options of nuclear power plants. For these purposes, a cross-section of the UK population (n=1304) has been surveyed using a novel questionnaire developed as part of the research. The following sections describe the development and the content of the questionnaire and how the survey was carried out. The statistical analysis is discussed in section 3.

2.1. *An Introduction to the Questionnaire*

An on-line survey by questionnaire was selected for this work because of the need to consult a reasonably large and representative sample over a relatively short period of time. The former was necessary to ensure that the public's views are as representative of the UK population as possible and the latter to minimise the effect of possible events that could occur in the course of carrying out the survey (such as a nuclear accident) and possibly affect the public's views on nuclear power. For these reasons, interviews or focus group discussions were disregarded as inappropriate. It was also deemed impractical to have an open-ended questionnaire due to the complexity of the subject, so the questions were designed to focus on specific aspects with the respondents being able to choose among multiple-choice answers.

The development of the questionnaire was carried out in two steps. A pilot was developed first and tested on a small sample of the public (n=80) to find out if the concept would work and ensure that the questions were clear. As a result, the full questionnaire was developed, comprising three sections:

- Section A, with questions on the participants' familiarity with, and their existing views on, nuclear power and the nuclear industry;

- Section B, with questions on 12 different aspects of nuclear plant design, such as siting and size of new plants, type of safety system and nuclear fuel recycling; and
- Section C, with a range of questions to determine the demographics of the sample.

The full questionnaire can be found in the appendix attached to this paper. The following sections provide further detail on the development of Sections A-C of the questionnaire.

2.2 Development of the Questionnaire and Critique

2.1.1. Section A of the questionnaire

Section A was included in the questionnaire to find out if and how the respondents' underlying views and beliefs about nuclear power (independent variables) may influence their choice of design options in Section B (dependent variables).

There are many factors that could influence the public's opinion on different design options for nuclear power plants and it would be impossible to probe all areas within one piece of work. As much of the previous research has investigated how the public's perception of risk has affected their views on nuclear power and the nuclear industry (as discussed in Goodfellow et al., 2011), this was chosen as an appropriate starting point for the current research. Therefore, to ensure consistency and to enable cross-comparisons with previous studies on the public's general views on nuclear power, several of the questions are either identical or similar to the questions asked by other researchers, as follows:

- Q1.1 on how well people feel they know the nuclear industry, Q1.2 on how favourable the respondents' opinion of nuclear power, and Q1.5 on whether they would support or oppose new nuclear build in the UK, were asked by Ipsos MORI 2010; 2011) and the Environment Agency (2010); and
- Q1.6 on how risky the respondents think it is having nuclear plants in the UK was similar to a question asked by Eurobarometer (2010).

The other questions in section A are driven by a variety of factors:

- Q1.3 on how well respondents understand the technical aspects of nuclear power was used, as the design of a nuclear plant is a technical endeavour and it seemed logical to understand how much (if any) impact the level of technical knowledge had on the responses provided;
- Q1.4 focussed on the impending ‘energy gap’ in the UK (Greenhalgh and Azapagic, 2009). This is one of the primary drivers for new build of power plants (nuclear or otherwise) in the UK and therefore it seemed appropriate to see if knowledge of this influenced responses provided;
- Q1.7 on whether nuclear power was perceived as low carbon and Q1.8 on whether there is a clear way forward on nuclear waste were inspired by recently published research which suggested that the public’s attitude to nuclear power in the UK was governed by a risk vs. risk trade-off between the risk of nuclear waste and the risk of climate change (Poortinga et al., 2005; Bickerstaff et al., 2008; Pidgeon et al., 2008); and
- Q1.9 and Q1.10 were asked in an effort to understand if respondents’ interest in nuclear power or other general issues (e.g. by volunteering activities) affected the answers in the rest of Section A of the questionnaire. It was decided to ask about volunteering as any future engagement activity designed to engage the public on nuclear design would require volunteers. If it was the case that people who volunteered had wildly different views on nuclear issues from people who do not volunteer, then this could be relevant for the analysis of the responses.

2.1.2. Section B of the questionnaire

The questions in section B were the main objective and focus of this research. Selection of design aspects to be included in the questionnaire was carried out by analysing previous research and focussing on the nuclear issues that caused the public the greatest concern. Some of these findings are summarised in Table 1. For example, Ipsos MORI (2010) found that the UK public was most concerned with nuclear waste disposal, followed by safety and radiation discharges.

Table 1. Percentage of respondents that stated that the issue in question was something that they had concerns about. Only the most populous responses (highest percentages) are shown.

Question type	Free choice (prompted list)			Free 'open' response	'Agree' with statement		
Source*	Ipos MORI (2007)	Ipsos MORI (2008)	Ipsos MORI (2009)	Butler et al. (2007)**	Environment Agency (2010)	Eurobarometer (2007)	Eurobarometer (2010)
Nuclear waste disposal	45%	36%	35%	24%	86%	50%	49%
Safety	41%	31%	28%	9%	29%	31%	31%
Radiation discharges	44%	36%	24%	4%	50%		
Environmental impact	22%	13%	11%	4%	49%	19%	52%
Terrorism	33%	11%	8%	13%	57%		
Costs of nuclear electricity	15%	7%	7%	13%			
Proliferation						46%	45%

* Respondents in Ipsos Mori and Environment Agency surveys were the UK general public, in Butler et al., UK NGOs and in Eurobarometer, the European public.
** Percentage data calculated from figures presented in Section 5 of Greenhalgh & Azapagic (2009).

Through an iterative process of discussing, brainstorming and analysing the data in Table 1, in consultation with a range of experienced academic and industrial experts, a list of different design aspects that might be behind the concerns documented in Table 1 was created. The initial brainstorming was carried out with the assistance of a number of experienced Rolls-Royce nuclear design engineers. This created an initial long-list of 30 aspects across a broad range of categories, shown in Table 2.

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Table 2. The long-list of design aspects generated during the brainstorming sessions.

Design Aspect	Safety Related?	Elaborate…	Description
Waste Disposal			
Polluter Pays Concept	N	As in Canada. What would be the reaction to nuclear operators in UK having to pay into a visible fund to cover the cost of waste disposal in the long term?	UK public acceptance of a polluter pays concept would result in utilities in the UK being required to pay into a waste disposal fund. This additional annual cost would have a number of potential consequences (positive and negative) and may make the volume and characteristics of waste produced in reactors a key product differentiator
Fuel efficiency	N	Would a novel reactor design that uses fuel more efficiently boost perception?	Current reactors run for approximately 18 months between refuelling, a time period that is mainly constrained by fuel pellet integrity in modern PWRs. Would longer refuelling cycles, less downtime and potentially lower costs improve the public perception of nuclear? Or, by elongating the refuelling cycle and removing a preventative maintenance window would the effect be to reduce public confidence in reactor safety?
Waste reduction	Y	Would decreasing the amount of HLW produced (even further) provide benefits to perception?	The volume of waste produced by nuclear reactors has decreased significantly as designs have evolved and this has primarily been driven by economic factors. Has this reduction in waste volumes produced been communicated to the public? Would further reductions in waste provide a direct benefit to public perception?
Long term waste disposal?	N	Define publicly acceptable conditions and boundaries for long term waste disposal	A deep geological depository has become the scientifically accepted "best option" for the long-term storage of radioactive waste. However, such schemes have classically been criticised by the public. Given the choice and the evidence to make a robust decision, what would the preferred option for long-term waste disposal be if the decision was left to the British public?

Waste form	Y	Is it possible to have the spent fuel "come out" in a more manageable form?	Fuel currently comes in the form of large assemblies of fuel pins that can be several meters long. On removal from the core they are sheared into chunks and bathed in acid to dissolve the used fuel and separate the metallic cladding. Would fuel pins that have re-usable cladding (and allow for easier separation of fuel and clad) provide a benefit to the perception of the waste processing stream?
Safety			
Passive Safety Systems	Y	Is the public more or less comfortable with the "hands off" approach of passive safety systems?	Core question simplifies to hands on vs. hands off approach. Does the fact that a nuclear plant can "take care of itself" bolster confidence or does it leave people feeling that there is a sense of misplaced overconfidence in the technology?
Proven nature of the technology	Y	Does having a growing legacy of safe reliable plant operation improve perception of nuclear safety?	PWRs have been operational for approximately 40 years and have seen significant steps in design evolution. This is compared to potential future technologies such as fast reactors or high-temperature gas reactors that the world has much less experience in running on a commercial scale. Does the historical experience base that has been built with PWR technology provide a benefit to the public perception of nuclear power, or is the level of detail required to understand that there are different reactor types too complex?
Digital Computer Control	Y	Plant is controlled via modern digital computer and software system, do people "trust" the computer	Similar to the passive safety question. The public's everyday experience of computers and IT is likely to be experience of buggy and / or low integrity software that crashes quite regularly. High integrity systems for the nuclear industry are far removed from these "everyday" systems but does the public realise and/or trust in that, and can the use of software systems for nuclear I&C be justified in the eyes of the public?
Containment	Y	Test Krieg's (1993) hypothesis that more transparent logic in containment design will provide a public perception benefit?	Expose people to a variety of containment designs and "logics" and have them evaluate which they believe would be the safest to see if there really is a difference?
Radiation Discharges			

Is any amount of discharge OK?	Y	Some products from waste streams are currently released to the environment as they are scientifically low impact and expensive to remove, is this ever likely to be acceptable?	A great deal of money has been spent on projects for removing radioactive materials from discharge streams, such as removal of Tc99 from waste streams at Sellafield. This has been carried out for costs significantly higher than the economically balanced cost as determined by J-value methods (Thomas et al., 2006) etc. When placed in the context of a deep recession, is the public willing to pay "over the odds" for such marginal safety improvements?
Environmental Impact			
Site Selection	Y	What would be the impact of an alternative system that incorporated public decision making on sites at an earlier stage?	By allowing the public a voice in choosing the criteria used to select a site, and then giving them an enhanced input into the site selection will there be an improvement in the acceptance of the final sites selected? Would the criteria reached be the same or different or surprising?
Physical Plant Characteristics	Y	With the interest in SMRs growing is there a perception benefit to a larger number of smaller sites?	SMRs are an area of increased research activity. Would 4 small reactors on 1 large site be more of a perception issue compared to 1 large reactor on 1 site? Would 40 small reactors spread "evenly" across a nation be more of an issue than 10 co-located groups of 4 small reactors or 10 large individual reactors?
Social Impact	N	Nuclear plants often bring highly skilled jobs to areas that badly need them, what is the perceived benefit of this?	Risk and benefit are two sides of the same coin. How much does the effect of perceived economic benefits of nuclear plants located close by affect people’s willingness to accept risks? How far from the plant does this effect persist?
Appearance/Aesthetics	Y	Can more senstive designs that assist in fitting the appearance of the plant to its local surroundings reduce the impact of the plant and improve the perception of the plant?	What are the pros and cons of a "hidden in plain sight" approach? Does it reduce anxiety of living near a plant, or merely mask the physical detriments of a plant on its local surroundings without addressing the underlying issues. Would people feel more uneasy because they know that plant is there even if they can’t see it?
Terrorism			

Aircraft Impact	Y	Can clearer, more obvious defences against aircraft impact improve the public perception of plant security?	Since 9/11 aircraft impact has been a major concern for safety regulators and plant designers alike. Additionally, since 9/11 the public has been increasingly fearful of the potential for further terrorist attacks. There is potentially a significant difference between perceived and actual effects of such an incident. What options are there for more obvious, but viable, aircraft impact solutions for nuclear plants? How might these solutions contribute to the public perception of this risk?
Proliferation Concern	Y	Can more obvious security, or less proliferable fuel and waste forms improve the perception of plant safety?	A concern of the public is that nuclear material is stolen or smuggled out of a nuclear facility for use in a terrorist device (nuclear or conventional "dirty" bomb). Whilst the probability of such an event occurring are remote, due to the difficulty in handling nuclear materials, the public remains concerned by this (Table 1). Are there fuel forms (not separating Pu) or security measures that could be changed to improve public confidence in the security of material? International locations factors should be considered, as UK public confidence in UK plants is likely to be different to UK public confidence in foreign plants.
Economics			
Safety vs Cost of Licensing	Y	The cost of licensing a plant is high, but is required to satisfy the safety regulators. What is the relationship of this trade-off and is it money well spent in terms of perceived risk?	Licensing nuclear plants is a long, technically challenging and expensive task. However, it is absolutely crucial to the new build process. Regulators are widely seen by the public (at least in the UK) as relatively trustworthy organisations, and their stamp of approval on a design is a key factor in public acceptance (however reluctant) of nuclear power. However, questions have been raised about PRA results that are below 10^{-7} as the level of calculated risk is now so low that overall risk is probably dominated by unknown events that are unaccounted for in the PRA. With calculated risk levels so low, is there now a trade-off to be made saying that plants are as safe as could be reasonably accepted and therefore the licensing process ought to be streamlined? Or would this be rejected by the public?

Lower capital costs	N	Nuclear is classically seen as an expensive option	Nuclear power is recognised by many as an expensive option. This is largely due to the very high capital costs and the risks associated with decommissioning costs at an indeterminate point in the future. If nuclear was "cheaper" across its lifecycle would the public perception of nuclear power be improved?
Long term electricity market	N	Does carbon pricing factor into the public's perceived risk and benefit evaluations?	With the impending introduction of worldwide carbon pricing and the creation of a "carbon economy" will nuclear generated electricity become more competitive? If so, will this have any significant on the nuclear power risk vs. benefit trade-off?
External Factors			
Energy security	N	Is the energy security argument strong enough to support nuclear	An increased dependence on imported fuel sources, in particular gas, has left the UK exposed to rapid market price and availability fluctuations. This can be extremely detrimental to continuity of supply and electricity price. Nuclear is seen as a more stable option as the countries that mine Uranium are, by in large, friendly to the UK. Is this argument persuasive enough to alter perception of nuclear power? Will people feel that Uranium will just end up the same as gas as time progresses?
Earthquake	Y	Design changes to mitigate earthquake	Earthquakes pose a significant threat to nuclear plants in many areas of the worldIs there a more transparent method of designing plants to withstand earthquakes that will bolster public confidence?
Flood	Y	Design changes to mitigate flooding	Most of the UK based nuclear power plants are to be sited in coastal locations. With sea levels predicted to rise by anything between 1 and 9 metres in the next 50 years, Is there enough public confidence is such flood defences (particularly in the light of recent wide scale flooding in the UK) to reassure people that nuclear plants will not be swamped with water?
Pylons and transformers	N	Visibility aesthetics	Even if the aesthetics of a nuclear plant are improved, there still needs to be infrastructure connecting the plant into the national grid. Is this perceived as badly as the plant itself?

Regulation and Process Management			
Extra-nuclear 3rd party vetting /	N	How "independent" are the regulators perceived to be. Would suitable over watch by Greenpeace or another NGO increase credibility?	Does the public have enough confidence in the nuclear regulators to "believe" that when they say a plant is safe that it is? Would a more overtly transparent effort by the regulators, inviting deeper, embedded, cross-examination and scientific discussion, bolster public confidence?
Regulation differences	Y	Negatives of tick-boxes (prescriptive regulation)	The UK and US regulation systems are considerably different. Do people have a preference for one methodology over the other in terms of the best way to keep plants safe?
Agency reputations	Y	Links to above two questions. What is the effect of the reputation of the regulator?	Different regulators around the world are likely to be perceived differently by members of the public? What is the effect on risk perception caused by confidence in different regulators?
Gaps in agency	Y	Differences in certification etc.	Does the fact that the Environment Agency looks after some areas whilst the Office for Nuclear Regulation looks after others leave perceived gaps in jurisdiction? Do the public even perceive this?
Staff training visibility	Y	Would independently verifiable training schemes increase confidence in nuclear operations	The majority of the public will only understand nuclear safety engineers in the context of their day-to-day experiences, which may be limited to Homer Simpson. Would a more overt training and qualification regime for nuclear operators improve the perception of nuclear plant operators and thus, nuclear safety?
Design and local knowledge/cultural biases	N	How important is the application of local knowledge to the design and approval process?	Designing a nuclear plant as "one size fits all" is likely to be a bad idea, as there are many cultural differences in a global market that may impact on any design. Certain cultures hold certain numbers, shapes and characteristics to hold great meaning and misunderstanding these effects could significantly impact on the perception of the plant that you intend to build in the country in question. Can local knowledge be applied more thoroughly to nuclear plant design to assist in both the licensing process and in improving the public perception of the plant?

Anti-proliferation regulation	Y	Would an increase in the visibility of procedures and systems to prevent proliferation improve perception?	Recently, international agreements have been reached to document and control all highly enriched nuclear materials in an effort to prevent nuclear weapon proliferation. Are such efforts recognised by the public and would further efforts be useful in improving the perception of nuclear power?

These 30 aspects were refined by consulting 14 experienced individuals with differing experience of the nuclear industry including:

- nuclear engineers and engineering managers with significant experience of the UK nuclear industry (between 10 and 40 years);
- communications and stakeholder engagement professionals with substantial experience of the UK and global nuclear industry (between 20 and 40 years);
- industrial and academic professionals with experience of protest movements and the impact of corporations on culture and society.

The discussions held during the consultation period helped to reduce the original list of 31 aspects down to the 12 (shown in Table 3) by creating and applying the following criteria:

- relevance: does the aspect relate to the perceived risk and/or the ‘visibility’ of nuclear power (as previous research suggested that the public may care about such things);
- technicality: can the aspect be understood by the lay-person and can it be treated (at least to some degree) in isolation from other aspects;
- significance: would a positive or negative response relating to a chosen aspect lead to an obvious shift in the design of a nuclear plant; and
- range: do the aspects cover a range of different and relevant design features.

Some of the aspects in Table 2 were more obviously likely to be candidates for the short list than others. For example, answering the question of ‘Does carbon pricing factor into the public’s perceived risk and benefit evaluations?’ is likely to require a PhD worth of effort in itself (at the minimum). It also does not relate directly to a particular aspect of the design of a nuclear plant. Other questions, such as that relating to digital computer control and instrumentation systems, are more obviously viable for probing a specific area of plant design and public understanding. An iterative process of reviewing the aspects in Table 2, against the criteria discussed, resulted in a short list of aspects used to form the questions in Table 3.

The list of aspects covered in Table 2 and Table 3 is neither exhaustive nor ‘neutral’. Indeed, striving for such a situation might be considered to be an impossible task. Fifty years of design development in the nuclear industry have failed to result in a consensus as to what is the best technological approach to generating electrical power by means of controlled fission reactions. This is in spite of significant technological lock-in effects that essentially bias the industry towards just one or two different technologies because of the cost of developing alternatives (Cowan, 1990). Additionally, the various regulatory regimes around the world demonstrate that whilst broad principles, such as safety, are universally accepted, specific details relating to how designs are assessed are culturally sensitive. Recent initiatives, such as CORDEL (WNA, 2012b) and MDEP (NEA, 2012) are beginning the process of attempting to resolve such issues, but significant amounts of further work is required.

If the nuclear industry itself has not reached a design consensus, then once the disparate range of interested additional parties associated with debates on nuclear technology are included the likelihood of arriving at any form of consensus over aspects of design that should and/or should not be included in engagement activities is minimal. Therefore it was decided that with the level of resources available, this research should focus on the pragmatic approach of attempting to ask some questions and receive some answers. The intention is not to provide a definitive account of what the public desires, but rather to illustrate how such a thing might be achieved.

It was important to ensure that the design options presented to the public be as clear as possible and described in terms accessible to the lay-person. To this end, two ‘states’ were conceived for each design aspect: a ‘base’ state formed around the idea of a modern, generic Pressurised Water Reactor (the only type of reactor currently approved for future build in the UK), and a 'modified' state which was intended to be opposite to the base state (shown in Table 3). The opposite state was chosen so that there was a clear distinction between each end of the scale provided in the question; it was hoped that this would assist with making the questions clear to lay participants.

Questions were then defined, based on the design options listed in Table 3. The questions were designed to minimise implicit bias towards any particular response and to ensure that jargon and technical language was replaced with plain English. To increase clarity, some of the questions included images or a short explanatory text. Figure 1 shows an example of an image used for illustrative purposes in the questionnaire, showing a 'base' and 'modified' case. For full details, see the questionnaire.

Table 3. The final list of 12 design aspects with the 'base' and proposed 'modified' states.

Categories	Design aspect	'Base' state	Proposed 'modified' state
Waste disposal	Fuel type	Standard uranium fuel cycle	Recycled waste fuel
Waste disposal, Safety	Used Fuel storage	Underground disposal will work	Underground disposal will not work
Waste disposal, Safety	Waste transport	No waste transport	Waste transport via road, rail or sea
Safety	Active vs. passive safety systems	Fully active safety systems	Fully passive safety systems
Safety	Instrumentation & control	Analogue instrumentation and control with hard-wired systems	Fly-by-wire digital control systems (similar to those used in modern aircrafts)
Safety	Reactor	Existing reactor design with operational experience	New reactor design with little operational experience
Safety, Environmental impact	Proximity to population / hazard	Coastal location with sea defences	Site located away from the sea, closer to population centres
Safety, Terrorism	Aircraft impact protection	Concrete dome	Alternatives such as no protection, wind turbines or sunken with trees or vertical walls
Environmental impact, Safety	Co-location	One large reactor	2-4 smaller reactors on same site
Environmental impact	Cooling towers	Natural draught cooling towers when required	Fan-assisted cooling towers when required
Environmental impact	Visual appearance	'Typical' box and dome	Something more aesthetically sympathetic to the surrounding (rural) landscape
Proliferation, Safety	Proliferation	Standard uranium fuel cycle	Fuel recycled from nuclear weapons

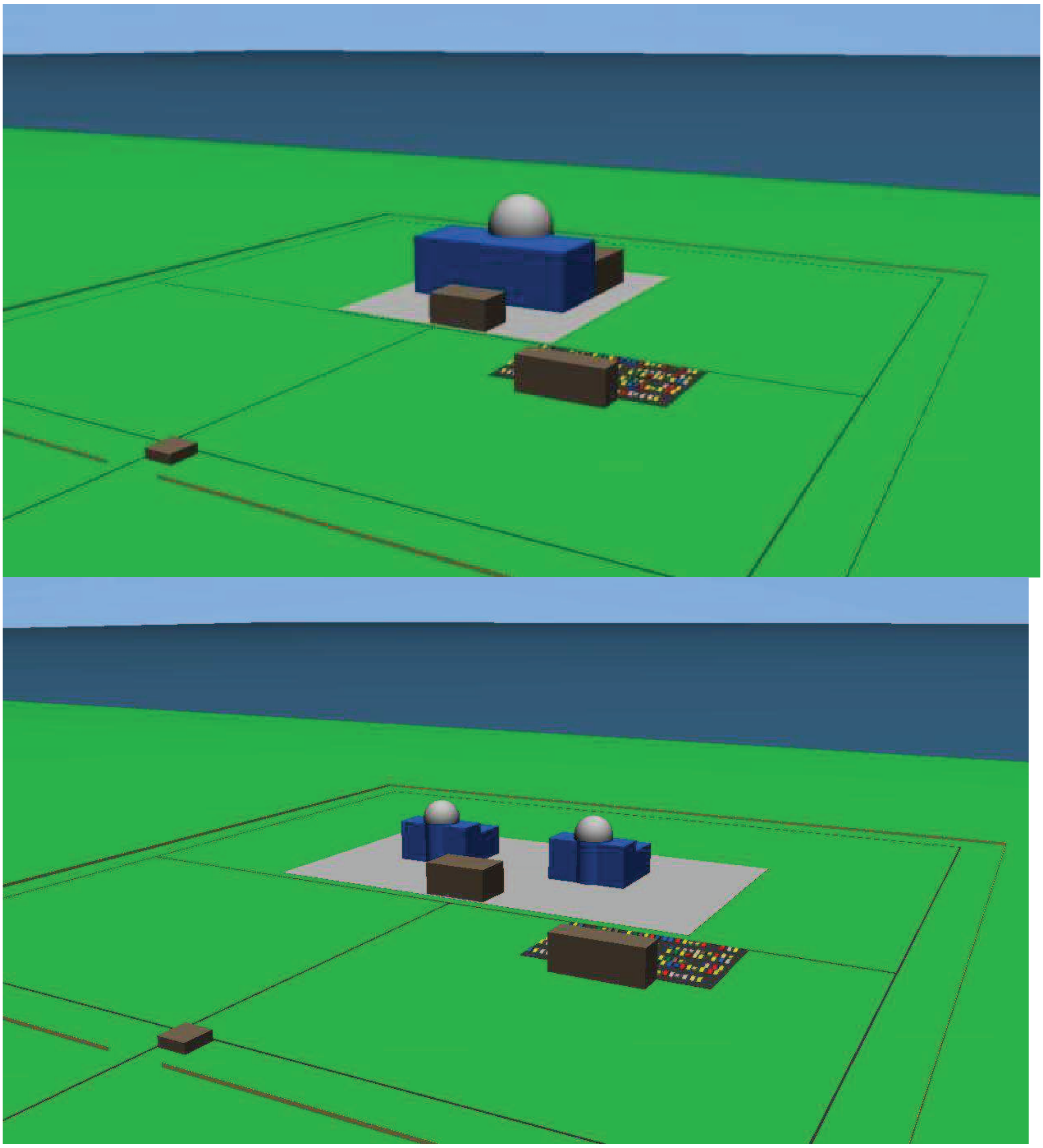

Figure 1. An example of illustrative images used in the questionnaire (originally larger). The image on the top shows a 'typical' nuclear power plant, with sea and sky in the background ('base' case). The image on the bottom shows a 'modified' case showing two smaller plants on the same site. Both images have been simplified and exclude several non-nuclear 'out-buildings' that would be similar in both cases. The car park in the lower centre right of the image is used to indicate the scale.

For completeness, a discussion follows below on of how these criteria were used to transform the question types in Table 1 into those used in the questionnaire and summarised in Table 3, including why certain aspects were included and others excluded from the final questions. The discussion below follows the order of the question types shown in Table 1.

As the questions related to nuclear fuel and waste disposal attracted the highest percentage of answers in different surveys (see Table 1), it was important to include several questions covering aspects of design related to these two issues. Many issues raised regarding nuclear waste are associated with final disposal which is something that does not necessarily influence power plant design. However, issues such as fuel and waste transport to and from site, recycling nuclear material, and using mixed oxide fuels (MOX) in new nuclear plants, do influence plant design. Whilst waste transport may not immediately seem to be part of the design of a nuclear plant, it is important to consider how the plant integrates into the wider environment. This includes a consideration of local infrastructure readiness/development and a consideration for how nuclear materials can be taken from and to the plant during its lifetime. The issue of nuclear waste transport has previously impacted large nuclear projects, including in some States in the USA, denying permission for waste to be transported through their territory en-route to the proposed final geological disposal site at Yucca Mountain in Nevada (State of Nevada, 2009).

Safety was also identified in various surveys as one of the most important issues of concern to the public (Table 1). Safety influences a wide range of design aspects which also relate to other categories (e.g. an outer impact protection dome is related to both safety and terrorism). Only three of the final 12 questions in section B of the questionnaire did not directly relate to safety. Three questions were included that dealt specifically with safety, covering:

- novelty of reactor design, setting newer designs against older designs which people are experienced at operating;
- safety system design, exploring the spectrum from fully active to fully passive systems; and
- the instrumentation and control system to be used, a key sub-system that integrates with all other systems.

Much of the recent debate in the area of radiation discharge has focussed on the applicability of the 'linear no-threshold' model for describing the physiological effects of exposure to low levels of radiation (Tubiana et al., 2006). As radiation discharges at modern nuclear power plants are typically very low, the UK Environment Agency states that "Radioactive discharges from nuclear sites account for about less than 1% per year of the average dose [*received by the UK population; authors' addition*]." (Environment Agency, 2012), it was decided that including radiation discharge in this investigation would likely result in a mirrored debate about the validity of that model and therefore radiation discharge was excluded pending further understanding of the impacts of low doses. In hindsight, with the advent of the Fukushima accident and the associated significant discharge of radiation (which came after the questionnaire had been fully prepared), it might have been interesting to investigated this aspect too, although comparisons between the actual level of harm caused and the perceived level of harm would still have been difficult.

The environmental impact of nuclear plants is part of larger considerations relating to other industrial facilities and is complicated by the wide range of different concerns that the public holds about the environment (Ipsos MORI, 2009). Environmental impact in the context of this research was therefore limited to aspects such as aesthetic design, visual impact and site location.

Terrorism relates to all aspects of the plant, but in very specific ways. Aircraft impact protection was a very clear example where it was hoped the public would be able to make a design choice.

All aspects of design relate to economics. There is a great deal of complexity in understanding the cost of designing and building a nuclear plant and around the cost of different parts of nuclear plants (Du & Parsons 2009). Cost had the potential to cloud any underlying risk perception effects, particularly in light of the current economic crisis and the high costs regularly associated with nuclear power. Also, expressing the cost of the various proposed design changes to the public in an understandable and justifiable way would be a significant challenge, separate to the challenges that this research was trying to address. Therefore, an explicit reference to the costs of nuclear plants was not included in the questionnaire.

Proliferation is another issue that public have expressed concerns about (see Table 1). The proliferation of nuclear material is most easily accomplished with material that has not recently passed through a nuclear reactor and has been refined to the high isotopic concentrations required for use in weapons. Military grade plutonium which has been stored in a ‘pure’ form for possible future use in weapons poses one of the highest proliferation risks. In recent years such material has been down-blended for use in mixed oxide fuels in nuclear plants (USEC, 2012). However, there have historically been protests and objections to nuclear weapons and the civilian nuclear industry has been keen to distance itself from military applications (Kasperson et al., 1980).

2.1.3. Section C of the questionnaire

The questions included in section C related to participant demographics to allow for characterisation of the sample and any potential biases among the different groups. This included information on respondents’ age, sex, and geographical location.

2.3 Carrying out the Survey

The survey was carried out on-line using the services of TNS who have access to a large cross-section of UK population. A sample of n=1304 adults aged 16+, and demographically representative of the UK population, was surveyed over the period 18-22 August 2011. Selected demographic characteristics of the sample are shown in Table 4.

Table 4. Summary of selected demographic characteristics of the sample in comparison with the UK population.

		This survey		*UK census data (ONS 2006)*
		Number of respondents	*Percentage*	*Percentage*
Age	16-24	160	12%	15%
	25-34	244	19%	16%
	35-44	245	19%	19%
	45-54	225	17%	16%
	55+	430	33%	34%
	Total	**1304**	**100%**	**100%**
Sex	Male	643	49%	49%
	Female	661	51%	51%
	Total	**1304**	**100%**	**100%**
Region	Scotland	126	10%	9%
	North East / Yorks / Humber	169	13%	13%
	North West	160	12%	12%
	East & West Midlands	237	18%	17%
	South East / East of England	311	24%	24%
	Greater London	118	9%	13%
	Wales & West	183	14%	14%
	Total	**1304**	**100%**	**100%**

Care was taken to ensure that other research in the TNS research omnibus that week was dissimilar from this research in an effort to minimise any potential for crossover influence on responses. The following sections present and discuss the results of the survey.

3. RESULTS

The full data tables from the questionnaire are included on the attached CD/DVD. They are not included in hard copy in Appendix A as they are several hundred pages long. Abridged data tables are included and discussed in the following sections.

3.1 Section A – Public's Views on Nuclear Power

The responses to the questions on respondents' views on nuclear power asked in Section A are outlined in Table 5. The responses suggest that there is slightly more support for than opposition to nuclear power and associated new build in the UK. However, this is tempered by a significant level of concern about the level of risk posed, and a lack of awareness or information around key issues such as long-term waste disposal, carbon production status and understanding of the technical details of nuclear power. Finally, the fact that half of the respondents only thought about nuclear power when prompted and almost two thirds have never volunteered for anything, suggests that engaging the public in issues related to nuclear power may be challenging.

Table 5. The results from Section A of the questionnaire indicating public's views on nuclear power (n=1304). The numbers in brackets correspond to the numerical coding used for data analysis and were not visible to the participants.

Question	Answer					
Q1.1 How well do you feel you know the nuclear power industry?	Very well (1)	Fairly well (2)	Neither well nor not at all (3)	Not very well (4)	Not at all (5)	I don't know
Number of respondents	38	221	376	353	273	43
Percentage of total responses	3%	17%	29%	27%	21%	3%
Q1.2 How favourable or unfavourable is your opinion of the nuclear industry?	Very favourable (1)	Fairly favourable (2)	Neither favourable nor unfavourable (3)	Fairly unfavourable (4)	Very unfavourable (5)	I don't know
Number of respondents	112	355	411	201	110	115
Percentage of total responses	9%	27%	32%	15%	8%	9%
Q1.3 How well do you believe you understand the technical aspects of nuclear power?	I understand it very well (1)	I understand some parts well (2)	I understand it at a very general level (3)	I understand a little (4)	I really know nothing about it at all (5)	I don't know
Number of respondents	47	132	276	287	504	58
Percentage of total responses	4%	10%	21%	22%	39%	4%
Q1.4 By 2020 there may be a gap between the amount of energy the UK needs and the amount of energy the UK produces. Have you heard anything about this before?	Yes (1)	No (2)	I don't know			
Number of respondents	650	532	122			
Percentage of total responses	50%	41%	9%			
Q1.5 Would you support or oppose the building of new nuclear power plants in the UK?	Strongly support (1)	Slightly support (2)	Neither support nor oppose (3)	Slightly oppose (4)	Strongly oppose (5)	I don't know
Number of respondents	258	310	321	148	131	136
Percentage of total responses	20%	24%	25%	11%	10%	10%
Q1.6 How much of a risk do you believe having nuclear plants in the UK involves?	A great deal of risk (1)	Quite a bit of risk (2)	Not much risk (3)	Almost no risk (4)	I don't know	
Number of respondents	145	434	435	114	176	
Percentage of total responses	11%	33%	33%	9%	13%	
Q1.7 Please tell us your opinion about the following statement: 'Nuclear power is a low carbon option for generating electricity'	Strongly agree (1)	Slightly agree (2)	Neither agree nor disagree (3)	Slightly disagree (4)	Strongly disagree (5)	I don't know
Number of respondents	304	347	252	54	48	299
Percentage of total responses	23%	27%	19%	4%	4%	23%

Q1.8 Please tell us your opinion about the following statement: 'There is a clear way forward on how to deal with nuclear waste'	Strongly agree (1)	Slightly agree (2)	Neither agree nor disagree (3)	Slightly disagree (4)	Strongly disagree (5)	I don't know			
Number of respondents	57	166	323	228	211	319			
Percentage of total responses	4%	13%	25%	17%	16%	24%			
Q1.9 How frequently do you usually think about nuclear power?	Daily (1)	2-3 times a week (2)	Once a week (3)	2-3 times a month (4)	Once a month (5)	Less than once a month (6)	Only when I'm asked about it (7)	Never (8)	I don't know
Number of respondents	7	20	42	65	72	127	641	256	74
Percentage of total responses	1%	2%	3%	5%	6%	10%	49%	20%	6%
Q1.10 Are you involved in any form of voluntary work or civic engagement activity?	Yes, I currently volunteer (1)	I have volunteered in the past but I don't at the moment (2)	No (3)	I don't know					
Number of respondents	197	263	802	42					
Percentage of total responses	15%	20%	62%	3%					

On the subject of new nuclear build in the UK, Figure 2 shows the trends for public support and opposition over the last decade (see Table 6 for the questions asked). The general trend over the last nine years has been an increase in support and decrease in opposition to new nuclear build (Ipsos MORI, 2011). Immediately after the Fukushima incident there was a sharp dip in support and rise in opposition, although this has since reverted back to levels in line with the trends observed previously (FoE and GfK NOP, 2011; Ipsos MORI, 2011). The research detailed in this paper was carried out in August 2011 and Figure 2 suggests that the public's answers to the questions posed in the survey were probably not affected by the Fukushima incident, although it is difficult to rule out completely its potential influence. Research conducted in Switzerland by Siegrist and Visschers (In Press) suggests that downturns in the favourability of nuclear power, similar to that shown in Figure 2, can be observed in different nations. However, the extent of the observed 'rebound' may differ and requires further investigation.

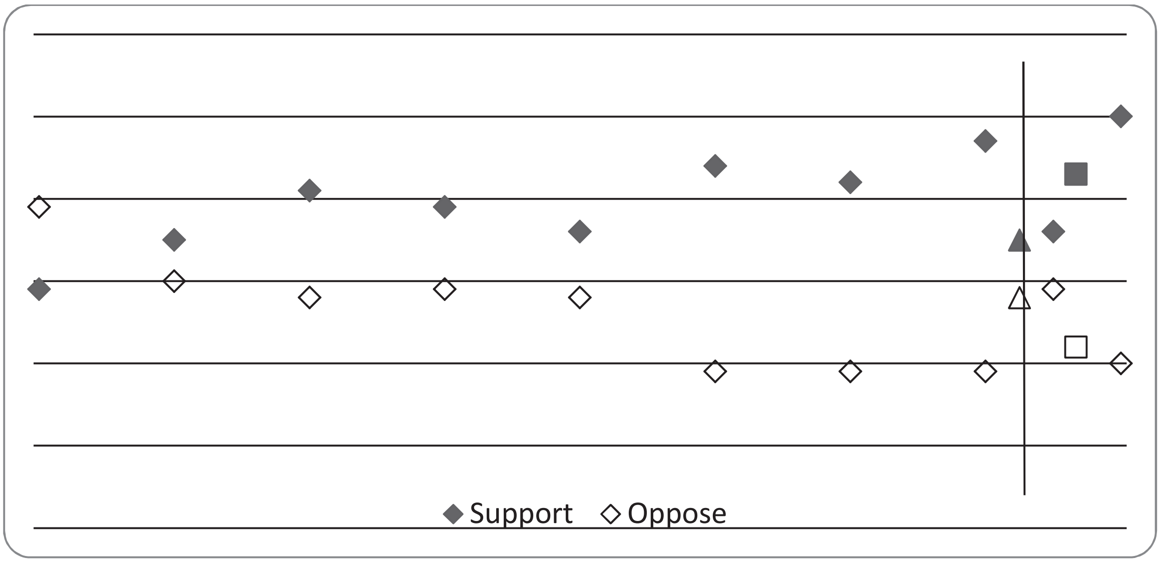

Figure 2. Support and opposition to new nuclear build in the UK (December 2003 – December 2011). Diamond data points represent research by Ipsos MORI (2011), triangular data points by FoE & GfK NOP (2011) and square points are data from this research. Vertical line denotes the date of the Fukushima nuclear incident.

Table 6. The questions used to plot the data in Figure 2. 'Strongly' and 'tend to' responses are combined to obtain the 'support' and 'oppose' data used in Figure 2.

Study	Question	Answer					
Ipsos MORI	To what extent would you support or oppose the building of new nuclear power stations in Britain TO REPLACE those that are being phased out over the next few years? This would ensure the same proportion of nuclear energy is retained.	Strongly Support	Tend to support	Neither support nor oppose	Tend to oppose	Strongly oppose	I don't know
FoE GfK NOP	The UK currently has a number of nuclear power stations that are due to be phased out over the coming years. To what extent do you support or oppose the building new nuclear power stations to replace those that are being phased out over the next few years?	Strongly Support	Tend to support	Neither support nor oppose	Tend to oppose	Strongly oppose	Don't know
This study	Would you support or oppose the building of new nuclear power plants in the UK? (Q1.5)	Strongly Support	Tend to support	Neither support nor oppose	Tend to oppose	Strongly oppose	I don't know

3.2 *Section B – Public's Views on Design Aspects*

As this is the first questionnaire to attempt to ask the public questions relating to nuclear design options the first 'test' was to find out if the public could answer the questions in a meaningful way. Whilst it is difficult to establish criteria to judge what a 'meaningful' answer is in this context, one criterion which does potentially highlight the level of difficulty that participants had in answering the design questions is the percentage that answered 'I don't know' for a given question. This is summarised in Table 7, with the three questions with the highest percentage highlighted in grey. It is important to recognise that the questionnaire is not designed to determine academic understanding of the subject matter. If the public expresses a preference for a technically deficient design option this is still a valid result as the importance lies in what the public feel is important, rather than an attempt at an objective judgment for what is technically correct.

Table 7. Percentage of 'I don't know' responses for each of the Section B questions (n=1304).

Question	**I don't know (%)**
Q2.1 What is your opinion about locating any future nuclear plants in the UK further away from the coast, perhaps closer to cities?	**22%**
Q2.2 How much of a difference would it make to your opinion of nuclear power if you could choose from different design options that 'fit in' more closely with the local environment?	**11%**
Q2.3 If you were given the choice by a utility company over which towers to use at a power plant to be built in your region, which of the following would best describe your opinion?	**21%**
Q2.4 Given the same total energy output, how does the idea of having several smaller reactors on one site instead of one large reactor make you feel?	**21%**
Q2.5 If a new nuclear power reactor were to be built, which of the following would best describe your opinion related to nuclear reactor design?	**27%**
Q2.6 Which of the following would best describe your opinion about possible protection measures from external impacts?	**20%**
Q2.7 If both active and passive safety systems are accepted for use on nuclear plants by the independent nuclear safety regulator, which of the following options would you prefer?	**32%**
Q2.8 If new nuclear plants used 'high integrity' digital computer controls that were certified by the independent nuclear safety regulator, how would you feel?	**23%**
Q2.9 Do you believe that nuclear fuel should be recycled?	**26%**
Q2.10 Do you agree or disagree that nuclear weapons material should be used to produce electricity?	**17%**
Q2.11 It is proposed that nuclear waste be stored underground indefinitely. I believe...	**22%**
Q2.12 Some of the options in the previous question on waste disposal would require the waste to be moved between sites. This can be achieved by rail, road or sea transportation (or a combination of these). How do you feel about this?	**16%**

The three questions highlighted in grey are arguably the hardest for any person to answer (including experts in the field) so it is perhaps unsurprising that they were the questions which participants seemed to struggle with most. It also seems unsurprising that the lowest 'I don't know' percentage (11%) is for question 2.2 which deals with aesthetic design, perhaps the easiest concept for participants to understand and identify with. Questions 2.1, 2.3, 2.4, 2.6, 2.8 and 2.11 all had 'I don't know' responses of slightly higher than 20% (20-23%). This is still a relatively high proportion, again suggesting that around one fifth of people either struggled to understand the question or to reach a decision. As always with this type of research, it is possible that a higher proportion of people did not know but 'guessed' an answer. However, the percentage of 'I don't know' answers obtained here is in line with values seen in other nuclear-related questionnaires (e.g. Eurobarometer, 2010), suggesting that the questions asked in the current research were not much more difficult for the lay public to answer than in other related surveys.

The full results from section B are shown in Table 8. Further analysis and discussion of the results are presented in the following sections. First, the relationships between the answers in Sections A and B are discussed. This is followed by the analysis of the answers for different demographic groups.

Table 8. Results from Section B of the questionnaire, indicating public's views on different aspects of nuclear plant design (n=1304). Only the questions are shown; the explanatory preamble text for questions can be found in the full questionnaire in the appendix attached to this paper. The numbers in brackets correspond to the numerical coding used for data analysis and were not visible to the participants.

Category	Question	Answer						
Safety	Q2.1 What is your opinion about locating any future nuclear plants in the UK further away from the coast, perhaps closer to cities?	Moving away from the coast, perhaps closer to cities, is a good idea (1)	Moving away from the coast, perhaps closer to cities, might be a good idea but I'm not sure (2)	I am indifferent to the idea of moving away from the coast, perhaps closer to cities (3)	Moving away from the coast, perhaps closer to cities, might be a bad idea but I'm not sure (4)	Moving away from the coast, perhaps closer to cities, is a bad idea (5)	I don't know	
	Number of respondents ***Percentage of total responses***	37 3%	93 7%	223 17%	252 19%	415 32%	284 22%	
Aesthetics	Q2.2 How much of a difference would it make to your opinion of nuclear power if you could choose from different design options that 'fit in' more closely with the local environment?	A big difference, it is worthwhile doing this (1)	Some difference, it is worthwhile doing this (2)	I'm not sure how much difference this would make	Some difference, it is not worth doing this	No difference, it is not worth doing this	I don't know	
	Number of respondents ***Percentage of total responses***	177 14%	346 27%	422 32%	64 5%	151 12%	144 11%	
Aesthetics	Q2.3 If you were given the choice by a utility company over which towers to use at a power plant to be built in your region, which of the following would best describe your opinion?	I have a strong preference for 'natural draft' cooling towers (1)	I have a slight preference for 'natural draft' cooling towers (2)	I don't have a preference for either type of cooling tower (3)	I have a slight preference for the 'fan-assisted' cooling towers (4)	I have a strong preference for the 'fan-assisted' cooling towers (5)	I don't know	
	Number of respondents ***Percentage of total responses***	79 6%	109 8%	358 27%	339 26%	150 12%	269 21%	
Reactor size	Q2.4 Given the same total energy output, how does the idea of having several smaller reactors on one site instead of one large reactor make you feel?	Much more safe (1)	Slightly more safe (2)	Neither more nor less safe (3)	Slightly less safe (4)	Much less safe (5)	I don't know	
	Number of respondents ***Percentage of total responses***	97 7%	328 25%	491 38%	64 5%	44 3%	280 21%	

Reactor type	Q2.5 If a new nuclear power reactor were to be built, which of the following would best describe your opinion related to nuclear reactor design?	I would prefer to keep the existing nuclear reactor design (1)	I would prefer to keep the existing nuclear reactor design, but more information on the alternative designs might persuade me to change my views (2)	Nuclear reactor design does not make any difference to me (3)	I would prefer a new, alternative nuclear reactor design, but I would like to see a slow transition (4)	I would prefer changing to a new, alternative nuclear reactor design (5)	I don't know		
	Number of respondents ***Percentage of total responses***	50 4%	197 15%	314 24%	255 20%	136 10%	352 27%		
Counter terrorism	Q2.6 Which of the following would best describe your opinion about possible protection measures from external impacts?	I have a strong preference for the hard outer impact dome (1)	I have a slight preference for the hard outer impact dome (2)	I have no particular preference on this issue (3)	I have a slight preference for alternative solutions (4)	I have a strong preference for alternative solutions (5)	I don't know		
	Number of respondents ***Percentage of total responses***	92 7%	116 9%	348 27%	284 22%	204 16%	260 20%		
Safety	Q2.7 If both active and passive safety systems are accepted for use on nuclear plants by the independent nuclear safety regulator, which of the following options would you prefer?	A fully active system (1)	A mainly active system with some passive backup (2)	A blend of active and passive systems (3)	Mainly passive systems with some active backup (4)	Just passive systems (5)	I don't know		
	Number of respondents ***Percentage of total responses***	94 7%	137 11%	415 32%	209 16%	35 3%	414 32%		
Control systems	Q2.8 If new nuclear plants used 'high integrity' digital computer controls that were certified by the independent nuclear safety regulator, how would you feel?	Much more safe (1)	Slightly more safe (2)	Neither more nor less safe (3)	Slightly less safe (4)	Much less safe (5)	I don't know		
	Number of respondents ***Percentage of total responses***	115 9%	321 25%	449 34%	81 6%	42 3%	296 23%		
Proliferation	Q2.9 Do you believe that nuclear fuel should be recycled?	Recycling nuclear fuel is definitely a good idea (1)	Recycling nuclear fuel might be a good idea but I need to know more (2)	I'm indifferent to the idea of recycling nuclear fuel (3)	Recycling nuclear fuel might be a bad idea but I need to know more (4)	Recycling nuclear fuel is definitely a bad idea (5)	Nuclear power should not be used in the first place	Other	I don't know
	Number of respondents ***Percentage of total responses***	254 19%	472 36%	112 9%	95 7%	25 2%	6 0.5%	1 0.1%	339 26%
Waste	Q2.10 Do you agree or disagree that nuclear weapons material should be used to produce electricity?	Strongly agree (1)	Slightly agree (2)	Neither agree nor disagree (3)	Slightly disagree (4)	Strongly disagree (5)	I don't know		
	Number of respondents ***Percentage of total responses***	358 28%	356 27%	251 19%	54 4%	65 5%	220 17%		

Waste	Q2.11 It is proposed that nuclear waste be stored underground indefinitely. I believe...	Storing nuclear waste underground indefinitely will work (1)	Storing nuclear waste underground indefinitely might work but I need more information (2)	I have no opinion on this matter (3)	Storing nuclear waste underground indefinitely might not work but I need more information (4)	Storing nuclear waste indefinitely in any way will never work (5)	Other	I don't know
	Number of respondents	69	325	158	264	199	8	281
	Percentage of total responses	5%	25%	12%	20%	15%	1%	22%
Waste	Q2.12 Some of the options in the previous question on waste disposal would require the waste to be moved between sites. This can be achieved by rail, road or sea transportation (or a combination of these). How do you feel about this?	I believe nuclear waste transportation is very safe (1)	I believe nuclear waste transportation is fairly safe (2)	I have no particular preference on this issue (3)	I believe nuclear waste transportation is fairly dangerous (4)	I believe nuclear waste transportation is very dangerous (5)	I don't know	
	Number of respondents	75	263	230	316	205	215	
	Percentage of total responses	6%	20%	18%	24%	16%	16%	

3.3 Analysis of relationship between Section A and B answers

Further analysis of the data from the questionnaire was carried out by cross-tabulating the results from section A with the results from section B to find out if the former had an influence on the latter. Somers D (abbreviated as 'D') has been used for these purposes (Somers, 1962). Somers D is a measure of the relationship between two ordinal variables; it's values range from -1 to 1 with a value of 1 indicating a strong positive relationship, -1 a strong negative relationship and 0 no relationship. The direction of the relationship is dependent on the direction of the numerical coding applied to the answers in the questionnaire, which is shown in Table 5 and Table 8. A positive relationship means that as variable A increases variable B also increases; it is important to remember that this 'increase' is in the coded value of the variable rather than the variable itself. This means that in some cases as the coding scale increases, the negative relationship with the coding scale (i.e. negative D value) may in fact indicate a positive relationship with the variable. As per standard practice in statistical analysis, only relationships with the probability of occurring of 99.95% and greater (i.e. with the p-value of $p \leq 0.05$) are deemed statistically significant. Because Somer's D is an ordinal-ordinal comparative relationship, responses such as 'I don't know' and 'Other' were discounted from the statistical analysis.

The data from sections A and B were cross-tabulated using the statistical analysis package SPSS 16.0 (IBM, 2013) and Somers D was calculated to determine the probability of the existence of any asymmetric (one-directional) relationships between dependent (Section B) and independent (Section A) variables. Few statistically significant relationships were found. Those that were discovered are described below. Only relationships with $p<0.05$ and of a strength greater than 0.2 or -0.2 were considered to be meaningful. Even so, a relationship strength of 0.2 or -0.2 is still weak. However, any number of different factors might influence an individual's responses to the section B questions. Therefore it is unsurprising that the only relationships found between the relatively short list of section A questions and the section B questions are weak.

In particular, the following relationships are observed between questions in Section A and B, respectively:

- As familiarity with the nuclear industry decreases (Q1.2 in Section A), dislike of weapons material recycling increases (Q2.10 in Section B, D=0.356, p<0.005), belief in a long-term solution for nuclear waste declines (Q2.11, D=0.354, p<0.005) and the perception of waste transport being unsafe increases (Q2.12, D=0.470, p<0.005).
- Similarly, as support for new build decreases and opposition increases (Q1.5), dislike of weapons material recycling increases (Q2.10, D=0.400, p<0.005), belief in a long-term solution for nuclear waste goes down (Q2.11, D=0.351, p<0.005) and belief in waste transport being unsafe increases (Q2.12, D=0.469, p<0.005).
- As the level of perceived risk of nuclear power decreases (Q1.6), the belief that waste transport is safe increases (Q2.12, D= -0.385, p<0.005).
- People who perceive nuclear power as more carbon intensive (Q1.7) also have a tendency to believe that recycling weapons material is a bad idea (Q2.10, D=0.366, p<0.005).
- Respondents who have a more negative view on the existence of a clear solution for long-term waste disposal (Q1.8) are more negative about indefinitely storing nuclear waste underground (Q2.11, D=0.366, p<0.005) and believe that waste transport is less safe (Q2.12, D=0.334, p<0.005).

No significant relationships were found between the following section A questions and any of the B variables:

- Q1.9 on how often people think about nuclear power; and
- Q1.10 on whether they currently or have volunteer/ed.

Furthermore, no significant relationships were found between the following B and any of the questions in section A:

- Q2.3 on cooling tower choice;
- Q2.4 on size of plant and co-location;
- Q2.5 on nuclear reactor design;

- Q2.6 on external impact protection measures; and
- Q2.7 on active or passive safety systems.

The above are the main questions (Q2.3-2.7) relating to the technical design of the nuclear plant. A lack of any relationships with the section A questions suggests that the public's choices for design options may not be related to or influenced by their pre-existing views on nuclear power and the nuclear industry.

3.4 *Analysis of results for different demographic groups*

To analyse any influence of the demographic variables on the results, the data were split by gender, region and age, cross-tabulated for the questions in Sections A and B and Somers D re-calculated. Owing to space restrictions, only results where a difference between the values of Somers D was at least 25% are shown.

Somer's D was calculated separately for men and women; selected results where disparities between the genders existed are presented in Table 9. The analysis suggests that some of the section A variables (Q1.2, Q1.5) influence women more when plant aesthetics are considered (Q2.2) and that some of the section A variables (Q1.2, Q1.3, Q1.5, Q1.7) influence men more when fuel recycling (Q2.9) is considered.

Table 9. Somers D for relationships where gender split shows a substantial difference (>25%) in value. Grey highlights statistically significant results (Somers D > 0.2 or < -0.2 and p<0.05).

Relationship	Male	Female
Industrial favourability decreasing (Q1.2) and plant aesthetics making less difference (Q2.2)	0.165	0.317
Support for new build decreasing (Q1.5) and plant aesthetics making less difference(Q2.2)	0.136	0.340
Support for new build decreasing (Q1.5) and choice of control system tending towards passive (Q2.8)	0.182	0.296
Industrial favourability decreasing (Q1.2) and dislike of nuclear fuel recycling increasing (Q2.9)	0.309	0.173
Support for new build decreasing (Q1.5) and dislike of nuclear fuel recycling increasing (Q2.9)	0.354	0.194
Level of perceived risk posed by nuclear power decreasing (Q1.6) and dislike of recycling weapons material decreasing (coding scale is increasing hence negative relationship) (Q2.10)	-0.279	-0.189
Technical understanding decreasing (Q1.3) and perceived safety of nuclear transport decreasing (Q2.12)	0.214	0.129

Belief in a clear solution for waste decreasing (Q1.8) and the perceived safety of nuclear transport decreasing (Q2.12)	0.283	0.397

An analysis of the data, broken down by geographic region of North (Scotland, North-West, Yorkshire & Humberside and North-East), Midlands (East & West Midlands, East of England and Wales) and South (South-East, London and South-West) showed limited variability in Somers D between the regions. The results are shown in Table 10. This is probably because the geographic areas used in the breakdown are too large and incorporate too many different communities to allow a more granular analysis. However, it is not possible to carry out a more localised analysis with this data set as sub-samples in the breakdown are too small to allow meaningful statistical analysis.

Table 10. Somers D for relationships where geographic region shows a substantial difference (>25%) in value. Grey highlights statistically significant results (Somers D > 0.2 or < -0.2 and p<0.05).

Relationship	**North**	**Midlands**	**South**
Industrial favourability decreasing (Q1.2) and plant aesthetics making less difference (Q2.2)	0.194	0.291	0.231
Support for new build decreasing (Q1.5) and plant aesthetics making less difference (Q2.2)	0.199	0.291	0.214
Belief in nuclear being low carbon decreasing (Q1.7) and dislike of nuclear fuel recycling increasing (Q2.9)	0.254	0.312	0.222
Industrial favourability decreasing (Q1.2) and dislike of recycling weapons material increasing (Q2.10)	0.396	0.266	0.410
Technical understanding decreasing (Q1.3) and dislike of recycling weapons material increasing (Q2.10)	0.231	0.117	0.261
Support for new build decreasing (Q1.5) and dislike of recycling weapons material increasing (Q2.10)	0.433	0.303	0.473
Level of perceived risk posed by nuclear power decreasing (Q1.6) and dislike of recycling weapons material decreasing (coding scale is increasing hence negative relationship) (Q2.10)	-0.283	-0.206	-0.260
Knowledge of the nuclear industry decreasing (Q1.1) and the perceived safety of nuclear transport decreasing (Q2.12)	0.190	0.192	0.323
Belief in a clear solution for waste decreasing (Q1.8) and the perceived safety of nuclear transport decreasing (Q2.12)	0.429	0.273	0.308

A breakdown by age group was also carried out. In order to ensure that sub-samples were not too small for meaningful analysis, the categories were grouped into 16-34, 35-54 and 55+. Several relationships showed a variability by age group, as seen in Table 11. In many of the cases in Table 11, the younger respondents showed the weakest relationship between independent and dependent variable, and the older respondents the strongest; this is particularly obvious in the relationships associated with questions on nuclear waste disposal (Q2.11) and nuclear transport (Q2.12). The reverse is observed for the question on site location (Q2.1) where the responses provided by the young seem to have stronger relationships than those provided by the old.

Table 11. Somers D for relationships where age group shows a substantial difference (>25%) in value. Grey highlights statistically significant results (D>0.2D<-0.2 and p<0.005 unless indicated differently).

Relationship	16-34	35-54	55+
Belief in a clear solution for waste decreasing (Q1.8) and the proximity of nuclear plants to cities decreasing (Q2.1)	0.236	0.247	0.136
Technical understanding decreasing (Q1.3) and plant aesthetics making less difference (Q2.2)	0.165	0.263	0.286
Support for new build decreasing (Q1.5) and plant aesthetics making less difference (Q2.2)	0.130 [a]	0.304	0.261
Industrial favourability decreasing (Q1.2) and nuclear fuel recycling being a bad idea increasing (Q2.9)	0.148	0.256	0.360
Support for new build decreasing (Q1.5) and nuclear fuel recycling being a bad idea increasing (Q2.9)	0.194	0.296	0.375
Technical understanding decreasing (Q1.3) and recycling weapons material being a bad idea increasing (Q2.10)	0.240	0.160	0.232
Level of perceived risk posed by nuclear power decreasing (Q1.6) and recycling weapons material being a bad idea decreasing (coding scale is increasing hence negative relationship) (Q2.10)	-0.241	-0.201	-0.295
Industrial favourability decreasing (Q1.2) and belief in the viability of underground disposal of nuclear waste decreasing (Q2.11)	0.249	0.383	0.383
Support for new build decreasing (Q1.5) and belief in the viability of underground disposal of nuclear waste decreasing (Q2.11)	0.248	0.384	0.371
Level of perceived risk posed by nuclear power decreasing (coding scale is increasing hence negative relationship) (Q1.6) and belief in the viability of underground disposal of nuclear waste increasing (Q2.11)	-0.117 [a]	-0.259	-0.354
Belief in nuclear being low carbon decreasing (Q1.7) and belief in the viability of underground disposal of nuclear waste decreasing (Q2.11)	0.149	0.257	0.229
Belief in a clear solution for waste decreasing (Q1.8) and belief in the viability of underground disposal of nuclear waste decreasing (Q2.11)	0.387	0.425	0.296
Support for new build decreasing (Q1.5) and the perceived safety of nuclear transport decreasing (Q2.12)	0.366	0.497	0.498
Level of risk posed by nuclear power decreasing (coding scale is increasing hence negative relationship) (Q1.6) and the perceived safety of nuclear transport increasing (Q2.12)	-0.256	-0.395	-0.462

[a] The p-value for these question was < 0.05.

4 DISCUSSION AND IMPLICATIONS

The survey carried out in this research has provided an indication of the UK public's view on a number of key aspects of nuclear plant design (Table 8). These views are based on and influenced by a wide range of factors, some of which have been identified via the questions in section A of the questionnaire (Table 5). Overall, the findings indicate that the design preferences expressed by the public are largely in agreement with the current approach taken by design engineers. These include a comprehensive approach to safety, integration of novel technology where appropriate and minimisation of waste and transportation of nuclear material (EUR, 2011). However, disparities exist between the public's view and the designs proposed for new nuclear build relating to aesthetics. For example, the containment buildings for the two proposed reactors (EPR and AP1000) currently undergoing approval in the UK are 60-70 m tall (WEC, 2003; AREVA, 2005). Two reactors of this physical size are planned for the site at Hinckley Point, three or four large reactors are planned for the site at Wylfa and two large reactors are planned at both the Oldbury and Sizewell sites (WNA, 2012c). This would seem at odds with the responses received to Q2.4 whereby a significant proportion (32%) of the public would prefer multiple smaller reactors.

The rate of 'I don't know' responses to the questions on aspects of nuclear design suggests that the public was able to comprehend some questions (and aspects) better than others, with questions involving technically ambiguous solutions being the ones that the public found most difficult to answer. Another significant finding was that expressed preferences relating to nuclear power plants do not appear to be influenced by background views on nuclear power, whilst expressed preferences relating to nuclear waste do appear to be influenced by background views on nuclear power. This research was unable to provide an answer as to why this is the case and further research will be required to investigate, validate and clarify this discrepancy. Understanding how well the public was able to understand the section B questions is a challenge and requires further research effort. A weakness of this research is that whilst the questionnaire allows for public participation it does not guarantee that those participating are fully engaged and understand the technical details presented. Enhancing the questionnaire research with qualitative techniques in a mixed methods approach would go some way towards addressing such issues (Johnson et al., 2007).

These results suggest that policy makers in roles related to strategic decision making and technology selection may need to place more emphasis on the role that the public's interpretation of the specific design features plays if they wish to improve the social acceptability of large infrastructure projects like nuclear plants. This is potentially of greater importance in countries with free energy markets as the public may expect and demand a higher degree of engagement. However, this does not weaken the case for better public engagement in other countries where nuclear operations are largely nationalised as they are as vulnerable to public opposition, protest and in extreme cases, direct action against new build; e.g. protests against the construction of new reactors at the Kudankulam nuclear power plant in India (Times of India, 2012a, 2012b).

In particular, in light of the UK government's draft Energy Bill (DECC, 2012b), these results suggest that more could potentially be done by the nuclear industry to pave the way for new nuclear build. Closer and deeper engagement with the public, through work such as that presented in this paper, may have the potential to further reduce the gap between public opinion and the drive for nuclear new build, as well as between perceived and estimated risk. However, as so many factors drive such issues at both local and national levels, further research is required before it is possible to say with more certainty what, if any, impact such engagement might have. When engagement does take place, care must be taken by those involved to ensure that facts are presented in a neutral manner and not 'framed' in a biased context. Framing is influenced by what information is provided and how it is presented. Limiting and controlling these issues can minimise bias but in doing so important context around the issues being discussed can be lost and it can be argued that removing any context, even to attempt a 'neutral' presentation of facts, is a form of framing. However, recent research has suggested that framing of issues may be less dominant than other factors (such as anchoring to existing beliefs) for the outcome of engagement processes (Jones et al., 2012).

As discussed in Section 1, this work is only a first step towards a better understanding and integration of the public's views into the design of new nuclear power plants. The second step relates to integrating the results from consultations, such as the survey discussed in this paper, into the design process itself. In reality, to gain a fully involved and representative view from the public for integration into reactor design, much more than a single questionnaire would be required. Other means, such as research interviews and facilitated focus groups should be pursued in an effort to gain a deeper understanding of what people want and, perhaps more importantly, why they want it.

A weakness of this research is that statistical techniques such as conjoint analysis (Louviere, 1988) cannot be applied to the output of the survey. Conjoint analysis requires an understanding of the orthogonality of the various parameters being investigated and this is currently lacking in this research. ‘Classical’ orthogonal factors relating to design might be factors such as cost, aesthetic appeal, functionality and safety. However, defining such terms for a nuclear plant in a way that is amenable to lay-public participation is a significant challenge. Indeed, cost was removed from the survey entirely because it was decided that it would be too difficult to provide a justifiable cost benchmark for each of the design options in consideration in terms that the public would readily understand. Future work should aim to improve on the survey questions used in this research so that analyses such as conjoint analysis can be carried out.

How best to represent the lay-stakeholder within the participatory design process has been an area of difficulty since the inception of participatory design approaches. For example, it is difficult to envisage a practical approach that involves every member of the public. An account of such difficulties is provided by Asaro, (2000) who identifies the various techniques which have been used by participatory designers over the years in an effort to address such difficulties. This research uses only two such techniques, those of mocked-up images of the ‘final product’ and of analogous explanations, to assist in bridging the gap between technical design information and lay-understanding of the design concepts in question. This is another limitation of this research, in that such methods have both the potential to implicitly bias the responses provided and are also open to a degree of interpretation by the participant which may stray from the original design intent.

It is also likely that local residents’ needs may be prioritised in the design and construction of new nuclear plants. This is tempered, however, by the pragmatism required in designing a reactor type that may then be situated on multiple sites, in multiple countries; the prevailing design vision that ‘one plant fits all’ may not fit with different public views in different locations. It would be quite uneconomic to customise each reactor for every site without significant changes in both the way that nuclear reactors are designed and the economics of their construction. Such considerations merit further research.

Finally, different national governments employ different discourses for engaging with their public on the topic of energy policy. This was highlighted in recent work by Teräväinen et al. (2011). Applying the findings of the work presented in this paper will require different strategies depending on the state of the discourse between relevant stakeholders in each country. Further research, asking similar questions to those detailed here, is required before the results of this research can be generalised beyond the borders of the UK.

5 CONCLUSIONS

This paper has presented a first attempt at understanding if the public can provide input into the design of nuclear power plants and what that input might be. A research questionnaire was chosen as the means to investigate this area. Although this allowed a large number of people to be questioned it limited the range of questions that could be asked and the depth to which underlying factors could be explored by means of statistical analysis. As such, this work should be considered as a first attempt to explore the public's preferences of design options for nuclear plants. Further research is required before definitive conclusions on design preferences can be drawn and underlying factors understood.

These findings suggest that policy and decision making related to new nuclear build should seek to understand and account for the various factors behind the public's perception of nuclear power. The analysis of this research does suggest that the public are willing and able to offer an opinion on this subject, though further work is required to ensure that such expressed opinions are a fair representation of the views of the wide range of individual views that coexist within the public.

Whilst a research questionnaire such as the one used in this research is a useful means for providing an overview of *what* people think, it is weak at explaining *why* people think such things. Therefore, further research is required to understand why specific design aspects were chosen by the public over the alternatives and to understand what factors might drive the public's preferences for the chosen design aspects. Furthermore, research is also needed on how to integrate such information into the existing engineering procedures to aid design of socially more acceptable nuclear plants. The latter is subject of the on-going work by the authors.

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APPENDIX – RESEARCH QUESTIONNAIRE

Note to editor, the data gathered in this research can be made available if a suitable publicly accessible repository can be located. The data is in SPSS *.sav file format and excel *.xls format.

The following is a document format copy of the questionnaire used in this research. Questions in section 2 appeared on individual pages, page breaks from the electronic version are denoted by solid black lines, such as the one below. TNS was already in possession of the demographic data for the sample, so those questions are not shown in this appendix as they did not specifically form part of this questionnaire.

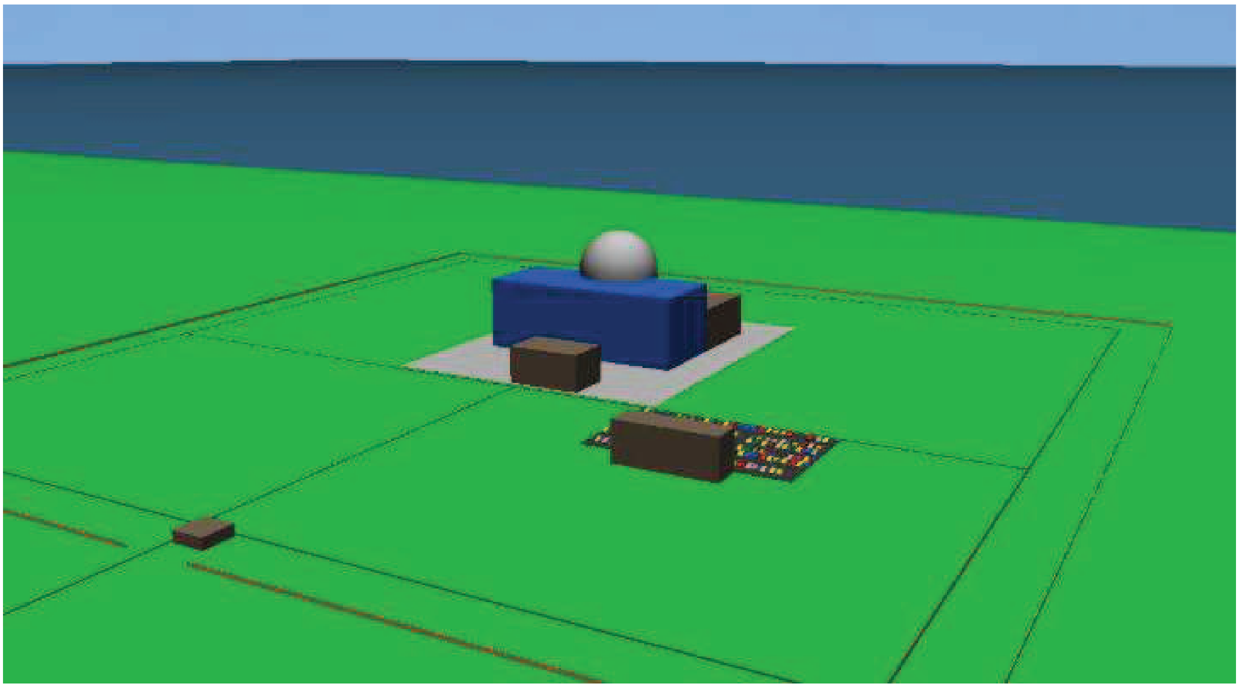
Page break

Changing the subject….

The following questions are about how different designs of nuclear plants may affect people's opinion of nuclear power. To do this we need to ask about your views on nuclear power and different nuclear design options.

The project is carried out at the University of Manchester within the Doctorate of Engineering programme in collaboration with Rolls-Royce.

The picture below shows you a 'typical' nuclear power plant



If you are interested in further information it can be found in the participant information sheet which is linked below.

LINK TO FAQ SHEET

Page break

This section of the questionnaire is designed to help the researchers understand how familiar you are with nuclear power. Please answer all the questions as best you can, based on what you know, believe or feel as an individual.

Q1.1 How well do you feel you know the nuclear power industry? (not the technical background of nuclear power, but the industry itself)

Very well (1)
Fairly well (2)
Neither well nor not at all (3)
Not very well (4)

Not at all (5)
I don't know (0)

Q1.2 How favourable or unfavourable is your opinion of the nuclear industry?

Very favourable (1)
Fairly favourable (2)
Neither favourable nor unfavourable (3)
Fairly unfavourable (4)
Very unfavourable (5)
I don't know (0)

Q1.3 How well do you believe you understand the technical aspects of nuclear power (e.g. technologies used, how a plant works etc.)?

I understand it very well (1)
I understand some parts well (2)
I understand it at a very general level (3)
I understand a little (4)
I really know nothing about it at all (5)
I don't know (0)

Q1.4 As various power plants (including nuclear plants) in the UK come to the end of their lives, and are closed down, by 2020 there may be a gap between the amount of energy the UK needs and the amount of energy the UK produces. Have you heard anything about this before?

Yes (1)
No (2)
I don't know (0)

Q1.5 To what extent would you support or oppose the building of new nuclear power plants in the UK? (some of which would replace existing, older, nuclear plants)

Strongly support (1)
Slightly support (2)
Neither support or oppose (3)
Slightly oppose (4)
Strongly oppose (5)
I don't know (0)

Q1.6 How much of a risk do you believe having nuclear power plants in the UK involves?

A great deal of risk (1)
Quite a bit of risk (2)
Not much risk (3)
Almost no risk (4)
I don't know (0)

Q1.7 Please tell us your opinion about the following statement: 'Nuclear power is a low carbon option for generating electricity'

Strongly agree (1)
Slightly agree (2)
Neither agree or disagree (3)
Slightly disagree (4)
Strongly disagree (5)
I don't know (0)

Q1.8 Please tell us your opinion about the following statement: 'There is a clear way forward on how to deal with nuclear waste'

Strongly agree (1)
Slightly agree (2)
Neither agree nor disagree (3)
Slightly disagree (4)
Strongly disagree (5)
I don't know (0)

Q1.9 How frequently do you usually think about nuclear power?

Daily (1)
2-3 Times a Week (2)
Once a Week (3)
2-3 Times a Month (4)
Once a Month (5)
Less than Once a Month (6)
Only when I’m asked about it (7)
Never (0)
I don’t know (0)

Q1.10 Are you involved in any form of voluntary work or civic engagement activity? (This includes activities such as volunteering for charity work, helping to run youth groups or regularly attending meetings relating to local issues)

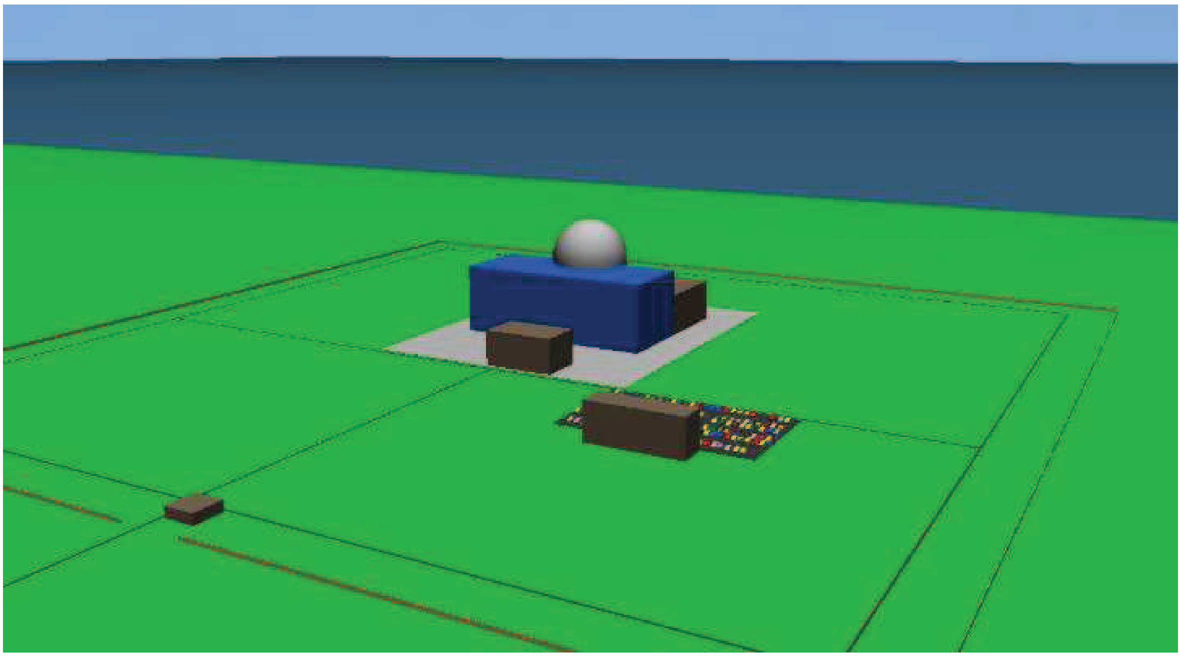
Yes, I currently volunteer (1)
I have volunteered in the past but I don’t at the moment (2)
No (3)
I don't know (0)

Page break

This section of the survey asks your opinions about a variety of design options for current and new nuclear power plants. As with section one, please answer all the questions as best you can, based on what you know, believe or feel as an individual.

2.1p A 'typical' nuclear power plant in the UK is located by the sea. An alternative would be to build future nuclear power plants further away from the coast, but that may mean moving them closer to cities

2.1i1 An example of a 'typical' nuclear power plant located by the coast



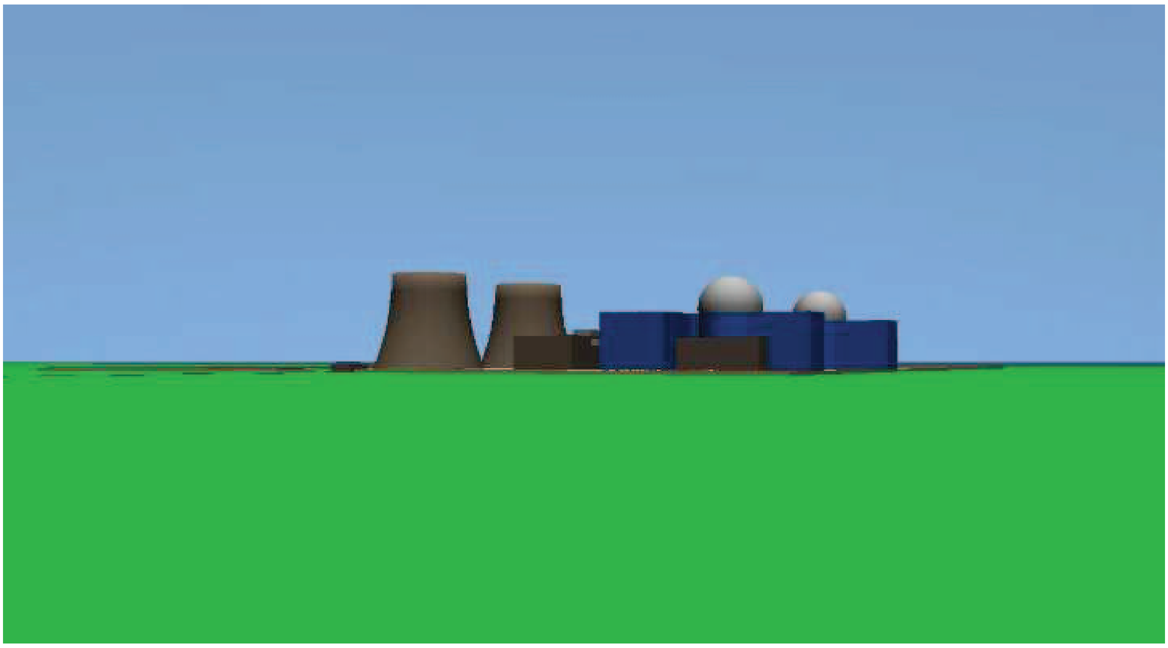
Q2.1 What is your opinion about locating any future nuclear plants in the UK further away from the coast, perhaps closer to cities?

Moving away from the coast, perhaps closer to cities is a good idea (1)
Moving away from the coast, perhaps closer to cities might be a good idea but I'm not sure (2)
I am indifferent to the idea of moving away from the coast, perhaps closer to cities (3)
Moving away from the coast, perhaps closer to cities might be a bad idea but I'm not sure (4)
Moving away from the coast, perhaps closer to cities is a bad idea (5)
I don't know (0)

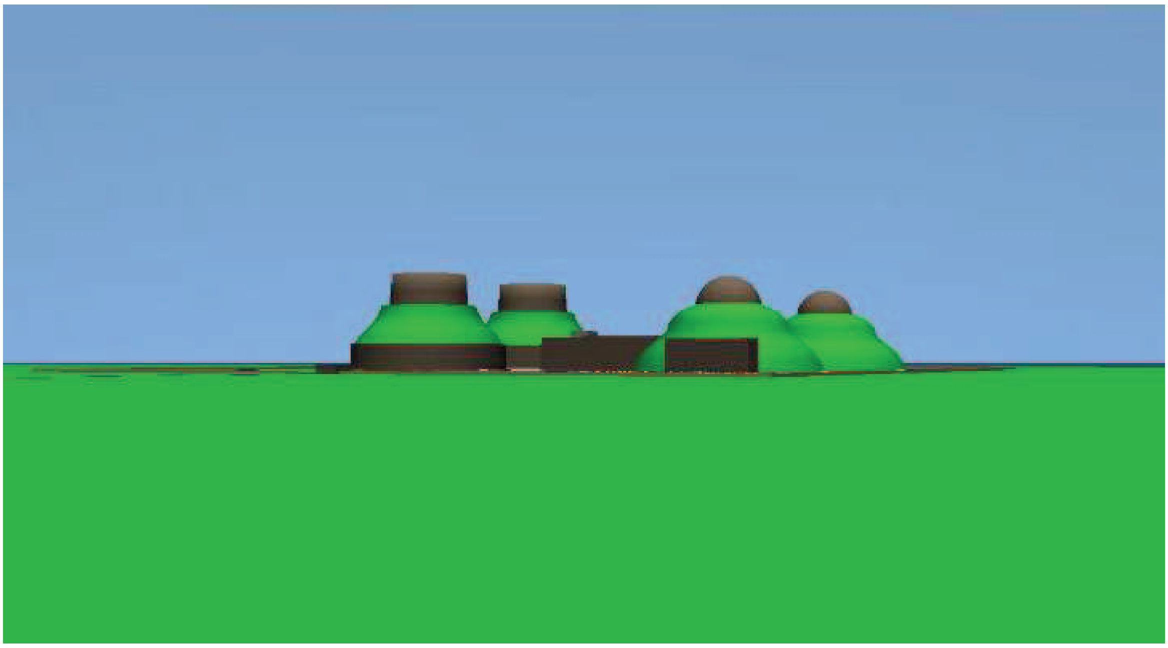
Page break

2.2p Nuclear power plants are industrial buildings which are often based in rural settings.

Q2.2i1 A two unit nuclear power plant with standard design



Q2.2i2 A two unit nuclear power plant located inside and under earth and grass banks that attempt to blend the main buildings and cooling towers with the surrounding environment



Q2.2 Q.2 How much of a difference would it make to your opinion of nuclear power if you could choose from different design options that 'fit in' more closely with the local environment?

(note: Set up as sliding scale)

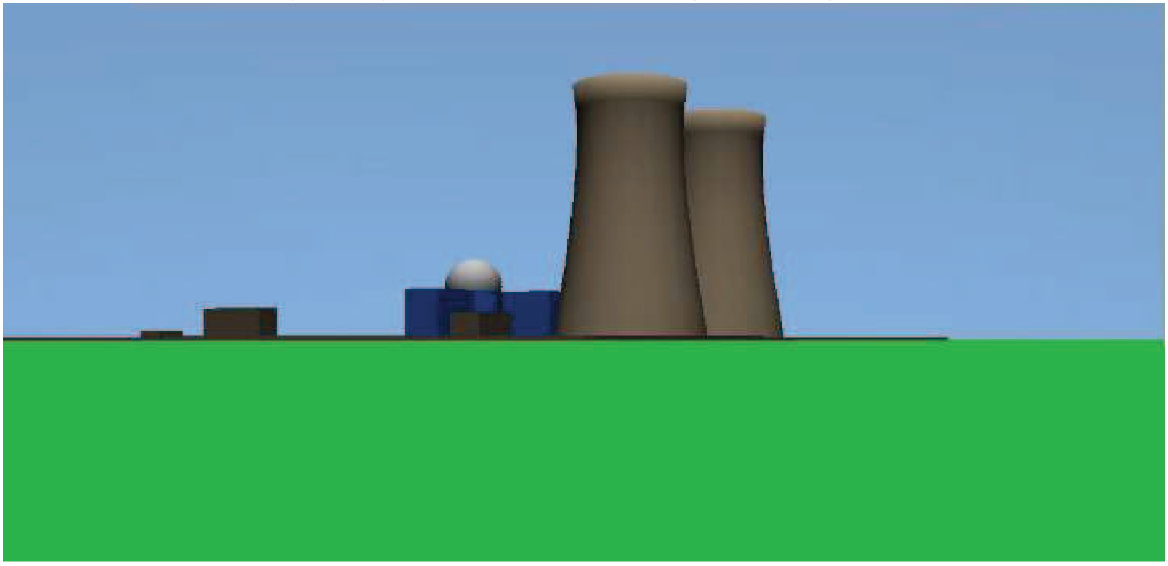
A big difference, it is worthwhile doing this (1)

Some difference, it is worthwhile doing this (2)
I’m not sure how much difference this would make (3)
Some difference, it is not worth doing this(4)
No difference, it is not worth doing this (5)
I don't know (0)

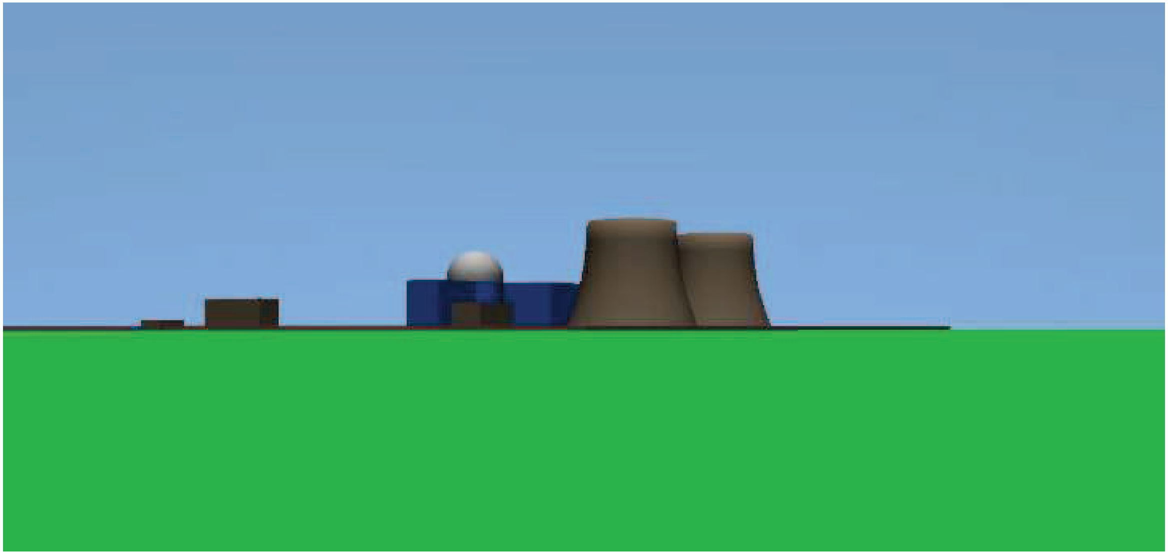
Page break

2.3p New nuclear power plants may need cooling towers. There are two main types of cooling towers: ‘natural draught’ and ‘fan assisted’. These are shown in the images below.

Q2.3i1 A new nuclear power plant with 'natural draught' cooling towers



Q2.3i2 A new nuclear plant with 'fan assisted' cooling towers



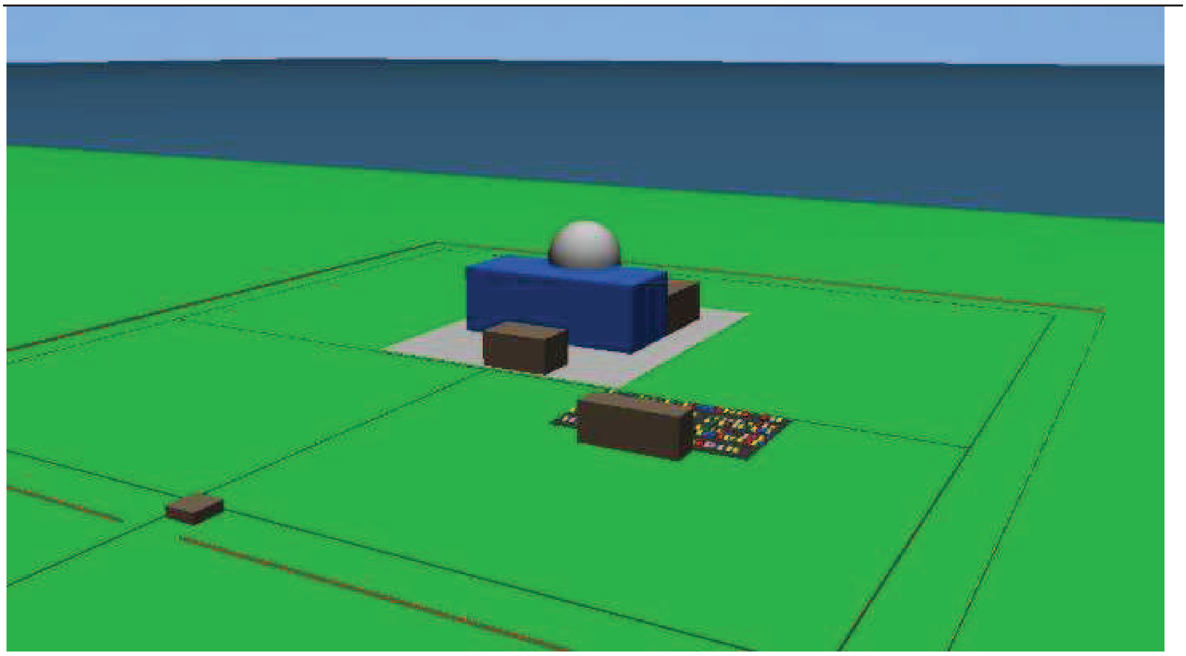
Q2.3 Q.3 If you were given the choice by a utility company over which towers to use at a power plant to be built in your region, which of the following would best describe your opinion?

I have a strong preference for 'natural draught' cooling towers (1)
I have a slight preference for 'natural draught' cooling towers (2)
I don't have a preference for either type of cooling tower (3)
I have a slight preference for the 'fan-assisted' cooling towers (4)
I have a strong preference for the 'fan-assisted' cooling towers (5)
I don't know (0)

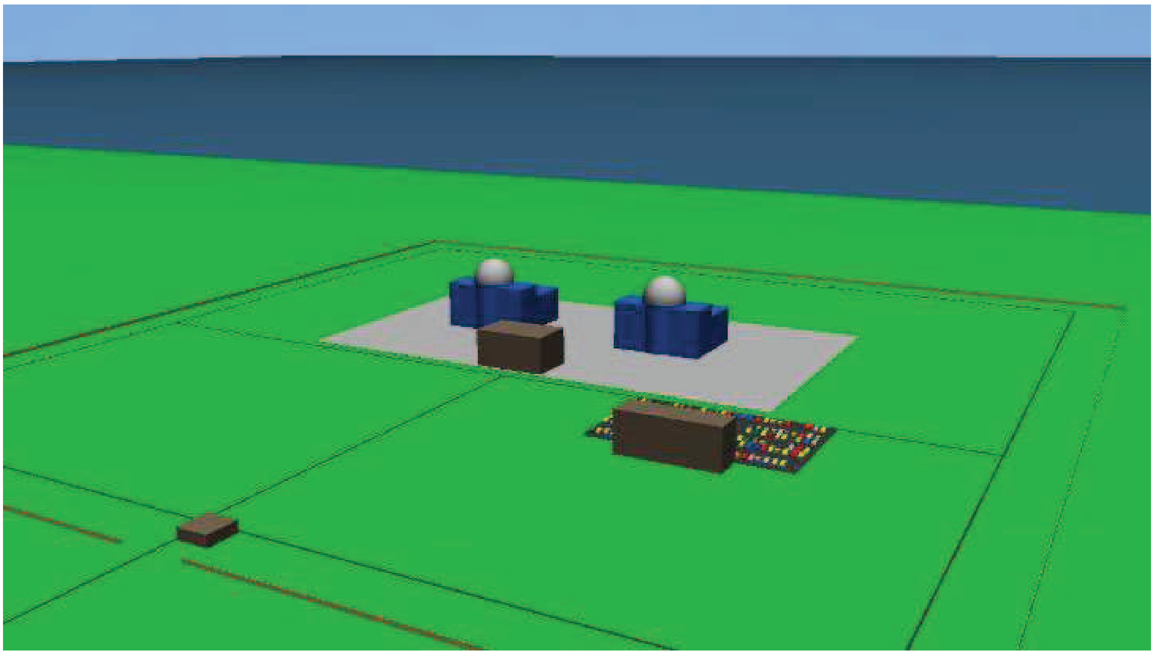
Page break

2.4p A 'typical' nuclear power plant has a single reactor that produces 1000 MW of electricity. An alternative would be to have a plant with several smaller reactors on the same site that provide the same amount of power in total. For example, instead of the single 1000 MW reactor, two 500 MW reactors or eight 125MW reactors could be used.

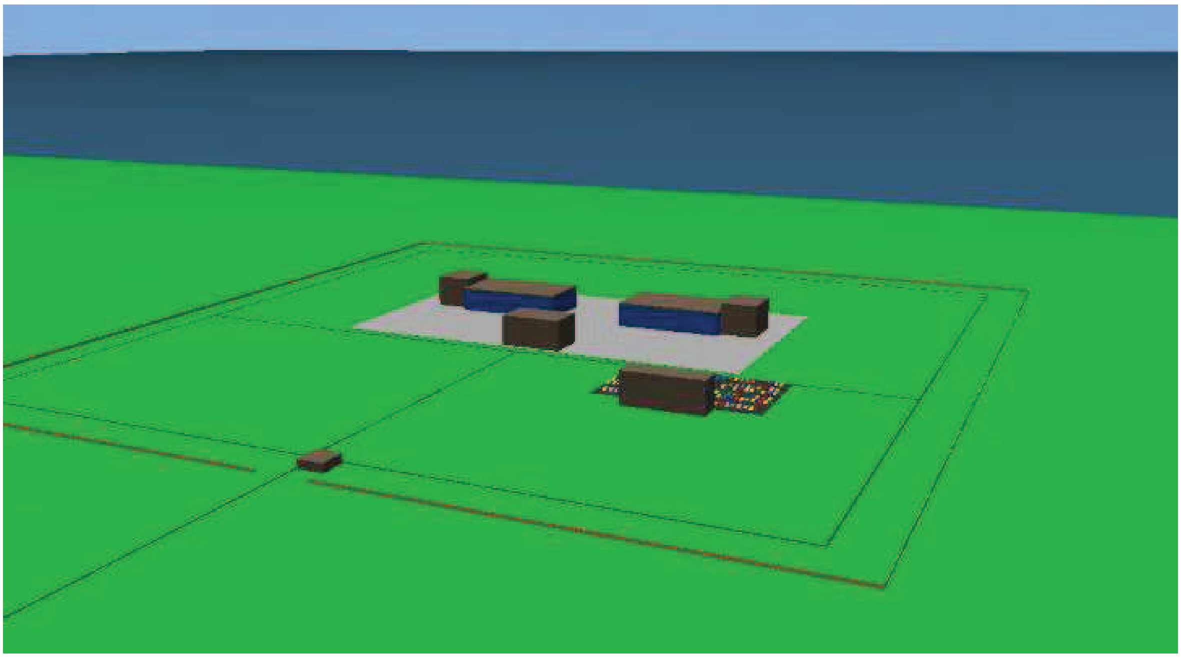
Q2.4i1 A 'typical' nuclear power plant



Q2.4i2 Two smaller nuclear power plants on the same site



Q84 Eight much smaller nuclear power reactors on the same site (four inside each blue plant building)



Q2.4 Given the same total energy output, how does the idea of having several smaller reactors on one site instead of one large reactor make you feel?

Much more safe (1)
Slightly more safe (2)
Neither more or less safe (3)
Slightly less safe (4)
Much less safe (5)
I don't know (0)

Page break

2.5 Globally, the most widely used type of commercial nuclear power reactor is the Pressurised Water Reactor (PWR) type. Because a range of PWR type nuclear reactors have been used around the world for over 40 years the nuclear industry has a lot of experience in building and operating them.

There are new, alternative designs of nuclear power reactor that are different to PWRs which might, in theory, be safer, or produce less waste but there is little or no experience of building or running these alternative types of nuclear power reactor on a global commercial scale.

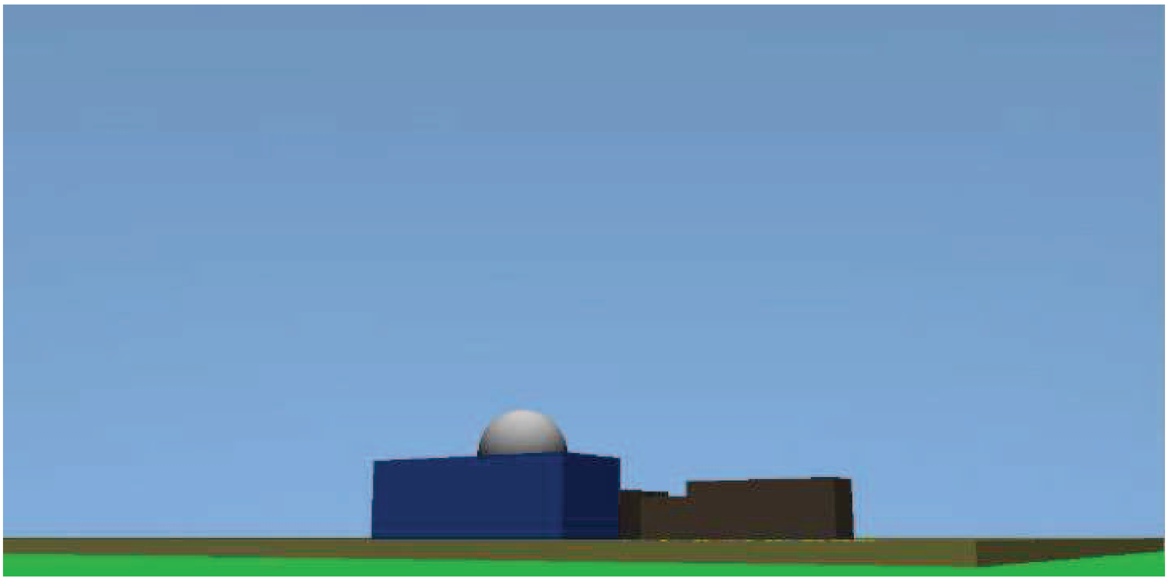
Q2.5 If a new nuclear power reactor were to be built, which of the following would best describe your opinion related to nuclear reactor design?

I would prefer to keep the existing nuclear reactor design (1)
I would prefer to keep the existing nuclear reactor design, but more information on the new designs might persuade me to change my views (2)
Nuclear reactor design does not make any difference to me (3)
I would prefer a new, alternative nuclear reactor design, but I would like to see a slow transition (4)
I would prefer changing to a new, alternative nuclear reactor design (5)
I don't know (0)

Page break

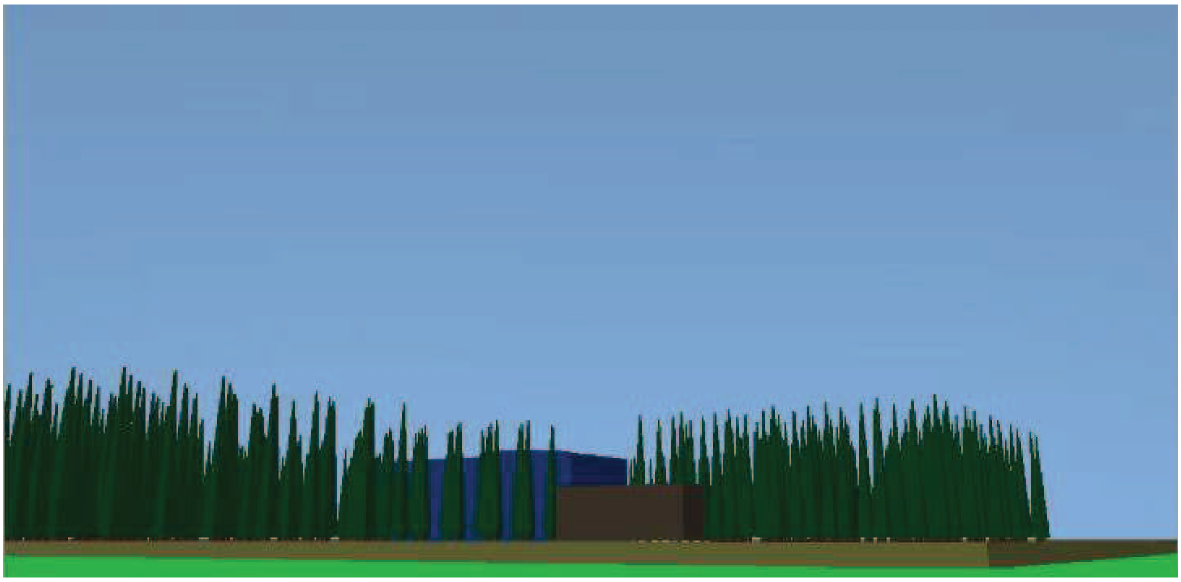
2.6 A 'typical' nuclear power plant has a hard outer dome that is intended to minimise the effect of external impacts (such as aircraft impacts). There are other potential methods for protecting nuclear power plants from external impacts. These include building large reinforced wind turbines around the plant or sinking the plant further into the ground and protecting it with trees.

Q2.6i1 A 'typical' nuclear power plant as seen from ground level with its impact dome



Q2.6i2 A 'typical' nuclear power plant now with the dome replaced by reinforced wind-farm defences

Q2.6i3 A 'typical' nuclear power plant now with tree defences



Q2.6 Which of the following would best describe your opinion about possible protection measures from external impacts?

I have a strong preference for the hard outer impact dome (1)
I have a slight preference for the hard outer impact dome (2)
I have no particular preference on this issue (3)
I have a slight preference for alternative solutions (4)
I have a strong preference for alternative solutions (5)
I don't know (0)

Page break

2.7 A 'typical' nuclear power plant uses an 'active' safety system that senses when an accident occurs and deliberately triggers a series of mechanical safety systems which attempt to prevent a release of radiation or a reactor ‘meltdown’. A new safety system has been proposed that is 'passive'. This means that the reactor and its buildings are designed so that in the case of an accident the laws of nature are used to assist in keeping the plant cool, in an effort to prevent meltdown and damage. In an ideal passive system, no active intervention by people or machines is required.

Q2.7 If both active and passive safety systems are accepted for use on nuclear plants by the independent nuclear safety regulator, which of the following options would you prefer?

A fully active system (1)
A mainly active system with some passive backup (2)
A blend of active and passive systems (3)
Mainly passive systems with some active backup (4)
Just passive systems (5)
I don't know (0)

Page break

2.8 A 'typical' nuclear power plant is controlled with ‘hard-wired’ electronic systems. These systems are not computerized and cannot ‘crash’. They can be disrupted by disasters such as power cuts, fire, flooding or earthquakes. New nuclear plants may start using ’high integrity’ digital computer controls. These are similar to the systems we have on our personal computers, but are designed to meet much higher standards so that they should not crash or lock-up (similar to modern electronic flight control systems seen in aircraft).

Q2.8 If new nuclear plants used 'high integrity' digital computer controls that were certified by the independent nuclear safety regulator, how would you feel?

Much more safe (1)
Slightly more safe (2)
Neither more or less safe (3)
Slightly less safe (4)
Much less safe (5)
I don't know (0)

Page break

2.9 A 'typical' nuclear power plant uses uranium as a nuclear fuel. Some of the used nuclear fuel can be recycled (also known as reprocessed) in a complex process which has advantages and disadvantages.

Q2.9 Do you believe that nuclear fuel should be recycled? (reprocessed)
Recycling nuclear fuel is definitely a good idea (1)
Recycling nuclear fuel might be a good idea but I need to know more (2)
I am indifferent to the idea of recycling nuclear fuel (3)

Recycling nuclear fuel might be a bad idea but I need to know more (4)
Recycling nuclear fuel is definitely a bad idea (5)
I don't know (0)

Page Break

2.10

Another source of material for nuclear fuel is from nuclear weapons. These weapons are no longer needed or wanted and the uranium or plutonium can be converted into nuclear fuel to be used in power stations.

Q2.10 Do you agree or disagree that nuclear weapons material should be used to produce electricity?

Strongly agree (1)
Slightly agree (2)
Neither agree or disagree (3)
Slightly disagree (4)
Strongly disagree (5)
I don't know (0)

Page break

Q2.11 It is proposed that nuclear waste be stored underground indefinitely.

I believe….
Storing nuclear waste underground indefinitely will work (1)
Storing nuclear waste underground indefinitely might work but I need more information (2)
I have no opinion on this matter (3)
Storing nuclear waste underground indefinitely might not work but I need more information (4)
Storing nuclear waste indefinitely in any way will never work (5)
I don't know (0)
Other (please describe) (0) ____________________

Page Break

2.12 Some of the options in the previous question on waste disposal would require the waste to be moved between sites. This can be achieved by rail, road or sea transportation (or a combination of these).

Q2.12 How do you feel about this?

I believe nuclear waste transportation is very safe (1)
I believe nuclear waste transportation is fairly safe (2)

I have no particular preference on this issue (3)
I believe nuclear waste transportation is fairly dangerous (4)
I believe nuclear waste transportation is very dangerous (5)
I don't know (0)

3.2. Data Tables

A selection of data tables used in the analysis of the questionnaire data can be found at the end of this thesis in APPENDIX A – Data Tables.

Full data tables are attached on compact disk (CD/DVD).

4. A Systems Design Framework for the Integration of Public Preferences into the Design of a Nuclear Power Plant

4.1. Introduction

The following paper is currently being prepared for submission to a peer reviewed academic journal. Leading candidates include Futures (Elsevier) and Technological Forecasting and Social Change (Elsevier).

The author of this thesis was the primary author of the paper, and the content of the paper reflects research carried out solely by the primary author under the supervision of the doctoral research supervisors. The paper was co-authored by Jonathan Wortley of Rolls-Royce and Prof. Adisa Azapagic of The University of Manchester. At the time of writing (during 2012) Wortley and Azapagic were the Industrial and Academic supervisors (respectively) for this doctoral research project. The co-authors contributed by providing comments on draft versions of the paper, guidance on language and writing style appropriate for a peer reviewed journal and contributed to discussions to generate ideas, concepts and topics for research. Table and figure numbers have been amended to fit into the structure of this document.

A Systems Design Framework for the Integration of Public Preferences into the Design of Nuclear Power Plants

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ABSTRACT

With the 'nuclear renaissance' on the horizon, attention is turning once again to the public's acceptance of nuclear power. Historically, several new nuclear build schemes have been delayed or halted entirely due to public opposition. Delays are unattractive to investors as they have the potential to increase significantly the cost of building new nuclear plants. This paper proposes a novel design framework which, as far as the authors are aware, allows for the first time the inclusion of the views of stakeholders such as the general public. Such a design framework has a potential to help make new nuclear plants more socially acceptable, reducing the risk of incurring additional costs due to opposition to construction. Existing engagement methods such as surveys and interviews are proposed as a means to elicit public design preferences. These preferences are then integrated into the system-level design of a nuclear plant via a modified Quality Function Deployment (QFD) process. These processes are described in detail in the paper and a case study is presented to demonstrate the framework in action. Further research is required to understand fully the public's design requirements and how these can be integrated into the design of plants in an economically viable way.

KEYWORDS

Nuclear Power; Participatory Design; Sustainability

1. INTRODUCTION

In recent years there has been renewed interest in constructing new nuclear power plants to meet the energy challenges of the 21st century. This interest has continued in many nations in spite of the Fukushima disaster of 2011 (Joskow and Parsons, 2012). There are many drivers and barriers to the construction of new nuclear power plants, as discussed by Greenhalgh and Azapagic (2009). In short, drivers include energy security, greenhouse gas emissions and an impending energy generation 'gap'. Barriers include factors such as economics, political will and the public's perception of the safety of nuclear technologies. The perceived risk posed by nuclear power is often a major factor in opposition to the construction of new nuclear power plants (Greenhalgh and Azapagic, 2009). Research carried out before and after the Fukushima accident shows that, in the UK, public support for the construction of new nuclear power plants is at its highest point for ten years (Ipsos MORI, 2010, 2011).

Significant research has been carried out to understand the public's perceptions of risk and to determine the underlying factors behind the perceived risk of nuclear power plants and nuclear material; for a review, see Goodfellow et al. (2011). Understanding of perceived risk was improved by the development of a number of theories including Psychometric Paradigm (Fischhoff et al., 1978), Cultural Theory (Douglas and Wildavsky, 1982) and the Social Amplification of Risk Framework (SARF) (Kasperson et al. 1988). Although understanding has improved, these theories are not yet able to describe all of the complex interactions that influence how the public perceive risks. Additionally, whilst much research has been carried out into understanding the public's perception of nuclear power as a whole, very little research has been carried out into understanding if specific aspects of nuclear plant design relate to public risk perceptions. Previous research by the authors suggests that existing attitudes held by the public towards nuclear power do not drive expressed preferences for particular design features (Goodfellow et al. 2013), but further research is required for a better understanding of this area.

Regardless of the reasons behind them, delays incurred in constructing nuclear power plants are very costly. Participatory approaches to design, whereby different stakeholders are asked to express their opinions on design options, have been used previously in other industries in an effort to reduce opposition to the construction of new facilities or a change in existing practices through the involvement of public stakeholders (Kensing and Blomberg, 1998). Research has shown that the main benefits of participatory design processes lie not just in the fact that they lead to socially informed designs but also that stakeholders (who could otherwise block or delay the development) feel that their views and perspectives are valued by the designer (Schuler and Namioka, 1993). Providing a means for genuine two-way dialogue between designer and stakeholders, including the public, can help in developing mutual respect and trust. Trust in nuclear power plants being designed and operated safely is a key driver behind the public perception of risk associated with nuclear energy (Slovic, 1993). At the same time, the cost of implementing participatory design processes and the resulting cost implications of the changed design must be weighed against the cost saving provided by reducing opposition to the construction of the new plants. Determining this cost balance is difficult, due to the complexity and the length of the design, licensing and build processes for nuclear plants and the lack of transparency in the financing of such industrial design and construction programmes (Nuttall & Taylor, 2009).

In this paper the authors set out a new framework for the design of nuclear power plants which facilitates the integration of the public's design preferences. This research builds upon previous work undertaken by the authors, whereby a nationally representative sample of the UK population expressed a preferences for different aspects of nuclear design (Goodfellow et al., 2013). It is hoped that by integrating public preferences, alongside the design requirements of energy companies and regulators, the resulting designs of nuclear plant will become more acceptable to the public. It is worth noting that a survey is just one of a variety of ways that can be used to engage with the public. Other approaches, such as focus group discussions, local liaison meetings and interviews, can also be used for further elicitation of public design preferences (Powell and Colin, 2008).

The proposed participatory design framework is described in Section 2. This is followed by a case study in Section 3 intended to illustrate how the framework can be applied. The case study presents an example conceptual design of a nuclear power plant generated using the framework and informed by the above-mentioned survey (Goodfellow et al., 2013). This design concept is compared to the two existing designs which have entered into the Generic Design Assessment (GDA) process in the UK, Westinghouse's AP1000 (WEC, 2008) and Areva's EPR (AREVA, 2005) which is now approved. The relative strengths and weaknesses of the approach in the proposed framework are discussed in Section 4 and conclusions are drawn in Section 5.

2. DESIGN FRAMEWORK

Nuclear design is evolutionary; the latest, so-called generation III+, designs are largely incremental improvements on generation III designs of a given type, which were improvements on generation II and so on. The design of nuclear plants is constrained by a strong technological lock-in effect (Cowan, 1990; Stamford and Azapagic, 2011) which has limited the diversity of technologies available for commercial deployment. These constraints have their roots in the origins of civil nuclear programmes, which largely grew out of early military efforts to produce material for nuclear weapons and/or to create nuclear propulsion systems for defence applications. These early military origins have also influenced how nuclear power is perceived by the public and have contributed towards its stigmatisation (Gregory et al., 1995).

In the last 30 years, the design of commercial nuclear plants in most countries has shifted away from being carried out by governmental institutions and is now predominantly carried out by the private sector (though national governments are often significant shareholders). As with most 'products', requirements provided by a 'customer' are the driving force behind the design. In the case of nuclear power plants, the customer is often an energy utility company (or a national government in countries where energy generation remains nationalised), although other stakeholders may be involved. The requirements of the customer are constrained by a wide array of different safety, radiological and environmental regulations. Constraints due to cost and the external ‘political environment’ also have a significant impact on design decisions. However, whilst it is possible that designers will try to take some account of concerns raised by the public, the authors have not found any published research or design processes for nuclear plants that explicitly involve the public in the early design stage of the development of a nuclear plant.

Currently, in the UK, the public is invited to comment on nuclear plant designs presented to the regulator, The Office for Nuclear Regulation (Podger, 2011) during the design approval process known as the ‘Generic Design Assessment’ (GDA) (HSE, 2009). However, there are three drawbacks to the current system:

1. it is unlikely that the majority of the public would have the time and/or technical knowledge to be able to read and understand the designs as they are presented in full and are therefore very large documents written in highly technical language; and
2. the public are able to comment on the design only once it is (largely) finalised. This increases the likelihood that the cost of changing a design would be high which in turn, has the potential to leave the public feeling disenfranchised. The implication being that regardless of how important the public feels the issues they have raised are, the designer will only implement changes if forced to by the regulator because of the high cost of doing so; and
3. the regulator has a focus on safety issues, therefore other non-safety issues may have a lower priority.

A logical solution to the above two issues would be to involve the public at the earliest possible design stage thus maximising their impact and minimising the cost of change. This would allow the potential for non-safety critical changes to be implemented in a cost effective manner. However, this still leaves the difficulty of the lay-public being able to understand the technical details of nuclear plant design for them to influence it. Previous work by the authors investigated the possibility of asking the public simplified questions relating to nuclear design (Goodfellow et al. 2013). The results suggest that the public could be engaged on technical design issues and provide meaningful responses.

The following sections detail how public preferences could be integrated into the design of nuclear power plants alongside the existing technical design requirements of the ‘customer’, i.e. the energy utility company.

2.1 The Participatory Design Framework

A participatory design framework which would enable incorporation of stakeholder preferences, including those of the public, must satisfy a number of criteria. It should:

i. allow different system design requirements for all stakeholders to be considered, resulting in an output in the form of technical system-level specifications of a nuclear plant;
ii. cope with varied requirements, some of which would be technical and quantitative and some of which could be qualitative and ambiguous;
iii. provide simple traceability of the integration of the requirements of different stakeholders, so that it could be demonstrated to all stakeholders that their input was being taken into serious consideration; and
iv. allow for the weighting of different requirements as some, such as safety requirements, are simply more important than others and this would need to be reflected within the framework.

There are many decision-support methods that can be used in system design, including General Morphological Analysis (GMA), Analytical Hierarchy processes, decision (Pugh) matrices and Quality Function Deployment (QFD) (Blanchard & Fabrycky 1998, Dieter 2000). QFD closely matched much of the above criteria and was therefore selected for use in the proposed framework. A full description of the ‘typical’ QFD method is not included in this work but can be found in Chan & Wu (2002). In short, QFD uses matrices to help designers incorporate customer preferences into product design. Figure 3 shows a standard QFD layout for reference; the following passages describe how the QFD method was modified and used as part of the participatory design framework.

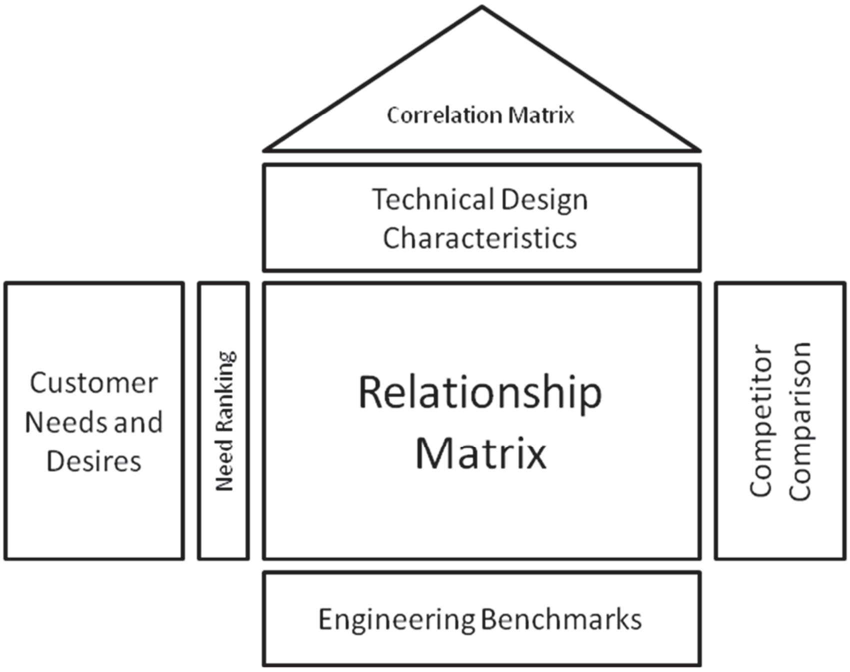


Figure 3. A standard Quality Function Deployment (QFD) sheet layout.

QFD was designed, and intended to be used, to interpret end-user customer requirements. By taking a standard QFD sheet and modifying the weighting system applied to requirements, so that requirements are weighted both on their technical importance and on their importance to different stakeholders, the QFD process was able to fulfil the criteria i)-iv) above. This modified QFD is part of a larger framework, as shown in Figure 4.

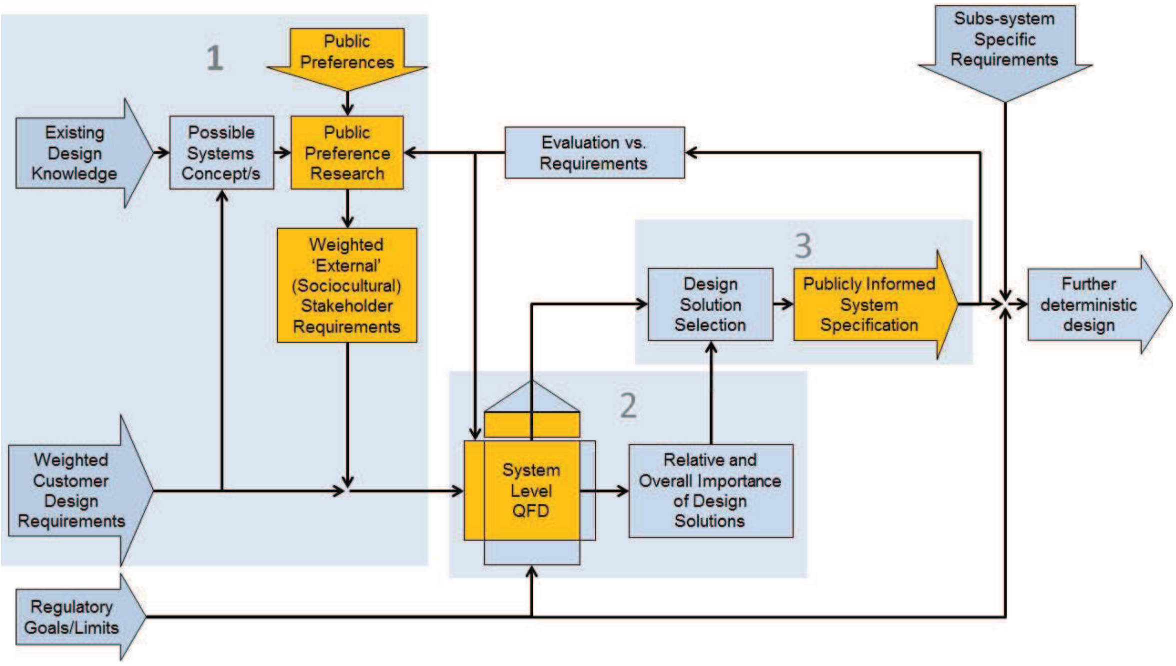


Figure 4. The proposed participatory design framework including the public's preference of design options within the system-level design process (highlighted). The three key steps of the process are numbered.

2.2 Framework Steps

The main steps in the framework shown in Figure 4 are:

1. Determination of the requirements of all stakeholders, including the lay-public.
2. Completing the system-level QFD sheet. This comprises multiple steps in keeping with traditional QFD methods.
3. Using the output from the QFD to define the system level specifications of the design.

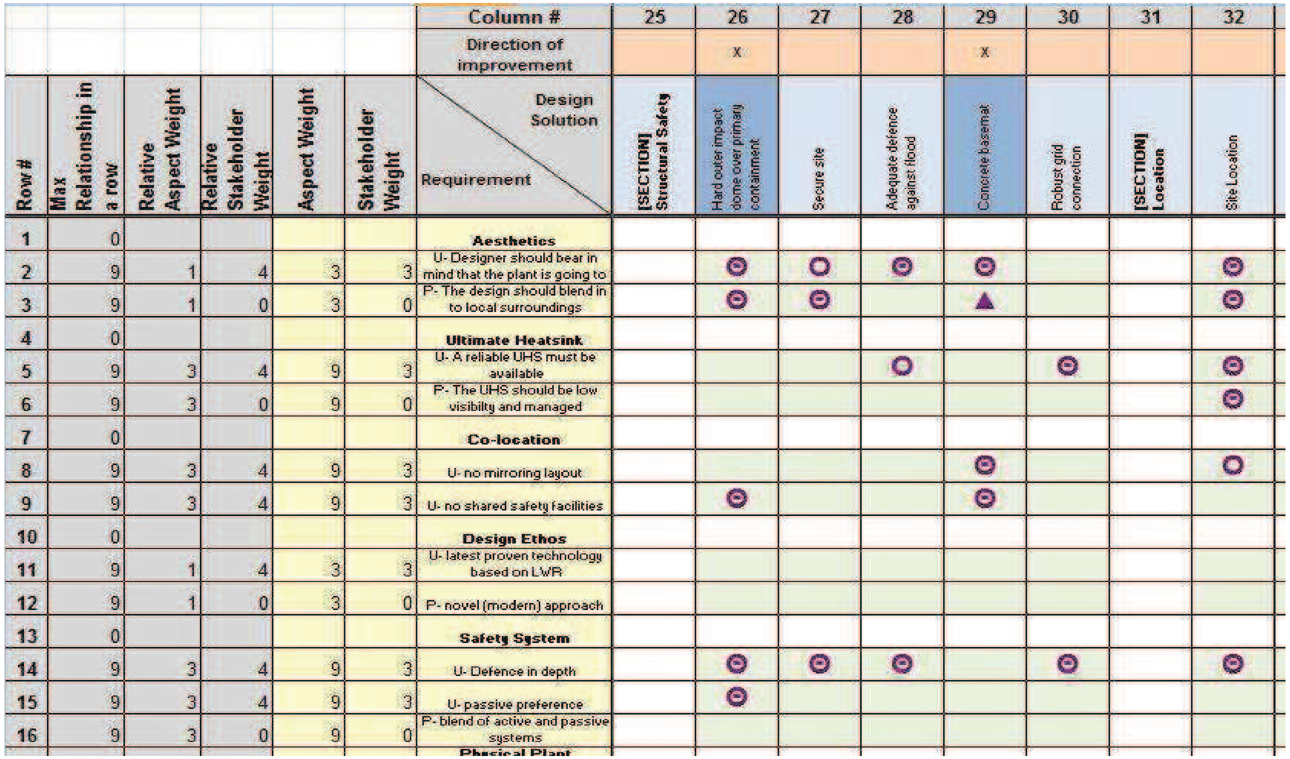
These steps are now discussed in further detail, with reference made to Figure 4 throughout. The 'designer' referred to is assumed to be a team of engineering professionals with appropriate skills and experience to carry out such a task.

2.2.1 Step 1 - Stakeholder Requirements and Public Preferences

The first step (as with many design processes) is to understand the requirements of the 'customer'. In this case, this would be the energy utility company who would have a set of requirements for what they need from a power plant. The proposed framework also calls for a set (or sets) of additional stakeholder requirements, such as the requirements of the public. In order to do determine these additional stakeholder requirements, the customer's requirements are combined with existing design knowledge to create a series of possible system concepts for aspects of the design of the plant, such as the ultimate heat sink, safety system or reactor type. These system concept options are then put to the stakeholders and their preferences elicited. As mentioned previously, this can be achieved in a number of ways such as questionnaires, interviews, focus groups or liaison meetings. The designer can then use the input provided by the stakeholders as a set of 'external' stakeholder requirements, which can be integrated alongside the customer requirements in the QFD sheet. It is up to the designer and the customer to decide who, within the public at large, is asked for their preferences. In some cases local views may be more important than a nationally representative view and, as with many endeavours, the cost of acquiring the 'external' stakeholder input must be balanced with the scope of input required.

2.2.2 Step 2 - System Level QFD - Requirement Weighting

Once all the requirements have been collected they can be input to the QFD sheet. A section of an example QFD sheet, modified from the 'standard' format for the purposes of this research, is shown in Figure 5. The full QFD sheet is shown in Appendix C. However, it is recommended that the reader review the full QFD sheet in its electronic format by accessing it in the supporting material on the attached CD/DVD.



Row #	Max Relationship in a row	Relative Aspect Weight	Relative Stakeholder Weight	Aspect Weight	Stakeholder Weight	Column #	25	26	27	28	29	30	31	32
						Direction of improvement		x			x			
						Design Solution / Requirement	**[SECTION] Structural Safety**	Hard outer impact dome over primary containment	Secure site	Adequate defence against flood	Concrete basemat	Robust grid connection	**[SECTION] Location**	Site Location
1	0					**Aesthetics**								
2	9	1	4	3	3	U- Designer should bear in mind that the plant is going to		⊙	○	⊙	⊙			⊙
3	9	1	0	3	0	P- The design should blend in to local surroundings		⊙	⊙		▲			⊙
4	0					**Ultimate Heatsink**								
5	9	3	4	9	3	U- A reliable UHS must be available				○		⊙		⊙
6	9	3	0	9	0	P- The UHS should be low visibilty and managed								⊙
7	0					**Co-location**								
8	9	3	4	9	3	U- no mirroring layout					⊙			○
9	9	3	4	9	3	U- no shared safety facilities		⊙			⊙			
10	0					**Design Ethos**								
11	9	1	4	3	3	U- latest proven technology based on LWR								
12	9	1	0	3	0	P- novel (modern) approach								
13	0					**Safety System**								
14	9	3	4	9	3	U- Defence in depth		⊙	⊙	⊙		⊙		⊙
15	9	3	4	9	3	U- passive preference		⊙						
16	9	3	0	9	0	P- blend of active and passive systems								

Figure 5. An example of the QFD sheet. Requirements are being translated into design solutions (dark shaded boxes under the category ‘Design Solutions’) and ‘sub-systems’ (light shaded boxes in the same category). ‘Sub-systems’ in this context are defined loosely as areas which require further design development and definition, which occurs later in the framework. The symbols in the relationship matrix on the right hand side define the strength of relationship between requirement and design solution on a scale 1,3 and 9 with 1 denoting weak and 9 very strong relationship; triangle = 1, empty circle = 3, circle with a dot in the middle = 9. No symbol means no relationship exists. U= customer requirement from utility company, P = requirement by the public.

Requirements in the QFD sheet are labelled depending on the stakeholders involved as follows:

- U - customer requirement from utility company;
- P - requirement by the public;
- G - governmental requirement; and
- C - combined requirement, i.e. all stakeholders share the same requirement.

For ease of use, the requirements have also been separated into categories covering general aspects of design such as aesthetics, ultimate heat sink and safety system (see Figure 5 for examples). Each requirement is given two weightings (rather than one as in the 'standard' QFD process) which are determined by the designer and the customer:

- Stakeholder Weight (S_s) defines the weight given to one stakeholder's requirements compared to another within each aspect of design; and
- Aspect Weight (A_a) defines the weight given to that particular aspect compared to other aspects of design.

The 0, 1, 3, 9 scale is used in keeping with typical QFD methods with 9 representing the highest weighting. The scale chosen for Stakeholder Weight (S_s) should be the same as that used for Aspect Weight (A_a) or comparisons of how stakeholders affect the importance of design solutions (described later) will be distorted. The values for S_s and A_a are normalised over all requirements (R) in their respective 'relative weight' columns (see Figure 5). Equation 1 and Equation 2 show how the Relative Stakeholder Weight (W_s) and the Relative Aspect Weight (W_a) are generated.

(1) $$W_s = \frac{S_s}{\sum_{r=1}^{R} S_s}$$

(2) $$W_a = \frac{A_a}{\sum_{r=1}^{R} A_a}$$

It can be noted that W_a is independent of any stakeholder input. This places the burden of responsibility for defining the importance of the aspects of design onto the technical expert and in particular onto the designer. The weighting system is set up this way because in all likelihood only technical experts will have the specialist knowledge required to define the importance of design aspects, i.e. how important safety is in comparison to plant aesthetics. W_a and W_s will be combined later to provide an indication of the importance of design solutions once the views of lay-stakeholders are taken into account.

A ‘zero’ weight is only given to those requirements that will not be taken into account. Usually, this is used when making comparisons between including and excluding a certain stakeholder’s views. Comparison can be achieved by duplication of the QFD worksheet so that one sheet includes the views of all stakeholders and the other sheet ignores the views of one of the stakeholder groups. A direct comparison of the ‘before and after’ to see the effect of ignoring a given stakeholder can then be made through analysis of the sheet output; this is described in Section 2.2.4. In the example used in this paper, the public, and their views, were ignored in the baseline sheet and then incorporated in the comparison sheet to facilitate an understanding of the potential impact that the public might have on the design.

Once all the requirements have been weighted, the designer can then begin to determine design solutions for each requirement. These are entered along the top of the QFD matrix. Some solutions will be complex and will require further definition as sub-systems whilst others can be defined completely at this, system-level, design stage. Some of the design solutions emerging at this stage will constrain sub-system design and can be considered to be both design solutions and emergent requirements that need to be incorporated in the definition of various sub-systems. Once the design solutions row is fully populated in the QFD matrix, the designer may wish to re-arrange them into logical groupings (see Figure 5 for an example).

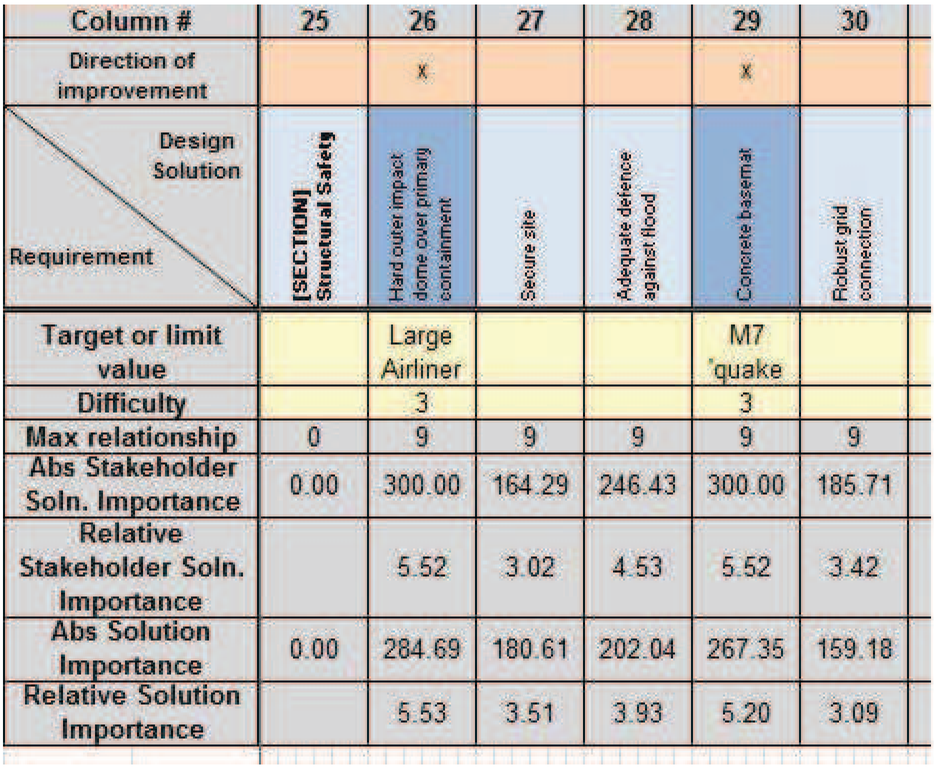
2.2.3 Step 2 - System Level QFD – The Correlation Matrix

The next step is to complete the correlation matrix. This defines the strength of the relationship between the requirements and the design solutions. This is an important stage, as some requirements will affect design solutions in ways that may not have previously been considered and these emergent relationships can have a significant effect on the resulting design specification. Symbols are used, in keeping with typical QFD methods, to denote the strength of the relationships. In this work, relationship strength is also assigned using a 1, 3, 9 scale and is represented by triangles, empty circles and circles with a dot in the middle, respectively, in keeping with traditional QFD methods. The designer is responsible for defining the strength of the relationship between requirements and solutions. This can be achieved using expertise and 'know-how' or by applying metrics to the requirements and solutions and carrying out numerical comparisons.

At the bottom of the QFD sheet the designer can also input targets or limits for design solutions (as shown in Figure 6 for aircraft impact protection and earthquake resistance). These can be driven by the designer themselves, or by external factors such as regulations, legislation or economic issues. Each target or limit can be assigned a value related to 'level of difficulty' to help define the difficulty in achieving the overall design. A scale from 1-3 can be used, where 1 represents the lowest and 3 the greatest level of difficulty. It is important to note that the majority of regulations will most likely affect the sub-system and component levels of design rather than the system level; however, this does not preclude some overall safety goals that may be interpreted and incorporated at the system level.

2.2.4 Step 2 - System Level QFD – Design Solution Importance

In the next step, the relative importance of the design solutions can be calculated, as explained in further detail below, using the relative weighting of the requirements referenced to the correlation matrix. This is indicated at the bottom of the QFD sheet, as shown in the lower half of Figure 6. The higher the value of solution importance, the more that design solution relates to multiple requirements and/or requirements with high weighting. This can be a powerful tool for assisting the designer and customer in understanding which parts of the system level design are most important.



Column #	25	26	27	28	29	30
Direction of improvement		x			x	
Design Solution / Requirement	**[SECTION] Structural Safety**	Hard outer impact dome over primary containment	Secure site	Adequate defence against flood	Concrete basemat	Robust grid connection
Target or limit value		Large Airliner			M7 'quake	
Difficulty		3			3	
Max relationship	0	9	9	9	9	9
Abs Stakeholder Soln. Importance	0.00	300.00	164.29	246.43	300.00	185.71
Relative Stakeholder Soln. Importance		5.52	3.02	4.53	5.52	3.42
Abs Solution Importance	0.00	284.69	180.61	202.04	267.35	159.18
Relative Solution Importance		5.53	3.51	3.93	5.20	3.09

Figure 6. Relative design solution importance calculated in the QFD sheet.

For a given design solution, Absolute Stakeholder Solution Importance (α_S) is calculated by the summation of the product of the Relative Stakeholder Weighting (W_s) and strength of relationship value (V_ρ) relating to the requirements associated with that design solution (ρ), as shown in Equation 3:

$$(3) \qquad \alpha_S = \sum_{n=1}^{\rho} W_s \bullet V_\rho$$

The Absolute Stakeholder Solution Importance is then normalised resulting in the Relative Stakeholder Solution Importance (I_S). This is shown in Equation 4 where N denotes all design solutions present in the QFD sheet:

(4) $$I_S = \frac{\alpha_s}{\sum_{n=1}^{N} \alpha_s}$$

The same process can be applied similarly to the Relative Aspect Weighting resulting in the Relative Solution Importance (I_A) as follows:

(5) $$\alpha_a = \sum_{n=1}^{\rho} W_a \bullet V_\rho$$

(6) $$I_a = \frac{\alpha_a}{\sum_{n=1}^{N} \alpha_a}$$

This then allows the designer to compare the relative difference in importance assigned to design solutions before and after a given stakeholder group's view is taken into account (i.e. that of the public). Figure 7 shows the percentage difference ($D_{\%}$) in Relative Stakeholder Solution Importance (I_S) before and after including the public's views, as calculated using Equation 7:

(7) $$D_{\%} = \frac{\left(I_S(after) - I_S(before)\right)}{I_S(before)} \times 100$$

For example, in Figure 7 it can be seen that 'Internal layout allows ease of access to maximise online maintenance' has reduced in calculated importance by around 20% whilst 'Secure Site' and 'Aesthetic Design' have increased by around 17% each. The whole graph is normalised, and zero-sum. Therefore any increases in the calculated importance of some solutions must be counterbalanced by decreases in the calculated importance of other solutions.

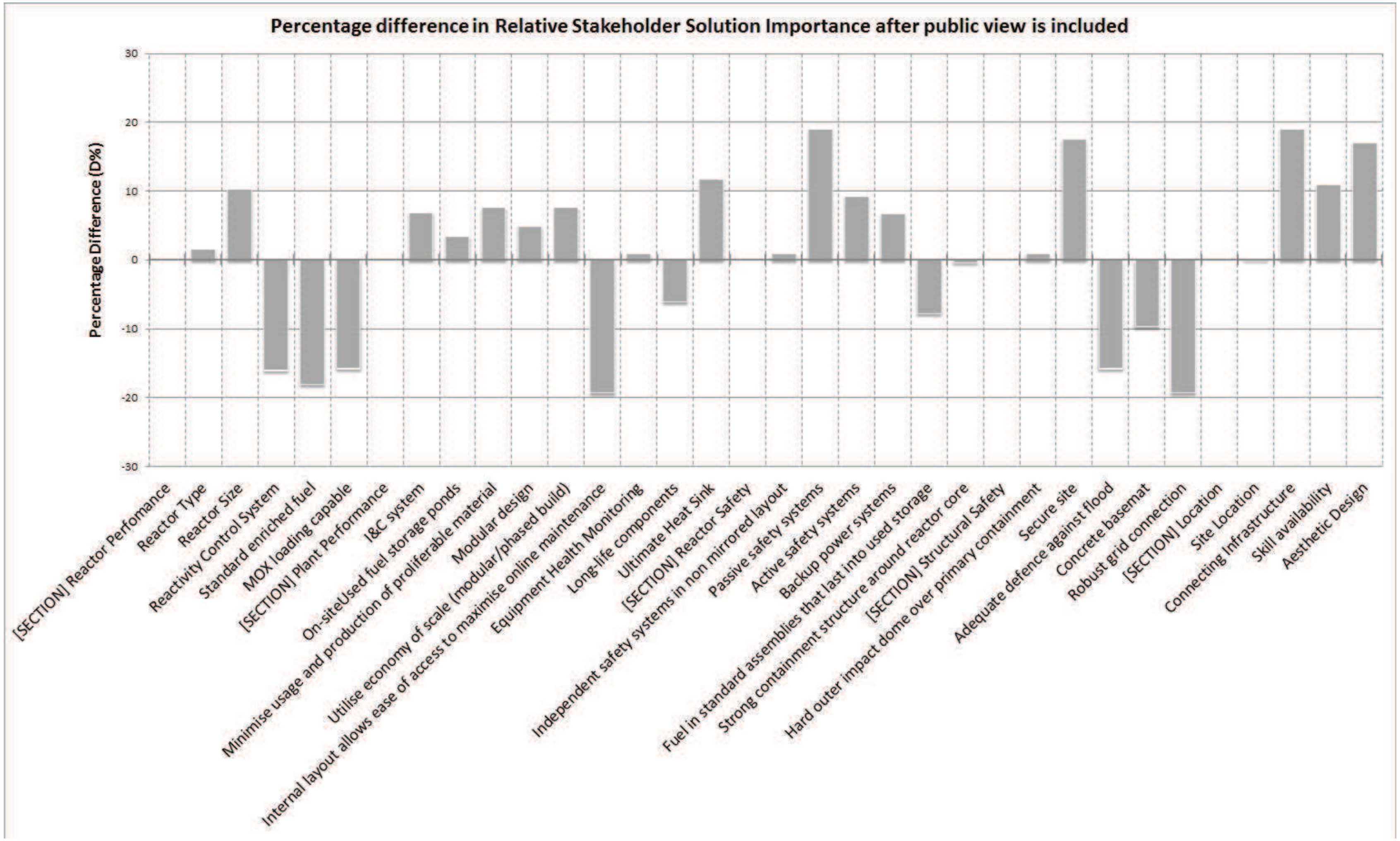


Figure 7. An example graph showing the percentage difference in Relative Stakeholder Solution Importance before and after including public views. Positive percentages equate to increased importance, negative percentages to decreased importance.

The Relative Solution Importance (I_A) will stay the same regardless of the weightings assigned to stakeholders, as it is independent of the Stakeholder Weighting (S_s) and Relative Stakeholder Weighting (W_s). However, by applying the difference between I_s (before) and I_s (after) to I_A, the change in the absolute importance of design solutions (as influenced by stakeholders) can be determined. This is achieved using Equation 8:

(8) $$I_A(after) = I_A(before) \times \left(\frac{I_S(after)}{I_S(before)} \right)$$

Figure 8 illustrates what happens when the relative differences in I_s are applied to the Relative Solution Importance (I_A) in this way. The white bars in Figure 8 are the Relative Solution Importance (I_A) before the public view is taken into account and the dark bars are calculated using Equation 8 and represent the Relative Solution Importance (I_A) after the public view is taken into account. The shift between the bars shown in Figure 8 relates directly to the percentage shifts shown in Figure 7. However, further clarity of the overall importance of various solutions is also included in the size of the bars in Figure 8. Looking at the same examples we can see that whilst ‘Internal layout allows ease of access to maximise online maintenance’ suffered a 20% drop in calculated importance, it is a relatively unimportant system level characteristic. Similar could be said of ‘Aesthetic design’, which experiences a rise but remains relatively unimportant. The increase in calculated importance experienced by ‘Site security’ pushes it higher than other solutions which it had previously been below, changing slightly the emphasis that a designer might give to the final system level design.

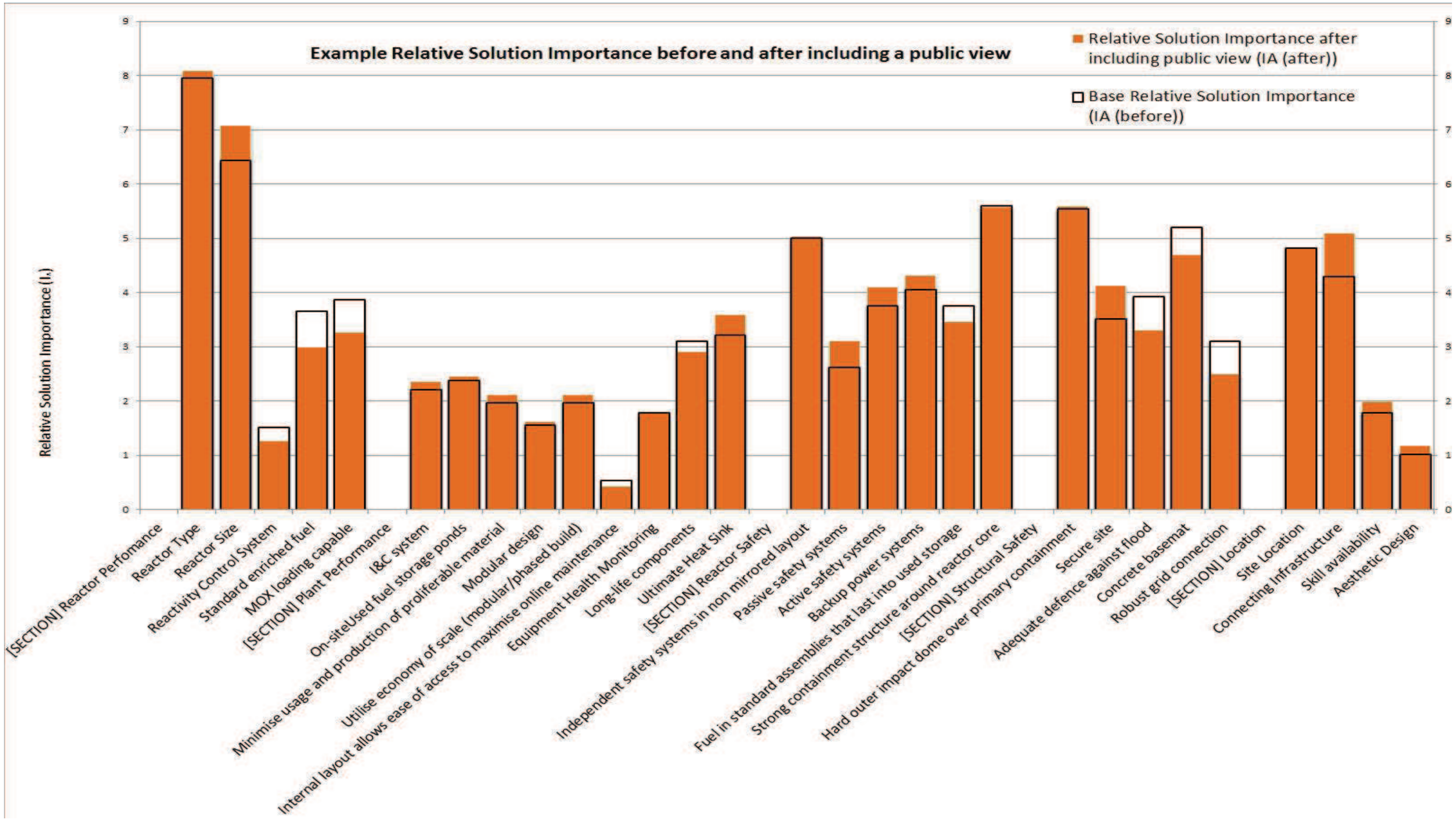
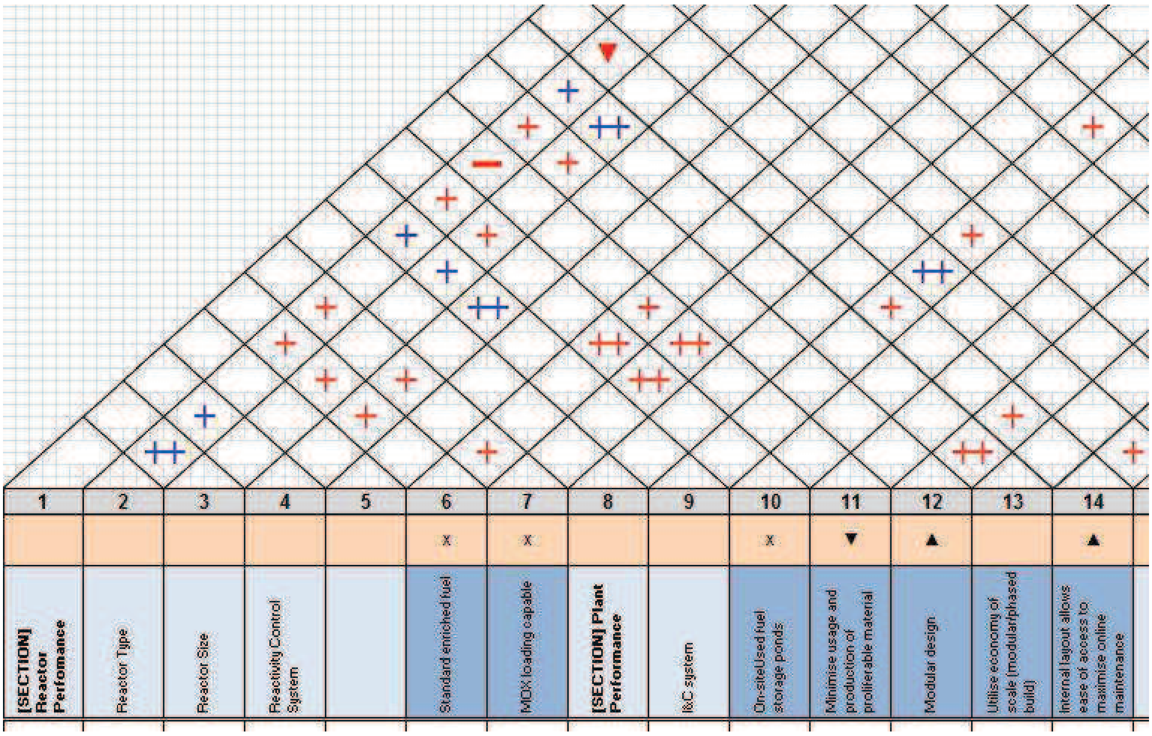


Figure 8. An example graph showing the Relative Solution Importance before (light bar) and after (dark bar) taking account of the views of the public. The scale is a relative importance scale, higher numbers are more important.

The graphs in Figure 7 and Figure 8 allow the designer to understand which parts of the system level design are influenced more (or less) by different stakeholder groups. However, it should be noted that, as with any analysis and modelling activity, the quality and usefulness of this ‘output’ information is entirely dependent on the quality of the ‘input’ information in the process.

2.2.5 Step 2 - System Level QFD – Design Solution Interactions

The final stage of the QFD process is to complete the top matrix, or ‘roof’ of the QFD sheet in order to define interactions between design solutions. This is shown in Figure 9. This stage remains unmodified from the approach taken in ‘typical’ QFD processes: Interactions between design solutions are shown on a scale from -2 (triangle), -1 (dash), +1 (single plus) and +2 (double plus), no entry in the matrix denotes no relationship. A negative relationship means that the design solutions will interact in a detrimental way; positive relationships mean that the design solutions are mutually supporting and compatible. Often, these relationships can be hard to determine at the system level because solutions are not yet fully defined. In such cases the designer can use the relationships identified in the ‘roof’ to ‘flag-up’ potential future conflicts so that they are not missed further on in the design process. The row above the design solutions shows if the target (provided at the bottom of the QFD sheet and described previously, see Figure 6) needs to be met (x), maximised (upward triangle) or minimised (downward triangle).



1	2	3	4	5	6	7	8	9	10	11	12	13	14
					x	x			x	▼	▲		▲
[SECTION] Reactor Perfomance	Reactor Type	Reactor Size	Reactivity Control System		Standard enriched fuel	MOX loading capable	**[SECTION] Plant Performance**	I&C system	On-siteUsed fuel storage ponds	Minimise usage and production of proliferable material	Modular design	Utilise economy of scale (modular/phased build)	Internal layout allows ease of access to maximise online maintenance

Figure 9. The top of the QFD sheet, or 'roof'. Requirement needs to be met (x), maximised (upward triangle), minimised (downward triangle).

It is important to recognise interactions between the design solutions and sub-systems as they can strongly influence the range of design options available. This is particularly the case for interacting sub-systems as it is important to ensure that they are mutually compatible. Some sub-systems are inter-dependent and in such cases the design of sub-systems must be prioritised to ensure the safety and performance of the overall system meet the related requirements. For example, Figure 9 shows a high compatibility relationship between the Reactivity Control System and the Instrumentation and Control (I&C) System (required to ensure the reactor can be operated safely). Care taken at this stage of the design process can save a great deal of time and effort later if issues and conflicts are discovered and rectified early.

2.2.6 Step 3 - Design Solution Selection

In order to provide specific and clear definitions for the functionality of the sub-systems identified in the QFD sheet, a number of additional decision-support tools can be applied. As mentioned previously, these include decision (Pugh) matrices which are particularly useful in situations where existing design solutions can be used to fulfil the requirements provided by stakeholders. This is likely to be the case for many nuclear plant sub-systems due to the historical and evolutionary nature of nuclear design, e.g. the safety system for a new plant is likely to be based on existing, proven technology that is deployed on current plants. Incremental improvements to these systems can then be made.

The output from this process is a set of system-level design specifications, which, when complete, can be re-evaluated against the original requirements and compared with designs proposed by competitors (if available, otherwise based on the designer's best estimates of competitor's performance). Further design iterations, including more public consultation if required, can then be carried out and the framework process repeated until the system concept design specifications fulfil the requirements. Once this has been achieved, further 'standard' design can be applied, resulting in a completed design ready for regulatory approval, sale to customers and ultimately, construction. This further 'standard' design phase reflects the reality that whilst lay-stakeholders may be able to engage with system level design concepts, such engagement will become increasingly difficult as the design becomes more detailed and dependent on prior technical knowledge. Although the framework demands the participation of lay-stakeholders at an early stage to inform the overall design, responsibility for designing the plant in full remains with the technical experts who are suitably qualified and experienced to do so. This has the potential to reduce lay-stakeholder confidence in the process, but is necessary to ensure the integrity of the detailed plant design.

The following section illustrates the application of the design framework on a nuclear reactor design case study.

3. CASE STUDY – DESIGN INFORMED BY THE PUBLIC

This section illustrates how the proposed participatory design framework can be applied. It is important to note that the design example in this case study is largely simplified and should only be considered as a 'demonstration of concept' in relation to the proposed design framework. Similarly, the views of the public are also an example based on the work by the authors (Goodfellow et al., 2013) and not a definitive representation of what the UK public want from the design of a nuclear plant.

3.1 *Using the Framework*

The following sets of requirements were combined and considered within the design framework:

- the European Utility Requirements (EUR) (EUR, 2011) which are a consolidated set of requirements generated by a consortium of European energy utility companies;
- a set of requirements representing ‘the public’ obtained from (Goodfellow et al. 2013); and
- a set of governmental requirements born from White Papers (BERR, 2008; DECC, 2012) and overarching international policy on nuclear material proliferation (IAEA, 2011).

As the data from Goodfellow et al. (2013) was used to generate ‘public’ requirements, no further engagement work was carried out during the course of this case study. Therefore the following description of how the case study plant was created involves steps 2 and 3 as defined in Figure 4. Table 12 lists the design requirements used in this case study. A more in depth table of requirements is included in Appendix B and on the attached CD/DVD.

Table 12. System design requirements used for the case study.

[U – utility requirements; P – public requirements; G – governmental requirements]

	Utility (EUR)	Public	Governmental
Co-location	U- No mirroring layout U- No shared safety facilities		
Design Ethos	U-Latest proven technology based on light water reactor	P- Novel (modern) approach	
Safety System	U- Defence in depth U- Passive preference	P- Blend of active and passive systems	

Physical Plant Characteristics	U- Single turbine output		
Site Selection	U- The plant should cope with site in a wide range of locations / conditions	P- The plant should be located away from people	G- The plant should be on an existing site
Aircraft Impact	C- The plant should have visible strong hard outer impact dome	C- The plant should have visible strong hard outer impact dome	
Instrumentation and Control (I&C)	C- A modern digital I&C approach should be taken	C- A modern digital I&C approach should be taken	
Weapons Reprocessing	C- The ability to use mixed oxide fuel (MOX) should be included	C- The ability to use mixed oxide fuel (MOX) should be included	
Waste Storage	U- Minimum of 10 years storage capacity available	P- Waste stored on site pending ultimate disposal	
Nuclear Transport	C- Movement minimised	C- Movement minimised	
Waste Form	U- Standardised		
Containment	U- Minimal release in extreme event		
Social Impact			G- Brings jobs
Proliferation Resistance			G- Minimise proliferation
Capital Cost	U- £1300 per kW		G- Non-subsidised
Natural Hazard Protection	U- Resistant to design basis accident		
Grid Connection	U- Able to cope with loss of offsite power		
Power Performance	U- 600MWe-1800MWe U- Load following capable	P- Multiple small reactors preferred	
Fuel Efficiency	U- 12-24 month cycle		
Availability	U- 90% or greater		
Design Life	U- 40 (60) year lifetime		

For the Aspect Weighting (A_a) required for the input to the QFD in step two of the framework (see 2.2.2 and Figure 4) the EUR terminology of 'shall, should, may' was used to define the weighting of 9, 3, and 1 respectively. 'Shall' refers to requirements that are non-negotiable, 'should' to requirements where equivalent alternatives may be considered and 'may' to requirements that are desirable but not essential (EUR, 2011). Two QFD sheets were then completed, one where the energy utility and government were given a Stakeholder Weighting of 3 and the public was given a Stakeholder Weighting of 0 (i.e. the public view was not taken into account) and a second where all stakeholders were given a Stakeholder Weighting of 3 (i.e. all stakeholders were treated equally). The 'middle' value on the 1, 3, 9 scale was chosen to allow future flexibility in comparing stakeholders by giving them stronger and weaker weightings (not presented in this paper). Completion of the QFD correlation matrix (see 2.2.3 and Figure 4) resulted in a set of design solutions as shown in Table 13. For this case study the author's completed the correlation matrix; in practice it is likely (and recommended) that a larger team of professional engineers complete the matrices to ensure that a pluralism of views are taken into account. The highlighted rows in the table indicate design solutions that need no further definition at the system level. These are also emergent requirements, meaning that they will impact on the definition of sub-systems where further definition is required.

Table 13. Design solutions resulting once the requirements from Table 12 have been processed in the QFD sheet.

Reactor Performance Related Solutions	**Level of definition achieved**
Reactor Type	Further definition required
Reactor Size	Further definition required
Reactivity Control System	Further definition required
Standard enriched fuel	System level definition complete
MOX loading capable	System level definition complete
Plant Performance Related Solutions	**Level of definition achieved**
Digital I&C system	Further definition required
On site used fuel storage ponds	System level definition complete
Minimise usage and production of proliferable material	System level definition complete

Modular design	System level definition complete
Utilise economy of scale (fleet build)	System level definition complete
Internal layout allows ease of access to maximise online maintenance	System level definition complete
Equipment Health Management System	Further definition required
Long-life components	System level definition complete
Ultimate heat sink	Further definition required
Reactor Safety Related Solutions	**Level of definition achieved**
Independent safety systems in non-mirrored layout	System level definition complete
Passive safety integrated into design	Further definition required
Active systems available and safety rated	Further definition required
Backup power systems	Further definition required
Fuel in standard assemblies that last into used storage	System level definition complete
Strong containment structure around reactor core	System level definition complete
Structural Safety Related Solutions	**Level of definition achieved**
Hard outer impact dome over primary containment	System level definition complete
Secure site	Further definition required
Adequate defence against flood	Further definition required
Concrete base-mat	System level definition complete
Robust grid connection	Further definition required
Location Related Solutions	**Level of definition achieved**
Site location	Further definition required
Connecting infrastructure	Further definition required
Skill availability	Further definition required
Aesthetic design	Further definition required

As mentioned previously, nuclear energy is subject to significant technological lock-in. This means that many of the requirements stated in the EUR document are prescriptive about the solutions that can be chosen within the design of a plant (EUR, 2011). Examples of this are:

- EUR 2.2, 1 Type and Plant Size, which states ‘The plant shall be a Light Water Reactor (LWR) nuclear power plant, either with a Pressurised Water Reactor (PWR) or a Boiling Water Reactor (BWR) Nuclear Steam Supply System (NSSS)’; and
- EUR 2.2, 3.1 Type of Fuel, which states ‘The core design will be optimised for UO_2 Fuel Assemblies.’

These requirements significantly constrain the design space within which the designer can operate. They may also rule out design solutions which other stakeholders would have a preference for, such as Thorium fuelled reactors or some of the more novel Generation IV nuclear plant designs which are not LWRs (Generation IV International Forum 2008).

For sub-systems and areas where further definition is required a number of existing design techniques can be used (per 2.2.6 and step three in Figure 4). As nuclear energy is a mature technology it is often possible to choose from a range of existing design solutions. As mentioned in the previous section, decision (Pugh) matrices can be used to help the designer to assess different options against each other by using the requirements for the system in question. An example of the Pugh matrices used in this case study is shown in Table 14. All Pugh matrices used in this case study are presented in Appendix D. Weighting corresponds to the strength of relationship between the requirement and the design solution in question, in this case ‘Ultimate Heat sink’. Any emergent requirements and related sub-systems that act as requirements would be added at the bottom of the list and the respective ‘Relative Solution Importance’ used to determine weighting value. In order to achieve this, the designer must look at the whole range of values for ‘Relative Solution Importance’ and determine an appropriate weighting scheme that translates ‘Relative Solution Importance’ into a weighting for use in the Pugh matrix. In this case study, ‘Relative Solution Importance’ values ranged from around 0.5 to 8 and it was trivial to transpose these values onto a 0, 1, 3, 9 scale by rounding to the most appropriate value.

The final total score (T) at the bottom of the table, the higher the score the better the design option fulfils the requirements, is calculated by multiplying the weighting value and score for each requirement, summed over all requirements for each design solution (Equation 9).

(9) $$Total = \sum_{r=1}^{R} Weighting \bullet Score$$

The score assigned to each design solution against each requirement can be subjective, based on the view of the designer, or objectively assessed against benchmarked data. For example, the third requirement in the list ‘Defence in Depth’ could be judged on a risk informed basis by using data showing power failure rates and flood/drought hazard probabilities. In this case a combination of benchmarks and variations has been noted in the table.

Table 14. Example of a Pugh matrix used to evaluate different options for ultimate heat sink.

Requirement and benchmark	Weighting			Natural Draught Cooling Towers	Fan Assisted Cooling Towers	The Sea	A River
U- A reliable ultimate heat sink must be available	Θ	9		4	3	5	3
Reliability							
P- The UHS should be low visibility and managed	Θ	9		1	3	4	4
Visibility							
U- Defence in depth	O	3		4	3	4	2
					Possible power failure		Water availability (drought/flood)
P- blend of active and passive systems	O	3		4	4	4	4
P- the plant should be located away from people	O	3		4	4	4	2
							Proximity to settlements and size of river

G- the plant should be on an existing site	Θ	9	2	2	4	1
					UK standard	
U- Resistant to DBA	Θ	9	4	3	4	2
				Possible power failure		Water availability (drought/flood)
U- able to cope with loss of off-site power (LOOP)	Θ	9	4	2	4	4
				Possible power failure		
			171	150	225	150

Once this process was completed for each of the sub-systems requiring further definition (from Table 13), a set of system level requirements was reached as shown in Table 15. Care was taken to ensure that the design solutions selected for each sub-system were mutually compatible (the 'roof' matrix in the QFD assists with this, see 2.2.5 and Figure 4).

Table 15. Example system specifications derived from following the proposed framework.

Reactor Performance Related Solutions	
Reactor Type	Dispersed Pressurised Water Reactor (PWR)
Reactor Size	~200MWe
Reactivity Control System	Integrated control rod system with chemical shim
Standard enriched fuel	Standard enriched fuel
MOX loading capable	MOX loading capable
Plant Performance Related Solutions	
Digital I&C system	Digital I&C system
On site used fuel storage ponds	Capacity for 60 years' worth of used fuel
Minimise usage and production of proliferable material	Use standard fuel assemblies and provide secure on site storage
Modular design	Optimised for fleet build
Utilise economy of scale (fleet build)	Optimised for fleet build

Internal layout allows ease of access to maximise online maintenance	Particular attention to steam-generator replacement
Equipment Health Management System	Monitoring system to assist preventative maintenance
Long-life components	For 60 year design life
Ultimate heat sink	The sea, or if site inland or sea insufficient then use forced-draught towers
Reactor Safety Related Solutions	
Independent safety systems in non-mirrored layout	Particular concern for rotatives and impact structures
Passive safety integrated into design	Gravity fed feed water system, accumulators for loss of coolant accident (LOCA) sequence
Active systems available and safety rated	Active containment residual heat removal system
backup power systems	Gas-turbine generators mounted high
Fuel in standard assemblies that last into used storage	17x17 standard PWR assemblies
Strong containment structure around reactor core	Concrete with steel liner
Structural Safety Related Solutions	
Hard outer impact dome over primary containment	Concrete dome on top of containment
Secure site	Defined site boundary, fenced with security patrols and CCTV
Adequate defence against flood	Site raised to adequate level above sea level (site dependent)
Concrete base-mat	Specified to provide solid foundation and design basis earthquake resilience
Robust grid connection	Multiple grid connections, physically separated to minimise loss of offsite power (LOOP) potential
Location Related Solutions	
Site location	Corresponding to local regulations on proximity to population centres, existing sites preferred
Connecting infrastructure	Direct rail connection for material transport. Unobtrusive road links for personnel and non-nuclear supplies
Skill availability	Local skill base in place (existing site), training facilities provided
Aesthetic design	Visible but fits into locale with minimum disruption to natural environment.

Standard design processes were then applied to further define the reactor. In reality, very few people would ever be required to design a nuclear plant from scratch, as most reactor vendors have considerable experience and a number of previous designs to build from. However, Lamarsh & Baratta (2001) provide an indication of the process to follow if one was to design a reactor from scratch. In any case, the framework proposed in the current work is compatible with approaches that start from a blank page as well as being compatible with approaches that use extensive previous design work to refine designs; the 'Existing Design Knowledge' input box (as shown in Figure 4) allows for this to take place.

The concept design presented below was created using the proposed design framework, beginning with a blank page, and then applying the type of design approach laid out by Lamarsh & Baratta (2001), starting with defining the power required, determining the amount of nuclear material in the reactor core and then working outwards through the primary and secondary systems using thermodynamic calculations. The example design is not optimised at this concept design stage. An overview of the design process used to turn the QFD sheet output into an example design is presented in Section 5.

3.2 The Resulting Example Concept Design

The resulting example reactor concept is a 735 MWth pressurised water reactor (PWR) with two primary side heat extraction loops. These connect to a secondary loop, which utilises a Rankine cycle (Zemansky and Dittman, 1997) with pre-heating via one high-pressure and two low-pressure steam turbines to produce approximately 240 MWe. Multiple units could be co-located on a site to increase power output; for example four (or six) such units could be used to provide 960 MWe (or 1440 MWe) of power to the electrical grid. A tertiary loop provides the plant with an ultimate heat sink, with flow requirements and heat output relatively comparable to those of proposed new nuclear plants (such as EPR (AREVA, 2005) and AP1000 (WEC, 2003)).

Several key characteristics of the proposed plant design are a direct consequence of the application of the participatory design framework and the results of the work documented in section 3 of this thesis; Public Perceptions of Design Options for New Nuclear Plants in the UK:

- The power of the reactor resulted from answers provided to question 2.4 of the research questionnaire where a preference for multiple smaller reactors was expressed;
- The type of reactor was largely dictated by the language of the EUR document which prescribes a light water reactor (LWR);
- The smaller physical size of the proposed plant corresponds to public demand for reactors the option to choose designs that ‘fit-in’ more closely with their environment, question 2.2 of the questionnaire;
- A ‘belt and braces’ approach to safety is taken, driven by responses to question 2.7 where the public expressed a preference for the use of both active and passive safety systems.

Sometimes finding mutually acceptable design solutions can be challenging. For example, taking into account the public’s views on the size of reactor found by Goodfellow et al., (2013). According to these results, the majority (71%) of the UK public felt that multiple small reactors on one site would be no less safe with 32% saying it would make them feel safer. This requirement was in contrast to the EURs which state that a plant should be of size 600-1800 MWe. However, the EURs do not say that such a plant would consist of only one reactor. Small reactor concepts have developed significantly since the EURs were last issued in 2007 and there is scope for multiple reactors to make up the capacity desired.

This is an example of how one area arising from the public consultation (a desire for smaller nuclear plants) can have a marked effect on the overall plant design; however, more research on understanding the public’s perspective is required to ensure that this design decision is truly representative of public views. Care must be taken to ensure that when one such issue (plant size) does have such a dominant effect on the design that all options are explored and that, ideally, additional consultations/research are carried out to ensure the issues are understood as completely as possible.

Figure 10 shows a side-profile schematic of the nuclear components of the proposed plant and a top down view of the same system is shown in Figure 11.

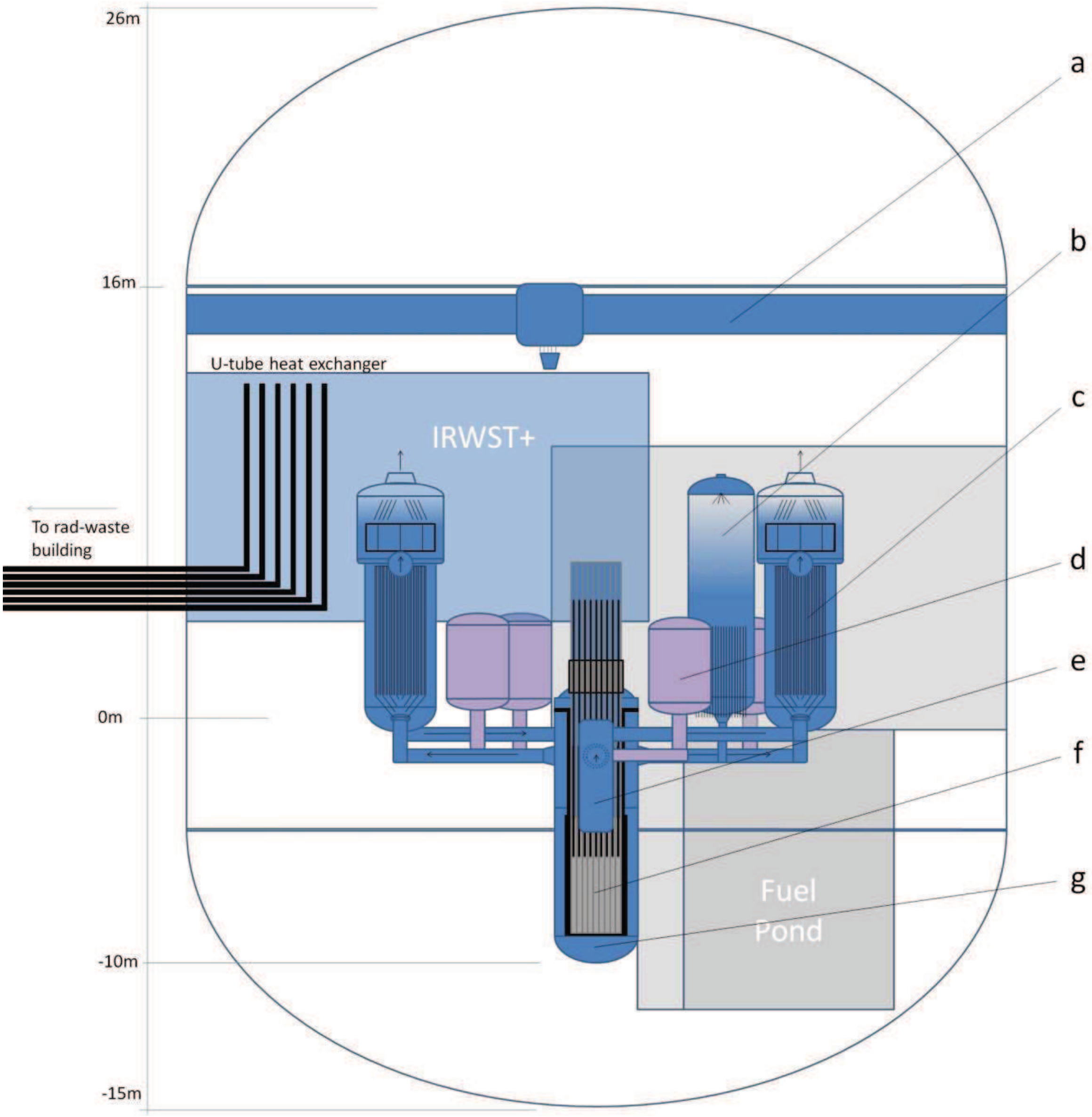


Figure 10. Side-profile schematic of the nuclear components of the proposed plant. In-containment refuelling water storage tank and residual heat removal system (IRWST+) is shown, shielding tank is not shown (see Figure 11). Key is described in Table 16 on the following page.

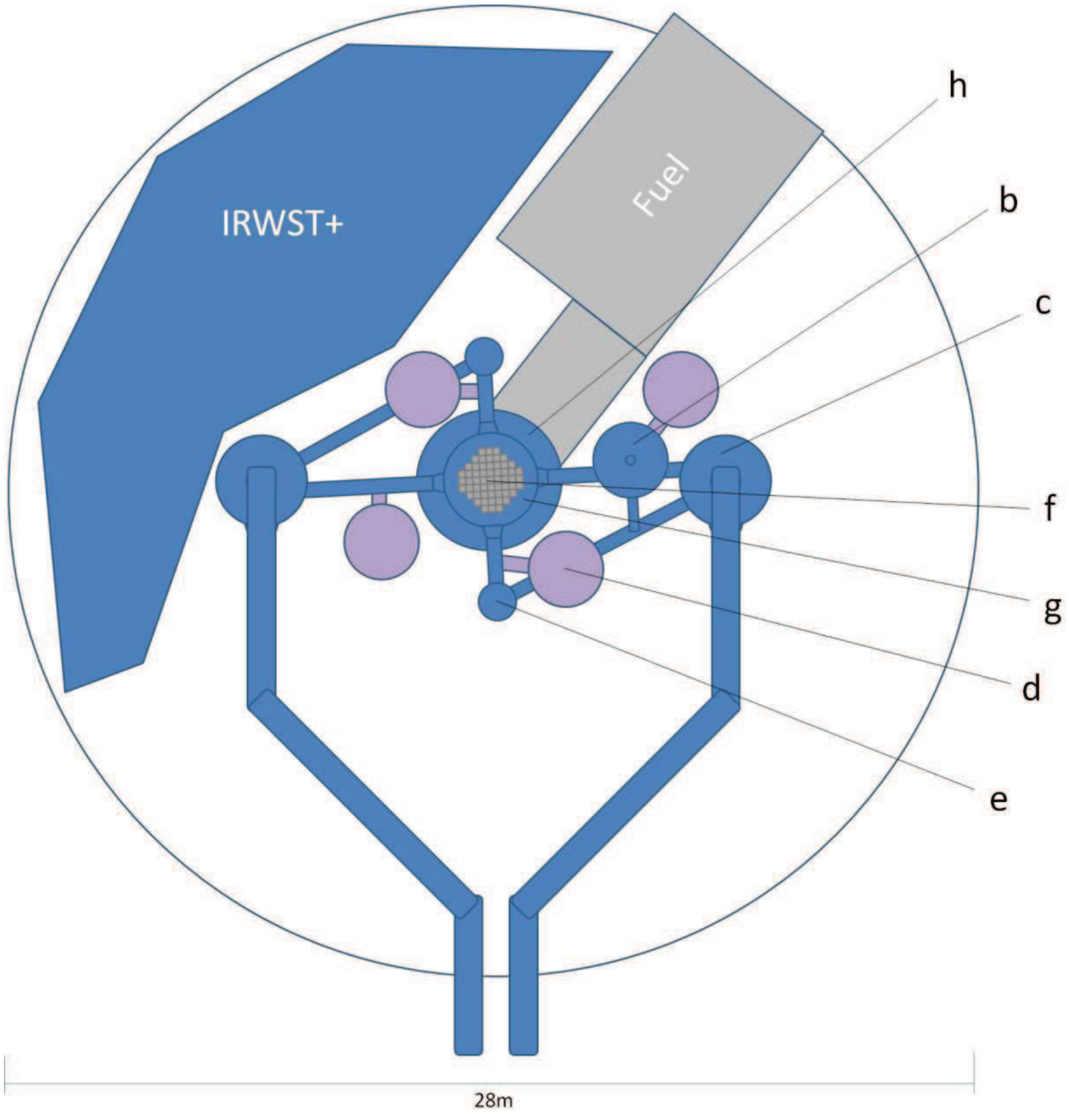


Figure 11. Top down view of the systems shown in Figure 10. In-containment refuelling water storage tank and residual heat removal system (IRWST+) is shown. Polar crane not shown for clarity. Key is described in Table 16.

Table 16. Key to the letters shown in Figure 10 and Figure 11.

a	Polar crane
b	Pressuriser
c	Steam-generator
d	Accumulator
e	Reactor Coolant Pump
f	Reactor Core (fuel assemblies)
g	Reactor Pressure Vessel
h	Shielding Tank

The fuel storage pond is shown on the right (Figure 10 and Figure 11), and In-containment Refuelling Water Storage Tank (IRWST+) is on the left (Figure 10 and Figure 11). The IRWST+ provides water during refuelling but also acts as the residual heat removal system and as an emergency low pressure feed water system and steam condenser. In the top down view the main steam-lines are shown protruding through the side-wall of the containment structure at the bottom of the diagram. Reactor pressure vessel shielding is shown around the reactor pressure vessel in the centre. IRWST+ feed-lines and residual heat removal heat-exchanger are not shown in the top-down view.

The primary loop is housed within a reinforced concrete containment structure which has an integrated steel liner which is intended to prevent any release of radiation should a primary loop leak incident occur. A concrete shield dome, intended to prevent damage to the reactor from external impacts, also tops this containment structure. The reactor uses 'standardised' 17x17 PWR fuel assemblies, which are currently commercially available. On site storage capacity for used fuel assemblies is provided to meet the 60 year design life of the plant. Space is provided for removal and replacement of the steam generators and pressuriser after 30-40 years.

Site footprint, shown in Figure 12, is approximately one quarter of that required by the AP1000 (WEC, 2003). This smaller size, combined with the lower height of the plant results in a lower visual impact. This corresponds to expressed public preferences for plants that are smaller and able to blend in to the natural environment more, as determined in (Goodfellow et al., 2013).

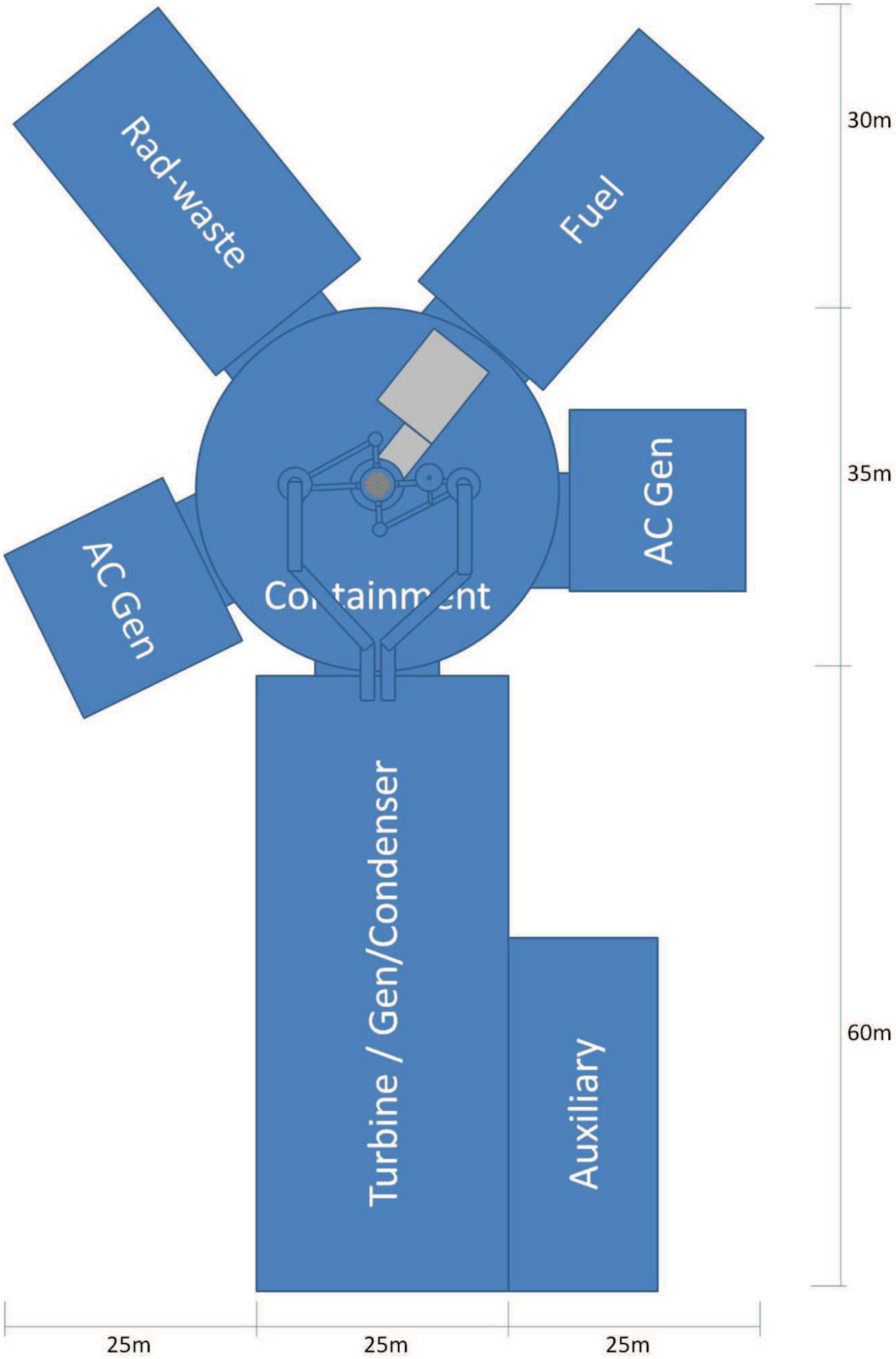


Figure 12. Top down site plan showing the layout of the constituent buildings for a single unit of the proposed design.

The plant relies on a combination of active and passive safety systems which are designed to work in the event of any critical plant failure. The cases of a Loss-of-Coolant-Accident (LOCA) and Loss-of-Offsite-Power (LOOP) have been considered and managed appropriately with the provision of multiple redundant safety systems. In the case of a LOCA high-pressure accumulators are used in the short term to make up primary circuit water volume until primary circuit pressure reaches ambient. At this point a residual heat removal and in-containment steam recycling system takes over, providing low pressure injection of liquid water until the plant reaches a cold shutdown state. Two 5 MWe gas-turbine generator sets are used to provide independent power to this residual heat removal system (along with Instrumentation and Control systems), allowing time following a 'scram' for the plant to turn off (technically known as cold shutdown state). These features are designed to provide a 'belt-and-braces' approach to safety with both active and passive safety systems used in combination with each other. Again, as stated previously, this corresponds to the preferences expressed by the public in work previously carried out by the authors (Goodfellow et al., 2013).

Table 17 provides a summary comparison of selected key system-level features of the proposed plant with the AP1000 and EPR.

Table 17. Selected design specifications for EPR, AP1000 and the proposed plant example, EPR and AP1000 data is taken from AREVA (2005), WEC (2003).

Reactor	EPR	AP1000	Proposed Plant
Thermal Power	4500 MWth	3415 MWth	735 MWth
Electrical Power	1600 MWe	1115 MWe	239 MWe
Efficiency	35%	33%	32.5%
Number of coolant loops	4	2	2
Coolant flow rate (per loop)	7.9 m^3/s	9.94 m^3/s	1.85 m^3/s
RPV inlet temp	296 °C	281 °C	290 °C
RPV outlet temp	327 °C	321 °C	320 °C
Steam flow rate	2554 kg/s	1886 kg/s	418 kg/s

Steam temperature	290 °C	273 °C	290 °C
Steam pressure	7.6 MPa	5.8 MPa	7.5 MPa
Steam-generator (SG) heat transfer surface	7960 m^2	11477 m^2	2250 m^2
Number of heat exchanger tubes	5980	10025	3200
SG outer diameter	5.2 m	5.6 m	2.1 m
SG height	23 m	22.5 m	8.5 m
Active core height	4.2 m	4.2 m	4.2 m
Equivalent core diameter	3.8 m	3 m	1.8 m
No. of fuel assemblies	241	157	57
RPV inner diameter	4.9 m	4 m	2.5 m
RPV total height	12.7 m	12 m	10.5 m
Pressuriser volume	75 m^3	60 m^3	25 m^3
Pressuriser inner diameter	2.6 m	2.3 m	2 m
Reactor coolant pump number	4	4	2
Flow rate	7.7 m^3/s	5 m^3/s	2.2 m^3/s
Pump head	100 m	111 m	100 m
Safety systems	*4 independent active systems:* >Medium head safety injection system >Low head safety injection system >Residual heat removal system >Passive Accumulators >Containment heat removal system >Core melt catcher	*Passive safety systems:* >Passive Accumulators >Passive core cooling system (via IRWST) >Passive containment cooling system >In vessel retention of melt >External impact protection	*Mix of active and passive systems:* >Passive Accumulators > Passive core cooling system (via IRWST) >Active containment heat removal system >Core melt catcher >External impact protection

	>External impact protection		
Backup power	8 x 8MW diesel for safety systems 4 x 3MW diesel in case of extended station blackout	None required – 2 x 4MW diesel in case of extended station blackout	2 x 5MW gas turbines for safety systems and station blackout
Time before operator intervention required following design basis accident	?	72 hours	>150 hours
Containment vessel vertical dimension (depth of containment vessel base)	67m (-10m below ground)	65.5m (-18.5m below ground)	41m (-15m below ground)
Containment diameter	46m	40m	28m

As can be seen from Table 17, the proposed plant is much smaller than the AP1000 and EPR designs that have been considered in the UK's Generic Design Approval (GDA) process: 239 MWe compared to 1115 MWe and 1600 MWe respectively. Much has been written recently about small reactors (Ingersoll, 2009) and in particular their economics. The general trend in nuclear power has been for larger single unit plants to maximise the economy of scale; smaller reactors are generally perceived to be more expensive than larger reactors because of this. However, research suggests that other factors, such as a lower investment risk profile, increased learning from constructing more reactors, and improved safety due to lower levels of residual heat, mean that smaller reactors may be competitive in certain market situations (Carelli et al., 2010).

The components required for the proposed plant are also much smaller than those required for AP1000 and EPR (Table 17). This has the potential to increase the number of locations able to manufacture nuclear components. In turn, this increases competition and has the potential to drive down costs. Furthermore, the size of the components on the proposed plant are much more in keeping with the size of pressure vessels used over the last 100 years meaning that additional experience in manufacturing, maintenance and defect correction exists. The downside of this reduced component size is that some components do not scale down very well. For example, although the output of the proposed plant is one fifth of that of the AP1000, the containment building is still large, roughly two thirds the height and diameter, reducing the potential for cost saving of the plant. This is the same for a number of other high cost parts of the plant, such as the instrumentation and control system.

Using the 'shall, should, may' terminology of the EURs leads to cost being given the same weighting as many other requirements. This is perhaps not a true reflection of the economic reality of designing a nuclear plant which, in most cases, is a largely commercial endeavour. Although this is a limitation of the case study, the proposed framework could quite easily account for more importance being given to cost if appropriately stronger weightings were assigned to cost related requirements. Further investigation and calibration of the weighting system with respect to cost is required.

4. DISCUSSION

The case study has illustrated how the proposed participatory framework can be used to achieve a publicly informed nuclear plant concept design. As far as the authors are aware, this is the first framework that allows for the integration of public design preferences alongside the requirements of the 'customer', i.e. the energy utility company. The resultant example concept design shows that whilst the integration of the public's preferences may lead to a different variant of plant, it does not necessarily lead to a plant that is unfeasible. As ever, the result is a compromise solution that is intended to fulfil as many of the different requirements as possible.

Techniques such as surveys, focus groups, interviews and local liaison meetings can be used to determine the public's preferences of reactor design options. These stakeholder views can then be translated into a set of system-level requirements and used in the proposed framework. A modified QFD process is proposed as a means to integrate the various stakeholders' requirements in an equitable and transparent way. This is of key importance, as trust in the process is integral to its success in improving the acceptance of plant design. The output from the QFD is twofold, firstly a broadly defined set of system-level specifications (some of which will be further defined using additional systems design tools) and secondly an understanding of which particular design solutions (within the system level) are most important to the stakeholders whose requirements have been used to generate the design. This information can be used by the designer to complete the system-level design and specification of the plant. Comparison against the original sets of requirements can then take place, followed by design iteration if required. Finally, the system-level design and specifications can be taken forward using ‘standard’ design practices.

This paper also presents a case study example design for a new nuclear plant which was created using a set of basic plant requirements from a variety of stakeholders including energy utilities and the general public. Further research needs to be carried out on both national and local levels to ensure that an appropriate spectrum of views is captured and considered in the stakeholder requirements capture process. This case study is intended as a proof of concept only, as further research is required to establish such a representative set of public stakeholder requirements.

The case study helps to highlight the importance of calibrating the weightings used in the modified QFD sheet; particularly the weighting of critical requirements, such as, for example, those relating to cost. The cost of implementing this novel design process must be assessed against the potential benefits. These cost changes are hard to define as they may rely on the probability that the plant will face opposition when constructed. Such opposition is heavily dependent on a wide range of cultural, social, political and economic factors and understanding how and if opposition will take place requires further research. As well as the cost balance between carrying out engagement and potentially facing opposition there are a series of potential engineering related cost challenges associated with making changes to a nuclear plant. Some design changes may only impact the capital cost of the plant (such as aesthetic design). However, other changes, for example using active safety systems rather than passive ones, could have serious implications for both the capital cost of the plant and the lifetime cost of operation and maintenance of hardware. Modelling these potential cost changes is complex and requires significant effort.

Other issues that require further attention relate to the aforementioned difficulty in determining a truly representative set of public requirements and also how to incorporate the levels of design customisation that the views of disparate groups of stakeholders might require. This is a critical issue in the context of substantial on-going effort by the nuclear industry to standardise both plant design and regulatory systems. Future work should focus on these areas to ensure that the framework is both practicable and applicable.

Using the framework does require additional requirements capture and system design effort on the part of the designer. Design organisations may not have expertise in public engagement and the nuances of ‘softer’ social research. Many options exist for outsourcing such work, allowing a designer to follow the proposed framework without requiring a significant expansion of skills and expertise in social science and public engagement. There will be a cost for this additional work, both in terms of finance but also in the time taken to execute the engagement processes, elicit public preferences and analyse the resulting data.

The time taken to bring a design to market also presents issues. Often the time taken between design work being carried out and a reactor being commissioned can be measured in decades. In the intervening period the public may become disenfranchised unless engagement activities continue and the public are kept informed about the progress being made. Additionally, public views on what is and is not acceptable may change over time depending on other external factors. In particular it would seem logical to assume that future accidents in the nuclear industry would potentially have a large bearing on public views on a design, though such effects could be temporary. Other more subtle factors may also become significant over longer periods of time. More research is required to understand these longitudinal factors and the impact which they might have on processes such as those proposed in this work.

An advantage of the proposed framework is that the use of tools such as QFD and Pugh matrices allows the influence of a requirement to be traced through the design process. This can assist in demonstrating to stakeholders that their input is having a demonstrable effect on the design. In turn, this assists in assuring stakeholders that their views are being taken seriously. Even if the resulting design is not exactly as any individual stakeholder would prefer, it can be shown that their view has been used in the process for arriving at that design. An improvement in the level of engagement between the designer and the public may also assist in the relationship between the energy utility and the public if the energy utility continues the process of engagement once a plant has been chosen for a specific site. This can be useful as certain design decisions, such as the choice of ultimate heat sink, are site specific.

Although the process of using the QFD matrices and additional design support tools is relatively straightforward in principle, carrying out this work using a full set of requirements for a nuclear plant can make the process increasingly complex. This would also be the case if (and when) a wider range of techniques is used to understand public design preferences. There is a risk of 'data overload' and it is imperative that the designer carefully manages the number of requirements used at the 'top' system level. This is a common issue with many system design processes and it can be successfully managed, but this does require the designer to use time and experience effectively.

The proposed framework is a systems design tool. Like any tool, the results that it produces are only as good as the information fed into it in the first place. Improper use, unusual circumstances, bad data and bad interpretation of requirements can all cause the resultant system design output to be flawed. Experience in eliciting requirements, particularly in gaining an understanding of the public's design preferences and experience in using the framework can help to minimise these issues.

Further research is required to improve understanding of the public's preferences, and perhaps more importantly, the underlying reasons behind these preferences. Additional research may be needed to understand how the output of different types of research into public preferences could be amalgamated and processed into a set of public requirements. For example:

- understanding how much work is required in combining the output of questionnaires, interviews and focus groups;
- understanding the views of different local and national groups of people and how best to engage them; and
- understanding the importance, accuracy and relevance of the data provided by each research method and group.

In this paper, the framework was demonstrated by designing a new reactor concept. In reality, it is perhaps more likely that a designer would take an existing design and seek to make incremental improvements. In principle there is no reason why this framework could not be used in that way. The opportunity exists during the public consultation to put forward examples of incremental improvements, using an existing design as a baseline, in an effort to elicit public preferences. It is impossible to rule out that there may be emergent issues that only arise in using the framework in this way as it has not yet been tested for this use.

5. CONCLUSIONS

This paper has described a novel framework for the design of nuclear power plants. It allows a reactor designer to incorporate a wider range of stakeholder views, including the views of the general public, into the system-level design of the plant. As far as the authors are aware, this is the first such framework to achieve this. It is postulated that by incorporating a wider range of stakeholder views at the early design stage, new nuclear plants can be designed that are more socially acceptable. In turn, this has the potential to improve the social sustainability of nuclear power.

The possible benefits of using a participatory design framework such as this one are twofold. Firstly, the design of the nuclear plant in question can be ‘improved’ as compared to the wider set of design requirements laid out by the additional stakeholders whose view is now considered (i.e. the lay public). Secondly, by involving a wider range of stakeholders, including the lay-public, nuclear designers gain an important new source of information which can be used to engage in two-way communication. Ultimately, if carried out successfully, the public gains trust in the design process and designers along with valuable insight into the considerations made during plant design and the designer gains the support of the public and a degree of social acceptance beyond that which nuclear power has previously experienced.

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5. Design Development of the Case Study Nuclear Plant

5.1. Method for developing the case study design

The following section describes the deterministic process of turning the example publicly informed system level specifications into the proposed plant presented in Section 4 of this thesis. This is not a formal design document, it is a conceptual feasibility statement for a hypothetical nuclear power plant design. The author decided that the design philosophy taken would be to utilise best current practice in terms of applicable technology and functionality of systems. To this end the design is a dispersed pressurised water reactor made from current state-of-the-art materials and using accepted (and codified) manufacturing processes. Such an approach is intended to minimise the amount of capital cost inherent in the construction of the plant.

5.1.1. Proposed Plant Design Scope outline

From the QFD, Pugh matrices and associated system design tools (Appendices C and D) we get the following overall plant system level specifications:

Reactor Performance

Conservative Integral PWR design
8 x 200MWe reactors
Flexible reactivity control system
Standard enriched fuel
MOX loading capable

Reactor Safety

Independent safety systems in non-mirrored layout
Passive safety integrated into design
Active systems available and safety rated

Backup power systems

Fuel in standard assemblies that last into used storage for a period of at least 50 years

Strong containment structure around reactor core

Structural Safety

Hard outer impact dome over primary containment

Secure site

Adequate defence against flood

Concrete basemat

Robust grid connection

Plant Performance

Digital I&C system

On site used fuel storage ponds

Minimise usage and production of proliferable material

Modular design

Utilise economy of scale (fleet build)

Internal layout allows ease of access to facilitate online maintenance

Equipment health management

Long-life components

Sea as ultimate heat sink (with fan assisted cooling towers if sea insufficient)

Location

Coastal location on existing site

Direct rail connection

Site located such that workforce available

Aesthetic design fits with locale

These specifications are based around the concept that most PWRs are all based around the same configuration, as shown below in Figure 13.

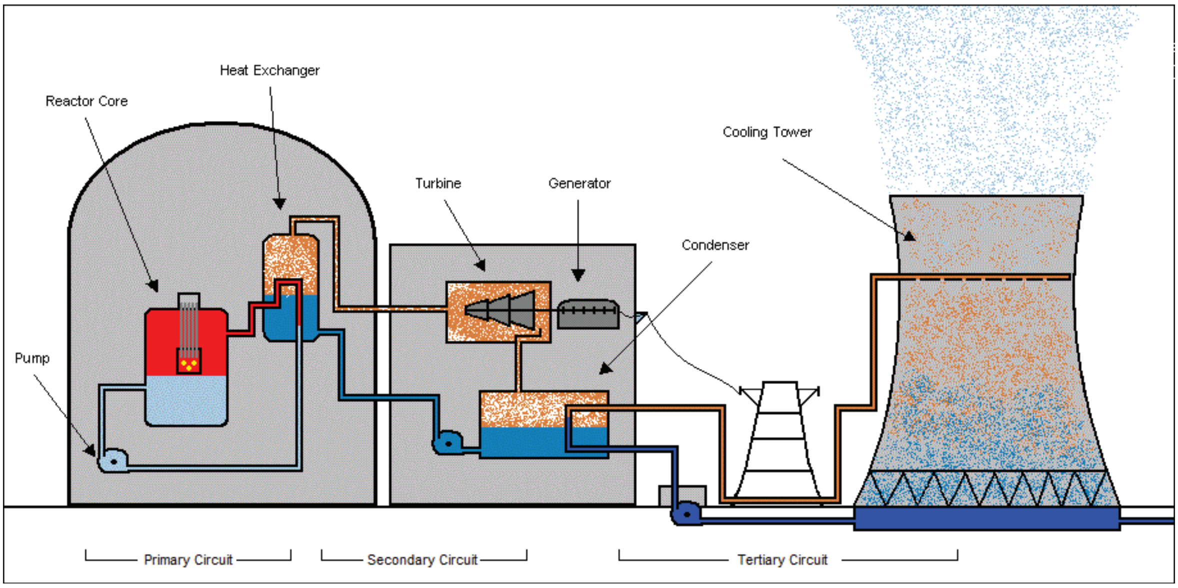

Figure 13. A nuclear power plant (PWR)

Three circuits make up the means to transfer heat generated by nuclear fuel into useful energy in the form of electricity, and wasted energy in the form of heat. The primary circuit in a Pressurised Water Reactor consists of a reactor core which houses nuclear fuel. Through nuclear fission the core gets hot and heats water flowing around it. This water is pumped to a steam generator where it heats the secondary circuit water (but does not mix with it). The cooled primary circuit water then returns to the core.

The heated secondary circuit water (in the form of steam) drives steam turbines, which in turn drive electrical generators to produce electricity. The secondary circuit water is cooled by the tertiary circuit water (without mixing with it) in the condenser. The cooled secondary circuit water is then pumped back to the steam generator.

The tertiary circuit water is pumped into the condenser from the environment, it heats up when it removes heat from the secondary circuit. In some cases the warm tertiary circuit water is returned back to the environment warm (for example if it has been taken from the sea) with environmental regulations on just how warm it can be. In other cases, for example if it has been taken from a river, the tertiary circuit water is cooled in a cooling tower before being returned to the environment.

5.1.2. Reactor Core

A simplified means to calculate the power in the core of a nuclear reactor operating in a steady state is to use equation 1 (Lamarsh & Baratta, 2001). Equation 1 relates the number of atoms of fissile material involved in a nuclear fission reaction to the amount of power being produced by that reaction. In order to begin the design of the nuclear reactor assumptions are made on representative values from average capture cross section, neutron flux and energy per fission.

$$P = N\varphi\sigma_f E \tag{1}$$

therefore

$$N = \frac{P}{\varphi\sigma_f E} \tag{2}$$

Where:

P = Power

N = Number of atoms (U_{235})

σ_f = Average capture cross section

ϕ = Neutron flux

E = Energy per fission event

Assuming:

P= 600MW (thermal)

σ_f = 579 barns = 5.79×10^{-28} m^2

ϕ = 1×10^{8} $m^{-2}s^{-1}$

E = 200 MeV = 1.3×10^{-13} J

N is calculated from equation 2.

$$N = \frac{M_{U_{(235)}} \%_{U_{(235)}} N_A}{M_{molarU_{(235)}}} \tag{3}$$

Therefore:

$$M_{U_{(235)}} = \frac{N\, M_{molarU_{(235)}}}{\%_{U_{(235)}} N_A} \tag{4}$$

Where:

N_A = Avogadro constant = 6.022×10^{26}kg/mol

$M_{U(235)}$ = Mass Uranium (235)

$\%_{U(235)}$ = Enrichment (235/238) = 4%

$Mmolar_{U(235)}$ = molar mass U_{235} = 0.235kg

Substituting equation (2) into equation (4) gives:

$$(5) \qquad M_{U_{(235)}} = \frac{\left(\frac{P}{\varphi \sigma_f E}\right) M_{molarU_{(235)}}}{\%_{U_{(235)}} N_A}$$

Using above data, P=600MW gives $M_{U(235)}$ ~31 Tonnes

Fuel is UO_2 ceramic, 31 Tonnes U implies ~35 Tonnes UO_2 fuel.

In standard PWR fuel the fuel pellets are cylinders which are approximately 10mm tall, 10mm diameter. There are approximately 370 pellets per fuel pin (derived from the 3.7m tall active fuel area specified by fuel manufacturers (Nuclear Engineering International, 2004)) Fuel pins are combined into assemblies in a 17x17 matrix with 25 'empty' slots arranged in the matrix to allow for control rods. This means 264 fuel pins per assembly.

The density of UO_2 is 10.97gcm^{-3} (or ~10,000 kg m^{-3}). Fuel that has been exposed to temperature and neutron irradiation will distort over time as the grains in the ceramic microstructure of the material begin to expand. Therefore the fuel manufacture process leaves a small amount of porosity (approximately 10%) in the fuel pellets to accommodate grain swelling. If the pellets are 10% porous to accommodate grain swelling, the density becomes 9.87gcm^{-3}.

Using basic geometry and assuming cylindrical shape, the volume of each assembly is $7.6 \times 10^{-2\ m3}$. Therefore each assembly can take ~750kg of fuel and it follows that 35 Tonnes of fuel implies a theoretical ~46.5 assemblies.

A 7x7 matrix of assemblies would require a total of 49 assemblies, show in Figure 14, alongside an alternate core configuration, which is more circular in the vertical axis, uses

57 assemblies. Working backwards through a re-arranged equation 5, a matrix of 57 assemblies would give a thermal power output of approximately 735MWth.

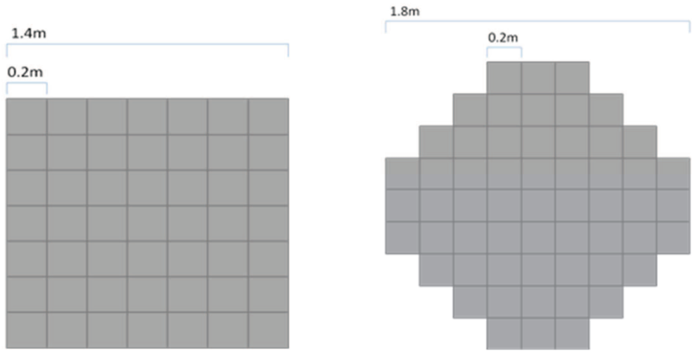

Figure 14. Core configuration of 49 fuel assemblies in a 7x7 arrangement (left). Alternative core arrangement which aims to improve core density is also shown (right) comprising of 57 assemblies in roughly the same space.

Fuel assemblies are around 4.2m tall and 0.2m x 0.2m square. Therefore using the alternative core arrangement and the dimensions above the core volume can be derived as 9.6 m^3. This core volume compares to that of the EPR which has a core volume of about 48 m^3 [~5 times bigger] and a power output of 4500 MW [~6 times bigger] (AREVA, 2005). The active surface area of the core, an important variable for core heat transport, calculated from basic geometry, is determined to be 2448 m^2. This compares to the EPR (8005 m^2) which is around 3.5 times bigger for 6 times the power output (AREVA, 2005). This volume to surface area comparison is favourable to the proposed reactor design and allows some design margin.

5.1.3. Reactor Pressure Vessel

The core, calculated from the fuel assembly dimensions above, is ~1.8m x ~1.8m x 4.2m. The size and shape of the reactor pressure vessel (RPV) can now be approximated. The RPV must be able to accommodate the core, control rods (fully removed), a radial Zirconium alloy reflector around the core (to compensate for the ‘tall and thin’ core configuration created through using standard fuel assemblies), inlet and outlet piping and the vessel head. An overview is shown in Figure 15 below.

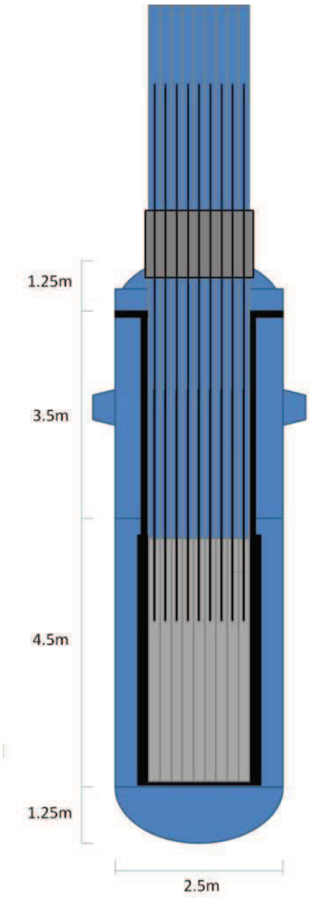

Figure 15. Configuration of the Reactor Pressure Vessel. Diagram shows core, surrounded by Zirconium alloy reflector (thicker black lines either side of core), control rods (half inserted), control rod drive mechanism (grey at top), and indicative positions of inlet and outlet piping.

To minimise the thermal stress on either side of a circumferential weld, which might lead to a failure, it is preferential that no such welds exist adjacent to the core. Therefore, the bottom ‘shell’ part of the RPV is 2.5m diameter and 4.5m tall. This is quite tall for a ring forging but is within the manufacturing capability of several steelworks.

The assembly arrangement leads to a diagonal ‘diameter’ of ~1.7m. A 2.5m diameter provides sufficient room for a reflector/blanket (around 0.2m thick on EPR) and main coolant flow outside of the core. 2.5m diameter ring forging is well within the size of an EPR pressure vessel, which is around 5m in diameter (AREVA, 2005).

RPV volume can be calculated using the basic geometry described in equation 6:

$$V = \frac{4}{3}\pi r^3 + \pi r^2 h \qquad (6)$$

Inputting dimensions to equation 6 gives a volume of 47.5m^3. This figure also becomes important when considering the volume of pressurised water required in the primary loop. Plant performance will be compromised if too little water resides within pipework. Plant safety may be compromised if too much water resides in the RPV as compared to the rest of the system.

5.2. *Thermal Cycle*

The proposed plant utilises a regenerative Rankine cycle (Lamarsh & Baratta, 2001) in common with many other modern power plants. The overall schematic of the thermal cycle of the plant is shown below in Figure 16. The following section will refer back to the letters marked at different positions within this diagram.

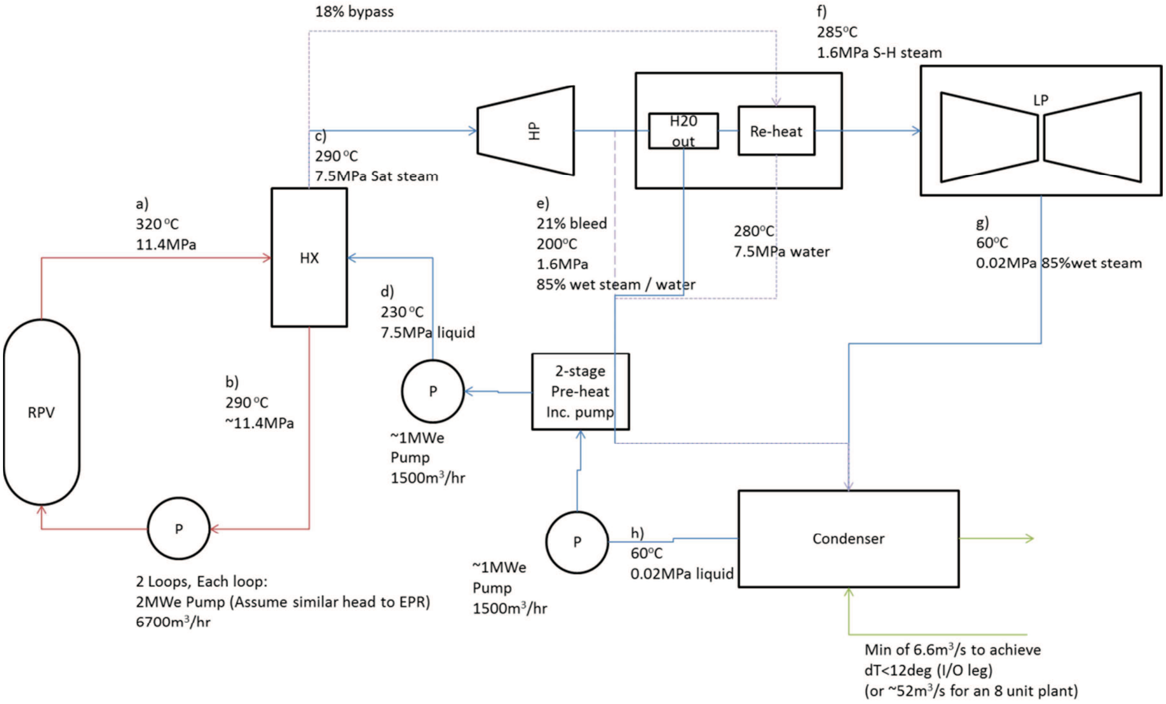

Figure 16. Schematic of primary and secondary loop showing major components relevant to steady state power cycle.

Some basic rules of thermodynamics are used to help calculate the values for temperature and pressure around the secondary circuit.

Thermal power, where Q = thermal power and Δh is enthalpy difference, is defined in Equation 7 as the change in enthalpy between two states when pressure is constant (Zemansky & Dittman, 1997):

(7) $$Q = \Delta h$$

Thermal power when volume is constant can also be defined using equation 8, where $\dot{m}$ is the mass flow rate of the heat transport medium.

(8) $$q = \dot{m}\Delta h$$

If we know the temperature (T) and pressure (P) at (a) and (b) we can determine the mass flow rate required in the primary circuit to remove the thermal power generated by the reactor.

(a) Primary Circuit 'Hot Leg'

T_{max} at (a) is around 325-340°C. This limit is defined by several factors, including the chemical properties of water at this temperature (which becomes very corrosive) and the materials used to construct the primary circuit (usually steel in the case of a PWR). P_{max} at (a) is defined by the strength of the materials used in the primary circuit, allowing a safety margin for wear and damage that may occur over the lifetime of the plant. A representative T_a=320 °C and P_a=11.4MPa (pressure derived from steam tables (ASME, 2009)) is used for this reactor system. Steam tables also give h_a=1461 kJ/kg for liquid water at this temperature and pressure.

(b) Primary Circuit 'Cold Leg'

T_{max} and P_{max} at (b) are largely dependent on the enthalpy drop created in the steam generator (HX). Typical values are in the region T_b=290°C (taken from EPR documentation). Steam tables give h_b=1289kJ/kg at this T_b (ASME, 2009). The primary circuit is almost isobaric $P_b \sim P_a$, with the only differential pressure being caused by losses from friction and vortices generated by the geometry of the primary coolant flow path.

We can now calculate the mass flow rate required to remove heat from the primary circuit using equation 8.

Using the above information and rearranging equation 8 the primary circuit mass flow rate required = 4273 kg/s

In practice it would be prudent for safety reasons (reducing the size of any possible loss of coolant accident) and for economic reasons (reduce the size of reactor coolant pumps (RCP)) to have two circuits coming out and back into the reactor via heat-exchanger/steam-generators. This implies a mass flow rate of around 2150kg/s for each loop, which equates to ~7740 m^3/hr per loop (with 2 loops). The RCPs on the EPR operate at a max of ~28,000 m^3/hr, which suggests the above value is of the right order of magnitude for this system (AREVA, 2005).

(c) Heat-exchanger (steam-generator) Output

A reasonable (based on EPR) heat-exchanger output is T = 290°C and P=7.5MPa (AREVA, 2005). At the same point in the EPR 2' loop T=293°C and P~8MPa. 'Choosing' the values of temperature and pressure at (c) is a design decision to 'fit' the steam production in the secondary circuit with the input required for the high-pressure steam-turbine (HP). In this system T_c=290°C and P_c=7.5MPa giving h_c=2766kJ/kg (saturated steam).

(d) Heat-exchanger Input

(d) is discussed further below

(e) Intermediate pre-re-heat stage (f) Intermediate post-re-heat stage and (g) Post Low Pressure Turbine stage

The secondary loop operates in a Rankine cycle that is an isentropic process. The simplest way to understand the enthalpy changes that occur in the HP (high-pressure) and LP (low-pressure) steam turbines is to use a Mollier chart. This allows a user to read off temperature and pressure values and determine enthalpy (h) along with steam quality (X) that is the fraction of water droplets in the steam (also referred to as wetness). Steam turbines will suffer poorer performance and increased wear if steam quality gets too low. X is one parameter that defines the maximum enthalpy extractable from a steam turbine.

Another parameter is the ratio of input to output pressure. If this ratio is too high it can place extreme design constraints on the turbine itself. A pressure ratio of 800-1000 is often considered nominal (Sayers, 1990). In this proposed plant the pressure ratio is 375 between HP inlet and LP outlet which is quite conservative.

As the Rankine cycle is isentropic (constant entropy or vertical on the Mollier chart [NB, this is ideal isentropic expansion, in reality there would be around 10% loss]) the temperature and pressure of (e) and (g) can be determined by drawing vertical lines on the chart. Temperature and pressure at (f) are determined by the separation of water from the 'wet' output from the HP turbine and a reheat stage (utilising a bypass of HP steam) to take the HP turbine exhaust steam back up to superheated temperatures.

Reading from a Mollier chart leads to:

T_e=200^{o}C, P_e=1.6MPa, h_e=2500kJ/kg, wetness = 85%
T_f=285^{o}C, P_f=1.6Mpa, h_f=3000kJ/kg, superheated steam
T_g=60^{o}C, P_g=0.02MPa, h_g=2250kJ/kg, wetness = 85%

(h) Post-condenser

The condenser then takes this exhaust from the LP turbine (cold and wet steam) and turns it back into liquid water. To simplify the calculations of this cycle, this is considered an isothermal process, $T_g = T_h$ in Figure 16. Using steam tables the values can be determined as follows:
T_h=60^{o}C, P_h=0.02MPa, h_h=251kJ/kg (liquid)

(d) Heat-exchanger Input

Finally the liquid water needs to be preheated and pressurised before being sent back to the heat-exchanger. This is to prevent too great a temperature/pressure differential being created within the heat-exchanger. Typical heat-exchanger input temperatures are around 230-240^{o}C with input pressure matching output pressure. In this system:

T_d=230^{o}C, P_d=7.5MPa, h_d=1289kJ/kg (liquid)

5.2.1. Secondary Circuit Mass Flow Rate and Electrical Power

The mass flow rate of the secondary circuit can now be calculated using equation 8 and assuming that q_1=q_2 (enthalpy is conserved between the primary and secondary circuits). Therefore:

$$\dot{m}_1 \Delta h_1 = \dot{m}_2 \Delta h_2 \quad (9)$$

Rearranging and inputting the relevant values gives secondary circuit flow rate of $\underline{\dot{m}_2\text{=418kg/s.}}$ This is a judged to be a reasonable mass flow rate for steam through a steam turbine.

5.2.2. Rankine Cycle

The following calculations assume no losses and 100% conversion at heat-exchange interfaces.

Reading from the Mollier chart, Δh from HP turbine outlet to LP turbine inlet = 500kJ/kg

This is approximately 18% of the value of h at (c), therefore an 18% off-take is introduced before the HP turbine to use as reheat in the intermediate stage before the LP turbine. 343kg/s now flows through HP turbine.

Pre-heat before the heat-exchanger requires Δh = 739kJ/kg. 222kJ/kg remains from preheat flow-through exhaust, 517kJ/kg make-up required from HP turbine outlet. A bleed of approximately 21% provides 525kJ/kg, leaving a flow rate of 271kg/s in LP turbine.

Using equation 8 and inputting Δh of the combined HP and LP turbines along with $\dot{m}_2$ gives a power of 295MWe (assuming 100% conversion from thermal to mechanical to electrical power).

Primary circuit pump sizes can now be determined. Assuming the same flow resistance as is the case in an EPR, due to similar geometry (AREVA, 2005). For simplicity internal pump efficiency is ignored. Equation 10 describes the fluid power of the heat-transfer medium (pressurised water).

$$P = q\Delta p \tag{10}$$

Where P=Fluid Power,
q=flow rate,
Δp=pressure differential (head)

The EPR pressure differential is 1MPa (Areva, 2005), the flow rate in the proposed reactor is 1.9m^3/s. Therefore P = 2MW.

In addition, three 1 MW pumps are required on the secondary circuit to recirculate the water. Now, using the previously calculated power outputs and requirements it is possible to estimate the efficiency of the nuclear power plant.

(295-4-3)/735 = <u>39.1% efficient</u>

However, this is gross efficiency. It is assumed in this case that losses in heat exchangers, pipe losses and mechanical/electrical motor losses will scale down this figure by a factor of approximately 10%. Non-isentropic expansion will also scale down the power by a further 10%. This results in a net efficiency in the region of 32.5% and power of 239MWe.

5.3. *Heat-Exchanger / Steam Generator Sizing*

Experiential 'know-how' from Rolls-Royce suggests PWR heat exchanger size of around 6-7m^2 per MW is reasonable for optimal heat-transfer in a practical system.

735 MW x 6 m^2 implies approximately 4500m^2, or 2250m^2 per loop in 2-loop configuration.

19mm diameter steam boiler tubes are used. This is a typical nuclear steam generator tube diameter (Areva, 2005).

Simple geometry for cylinders implies the length required (h) for a given radius (r) and surface area (A) can be determined by $h = \frac{A}{2\pi r}$, therefore h = 37.7 km per steam-generator.

The tubes are arranged in a triangular pitch to maximise the density of heat transfer surface area in a given volume. A U-bend configuration is used to facilitate the design of the heat-exchanger and simplify the pipework routing for heat-exchanger input and output. Figure 17 shows a top-down view of the triangular pitch of the heat-exchanger tubes.

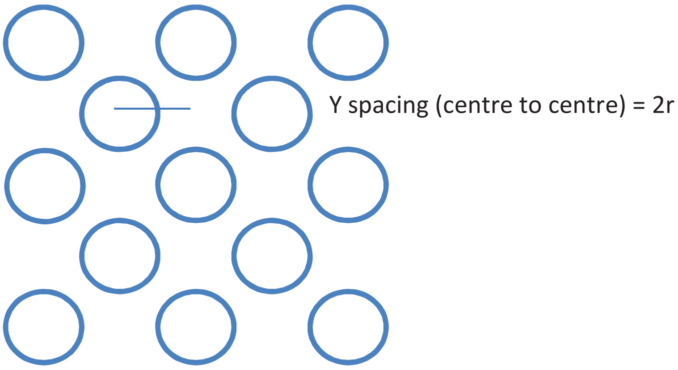

Figure 17. Representation of the triangular pitch boiler tube configuration.

If the heat-exchanger is approximately 6 m tall, each tube needs to be around 12m long. From basic geometry the number of tubes can be determined, 37.7x10^3/12=3142 tubes. A u-tube arrangement of 80x40 gives a total tube count of 3200 tubes.

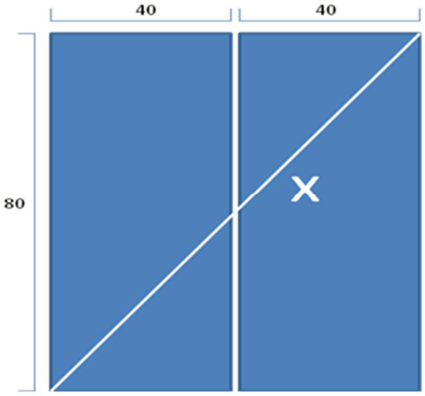

Figure 18. Top down view of SG U-tube configuration. Each blue rectangle contains 40 x 80 tubes. On the left side the flow is up, towards the reader, then the tubes loop over (not shown for clarity) the gap and the flow in the right hand blue rectangle is down, away from the reader.

The diagonal dimension of the 80 x 80 array (X in Figure 18) is 1.75m. This implies that the outer diameter of a cylindrical steam-generator housing the heat-exchanger needs to be approximately 2m. This forms to lower part of the steam-generator shown in Figure 19. The top section of the steam-generator comprises two additional stages to separate moisture from the steam. Firstly, swirl-vane separation is used to centrifugally remove moisture. Finally, a second steam-drying stage, using chevron screens, is present to minimise the moisture content that flows into the secondary circuit.

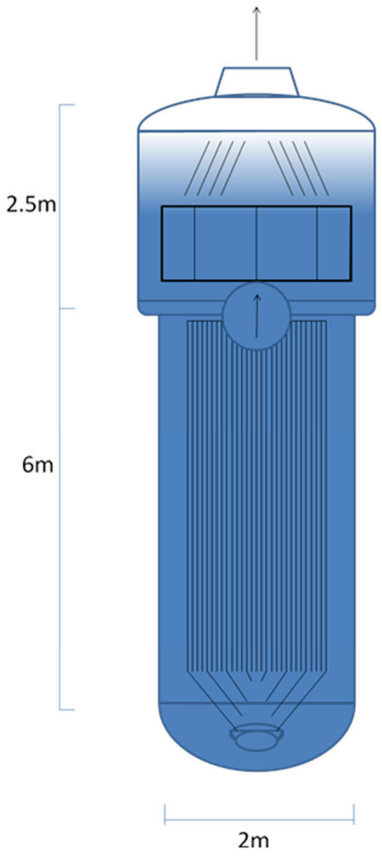

Figure 19. Schematic representation of a steam generator. Bottom section represents the U-tube boiler tubes. Top section is a swirl-vane separator stage and chevron dryer screen stage to remove moisture. Arrows show the side mounted secondary circuit input and the top located secondary circuit output pipe connections.

5.3.1. Sizing the Pressuriser

The EPR primary circuit is 455 m^3 with a 220 m^3 RPV and 75 m^3 pressuriser. The pressuriser volume is 34% of the RPV volume and 16.5% of the primary circuit volume (AREVA, 2005).

This would imply that the pressuriser volume in the proposed plant should be approximately 16 m^3.

The primary circuit volume of the proposed plant (y) is:

RPV + Piping (0.4m diameter pipe, 30m overall length) + 2 Steam Generators + Pressuriser (x)

$47.5m^3 + 4m^3 + 42m^3 + x = y$

If **<u>x = 25m³</u>**, y = 118.5m³ and x is 21% of the primary circuit volume and 53% of the RPV volume. Downsizing to a smaller pressuriser will likely provide only a modest cost and space saving. Retaining this larger pressuriser provides enhanced transient safety margins, smoother transient performance and potentially eliminates the need for some activated pressure relief valves (although certain regulatory regimes may prevent this), therefore reducing primary circuit penetrations. A larger steam space assists in smoothing both anticipated and unanticipated reactor transients.

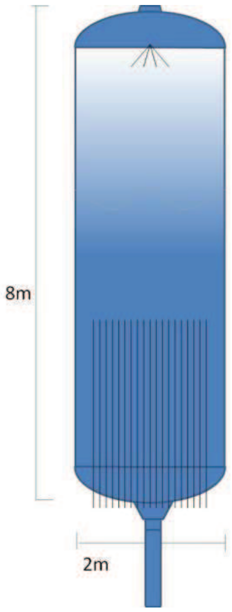

Figure 20. Pressuriser of 25m^3 volume showing representation of heating elements at the lower end and spray nozzles at the top. Surge line connection is also shown at the top (surge line itself is not shown).

The primary circuit components have now been defined. They are combined into the proposed two-loop configuration and shown in Figure 21.

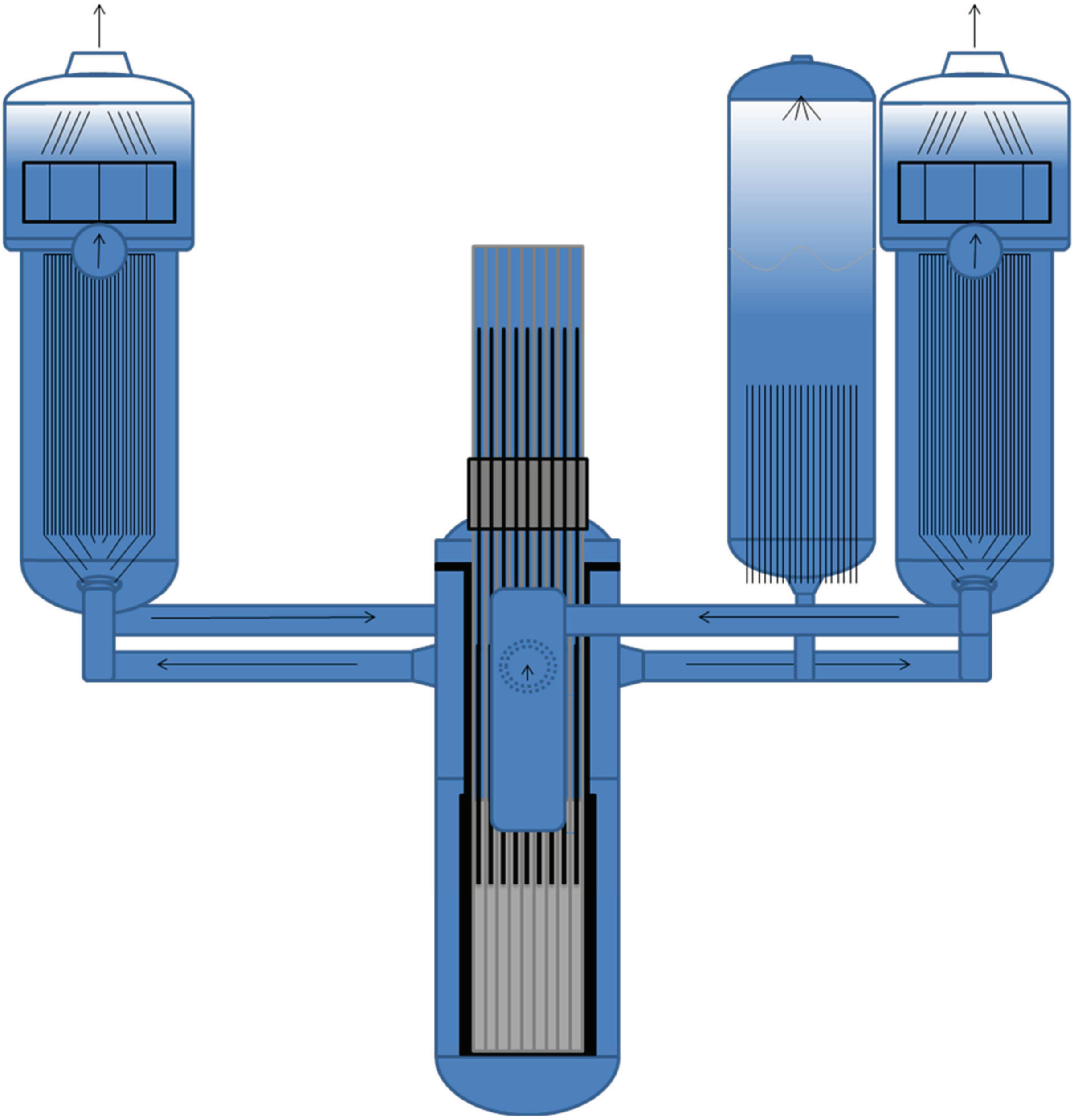

Figure 21. Primary circuit schematic. Pumps are shown in front and behind of RPV. Steam-generators (SG's) are far left and far right. CRDM system is mounted above RPV integrated into pressure vessel head package. Pressuriser with heating elements is shown between RPV and right side SG. Base of RPV to top of SG/Pressuriser is ~18m.

5.4. *Tertiary Circuit and Ultimate Heat Sink*

The enthalpy change (Δh) in the condenser is 2250 – 251 = 1999 kJ/kg

(11) $$q = \dot{m}\Delta h$$

Assuming 10% efficiency losses and 10% isentropic losses the total waste heat left to 'dump' can be calculated as:
$q = 735 - 239 = 496MW_{Th}$
therefore; the minimum mass flow rate required in the tertiary circuit to remove this heat can be calculated and is determined to be, $\dot{m} = 248kg/s$.

Target is set of less than 12.5°C heating of tertiary circuit inlet to outlet water, based on UK Environmental Agency figures (Turnpenny et al., 2010). Assuming a worst case 'hot' inlet temperature of 18 °C and outlet at 30 °C, Δh = 75kJ/kg

Using equation 11 and assuming conservation of power, the required mass flow rate ($\dot{m}$) in the tertiary circuit = ~6610kg/s or 6.6m^3/s (~23,700m^3/hr)

Environment Agency quotes the following values (Turnpenny et al., 2010):
EPR (1600MWe, 4590MWth) cooling water required is 72m^3/s
AP1000 (1100MWe, 3400MWth) cooling water required is 57 m^3/s

Four of the proposed reactors located on a single site (904MWe, 2940MWth) implies cooling water required is 27 m^3/s. However, this is absolute minimum. In reality it would be important to have the system producing significantly less than the maximum allowable temperature rise. Additionally, a safety margin would need to be engineered in order to avoid fouling issues and unforeseen circumstances. If both are taken into consideration, this brings the cooling water rate in line with the other reactors.

5.5. *Nuclear Island Plan*

Using the size of the primary circuit it is now possible to start to make judgements for the required size of containment.

The height of containment is dependent on the height required to remove the fuel from the reactor during shutdown. During this process the fuel must remain around 5 m underwater whilst being lifted out of the top of the pressure vessel. This implies that a polar crane must be positioned around 12 m (4.2 m fuel length + 5 m water + some margin) higher than the top of the RPV. This also allows clearance over the SGs. This is shown in Figure 22.

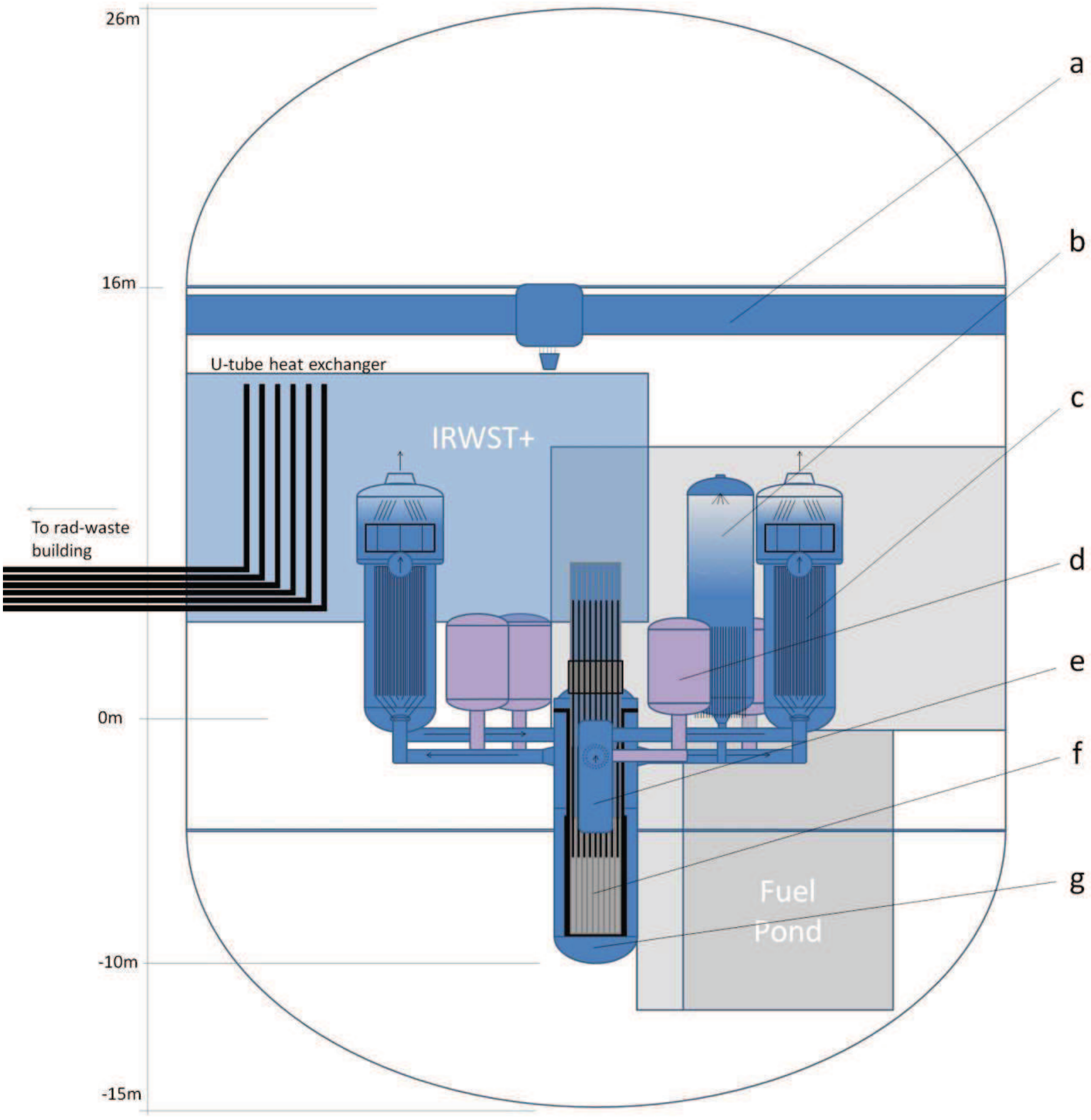

Figure 22. Schematic of the containment structure. Key provided in Table 18.

Table 18. Key to the letters shown in Figure 22 and Figure 23.

a	Polar crane
b	Pressuriser
c	Steam-generator
d	Accumulator
e	Reactor Coolant Pump
f	Reactor Core (fuel assemblies)
g	Reactor Pressure Vessel
h	Shielding Tank

In line with modern standards, the containment structure will be constructed from steel and is of a thickness sufficient to withstand the pressure caused by a LOCA and extended boiling of emergency cooling water. A pressure relief valve is required in the unlikely case of a containment overpressure scenario (to prevent explosive decompression). The containment structure is 'sunk' 15m into the ground to reduce the overall height and profile of the containment building. Even adding 5-10m to this to take account of the outer concrete impact protection structure the overall height comes to ~35m which compares favourably to the AP1000 (around 65m) (WEC, 2003) and EPR (63m) (AREVA, 2005). Safety features, such as the accumulators shown, are described in the following section. Figure 23 shows a top down view of the same structure which is ~28m diameter.

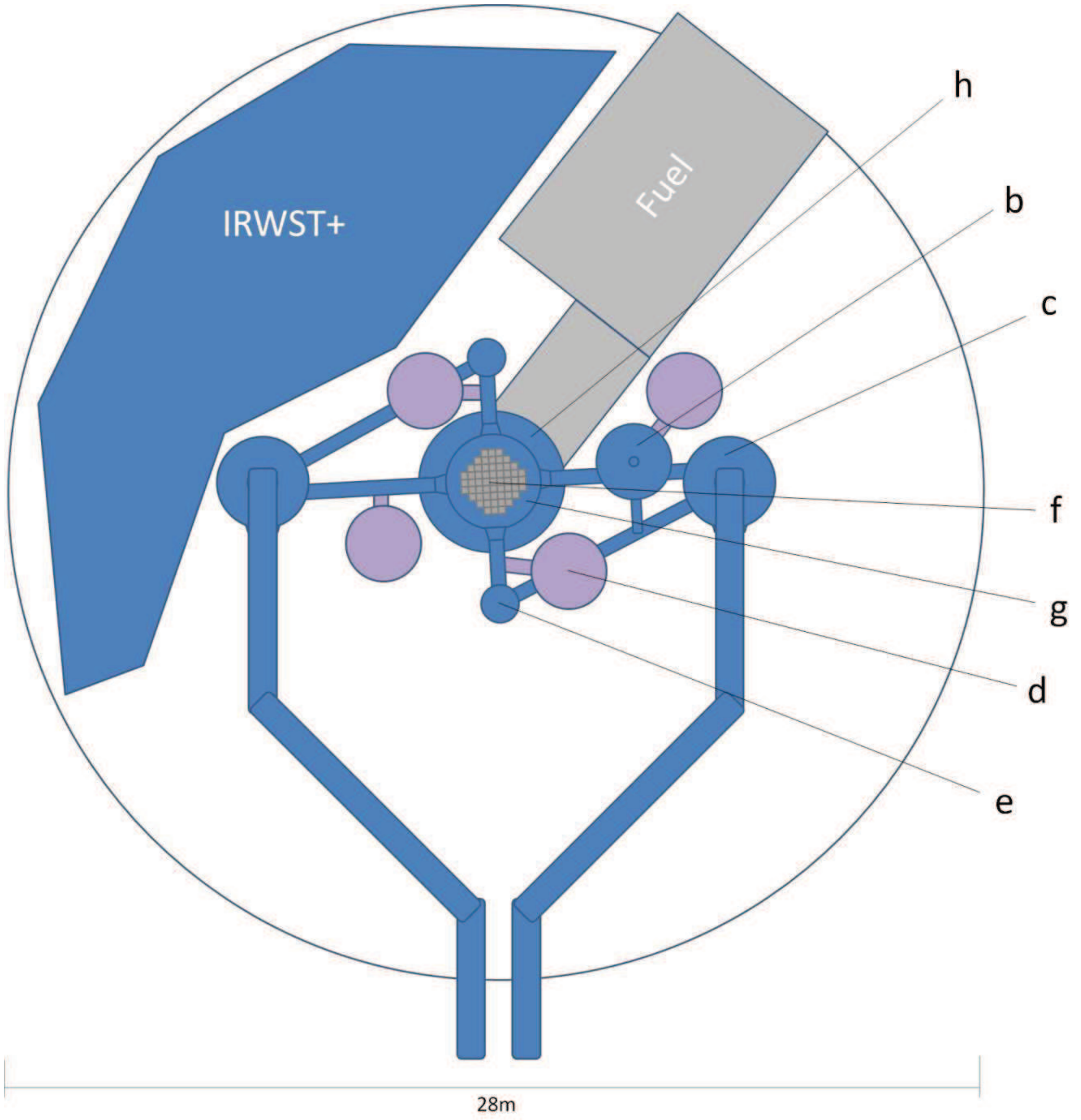

Figure 23. Top down primary circuit layout showing main steam lines exiting at the bottom. Grey area is fuel removal channel and interim storage pool. IRWST+ is shown along with accumulators (purple) (further description below).

The primary circuit is rotated by a few degrees to ensure both main steam lines are of the same length. This helps to ensure homogeneity in the secondary system. The grey area shown next to the RPV is a floodable fuel removal channel. The larger grey area is in-containment fuel storage pond. The outer blue annulus around the RPV is the shielding tank, a 1m annulus stainless steel plated tank containing boronated water which is intended to prevent gamma and neutron radiation from ‘leaking’ into containment.

A variety of additional structures are required to house the secondary side equipment, fuel handling area, waste treatment systems and backup/safety systems. These are shown in Figure 24.

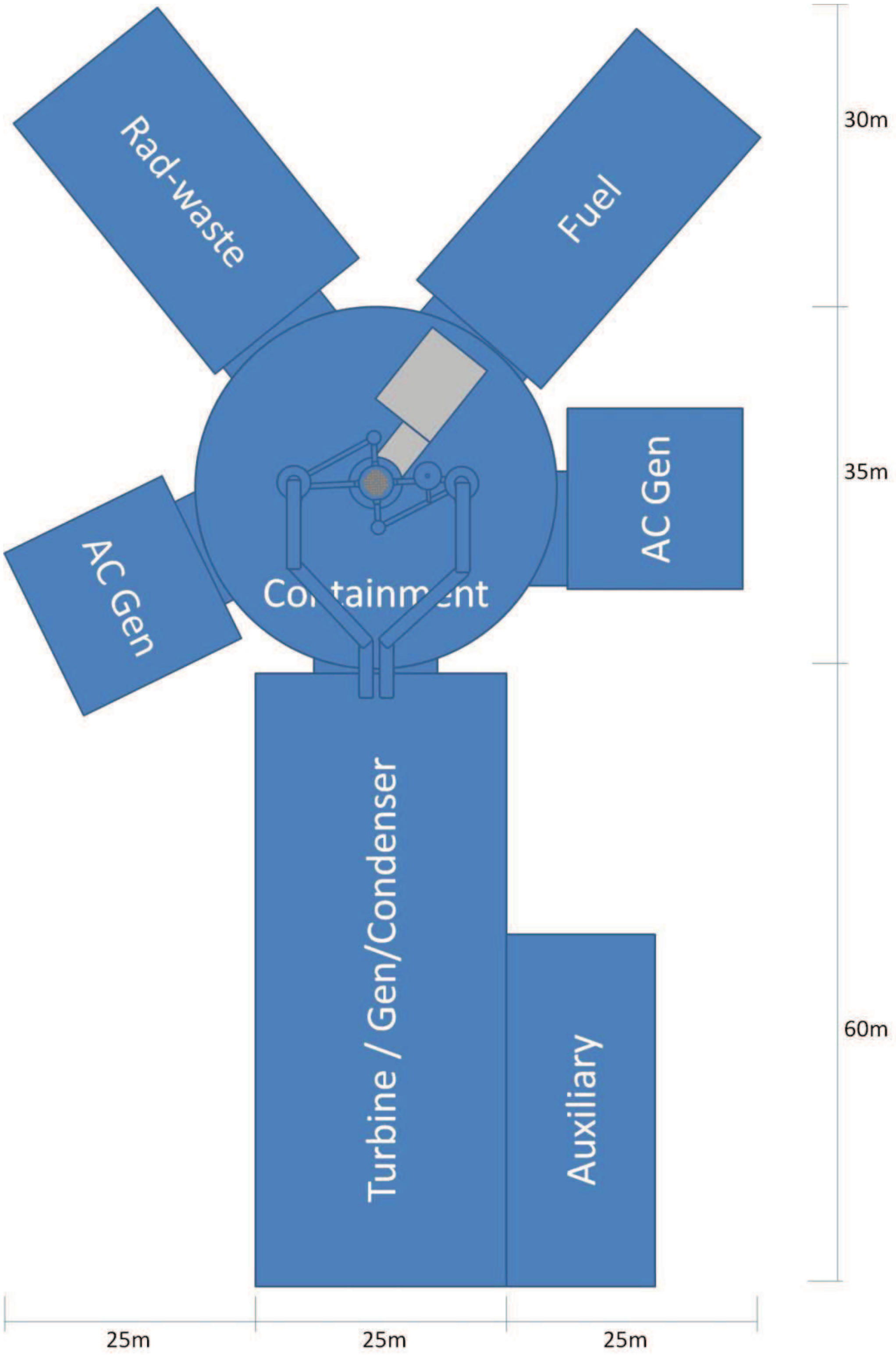

Figure 24. Overall top-down plant layout showing nuclear and non-nuclear structures.

The buildings are sized based on approximations of the space required to house a variety of auxiliary systems. Profile view is shown in Figure 25.

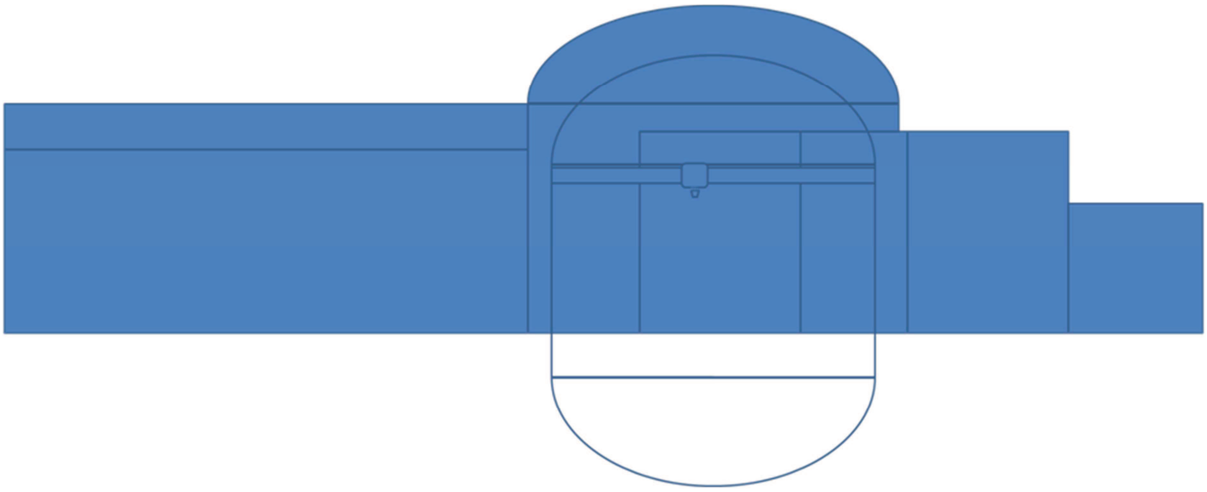

Figure 25. Profile view of plant layout.

The overall site layout for a single plant is around ¼ of the footprint of an AP1000 (WEC, 2003). This means that a 4 unit version of this plant could be placed on a site around 200m x 300m in size. There will be regulatory considerations to take into account when deploying multiple units at a single site. These vary from country to country but deal with similar logical issues such as maintaining access to plants if one or more of the units suffers from a radiological accident, alignment of rotating components such that a destructive accident does not cause collateral damage and provision of power and water to each plant and how the underground cabling and piping of these services is monitored and made resilient to natural hazards.

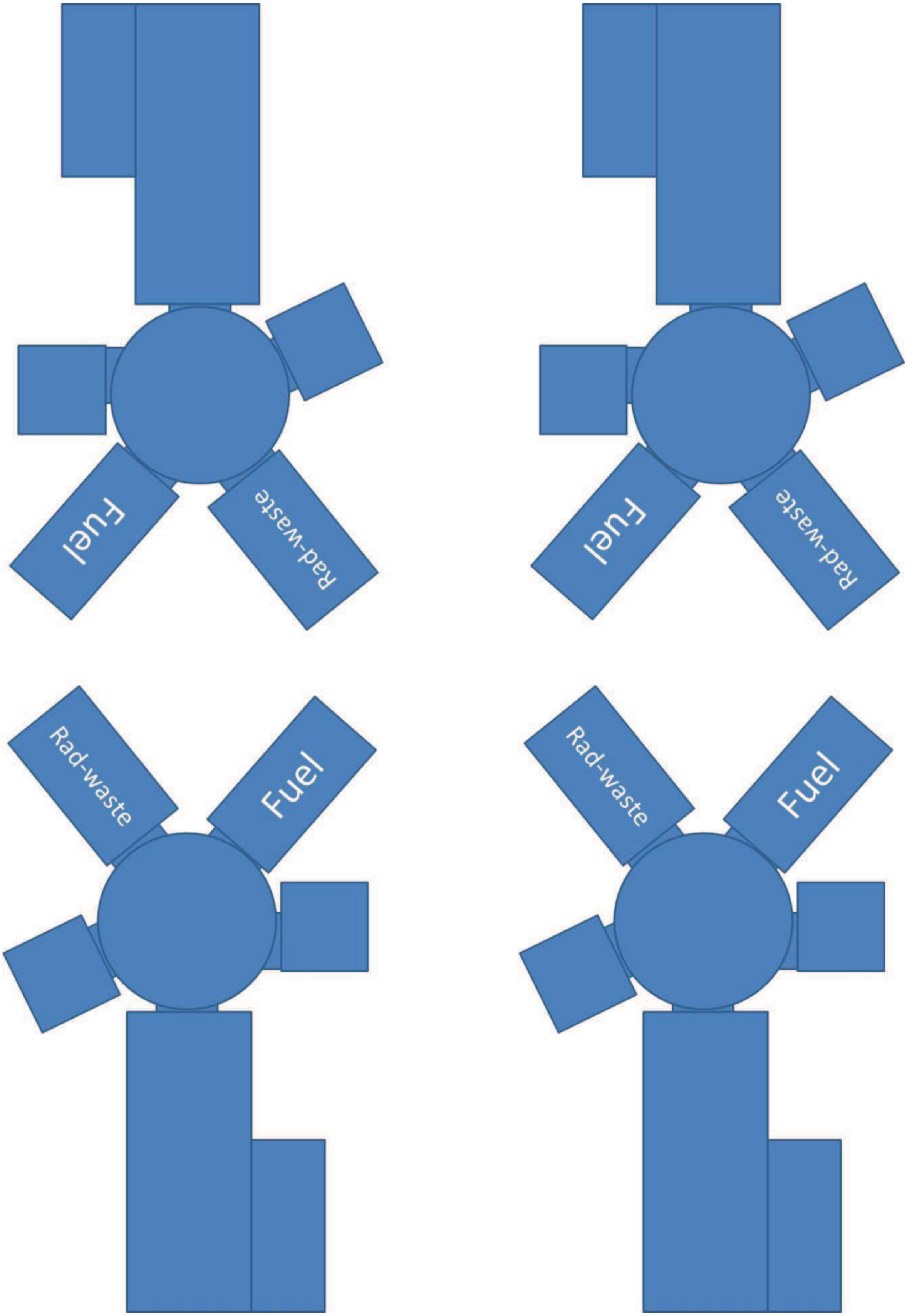

Figure 26. An example layout of a 4-unit (904MWe) plant.

The AP1000 fits onto a site around 250m x 233m. Comparatively, the proposed reactor produces 0.015 MW/m^2 and the AP1000 0.019 MW/m^2 (putting this reactor at about 83% of land utilisation). However, the AP1000 is almost twice the height of this reactor and therefore potentially has a substantially higher visual impact (WEC, 2003).

5.6. *Safety Systems*

For the purpose of this design exercise, two major accident types are considered; a large break loss of coolant accident (LOCA) and loss of off-site power (LOOP). A LOCA featuring a guillotine break of one of the hot-legs of the reactor is first considered. In this scenario, the primary circuit undergoes a rapid depressurisation during which the high-pressure liquid water first flashes to steam, with the remaining liquid water boiling off within the pressure vessel over a longer duration. Within this scenario it is imperative to continue to provide a source of coolant to the reactor core, as even with the control rods fully inserted and reactivity reduced to zero, residual core heat is significant. Equation 12 below (from Todreas and Kazimi (1990)) shows the relative decay power level after a period of time $T_{elapsed}$ has passed following shutdown assuming a reactor has been running for a given period of time, $T_{startup}$.

$$\frac{P}{P_0} = 0.066\left[T_{elapsed}{}^{-0.2} - \left(T_{startup} + T_{elapsed}\right)^{-0.2}\right] \quad (12)$$

Assuming $T_{startup} >> T_{elapsed}$, i.e. $T_{startup}$ = 1 year then Table 19 shows the approximate power levels remaining after a given amount of time.

Table 19. Power level remaining after a given amount of time calculated using equation (11) and associated assumptions.

Time since shutdown	Residual heat power level (approx)	Equivalent Power (approx)
1 s	6.3%	46 MWth
10 s	3.8%	28 MWth
12 hours	0.6%	4.5 MWth
1 day	0.4%	3 MWth

5.6.1. Hot Leg LOCA event sequence

T = -1 s

Power = 735 MWth

Initial pipe break, accessible liquid depressurises and flashes to steam. Assuming isenthalpic (adiabatic) flash the relative expansion can be calculated by using the appropriate relative enthalpies as shown in equation 13 (Zemansky & Dittman, 1997):

$$x = 100 \times \left[\frac{({H_u}^l - {H_d}^l)}{({H_d}^v - {H_u}^l)}\right] \quad (13)$$

${H_u}^l$= Upstream liquid enthalpy
${H_d}^l$= Downstream liquid enthalpy
${H_d}^v$= Downstream vapour enthalpy

Inputting the values for the proposed system leads to x = 46% I.e. 46% of the primary circuit immediately (almost) flashes to steam.

T = 0 s

Power = 735 MWth

Pumps shutdown, control rods inserted, (full reactor SCRAM). The shutdown of the primary circuit pumps is not necessary for safety reasons but does prevent undue damage to them caused by 'sucking' on steam rather than liquid water.

Primary circuit pressure and temperature is at hot-leg state, T_H = 320 ^{o}C (Pressure approximately 12 MPa) but quickly reducing.

T = 1 s

Power = 46 MWth

Primary circuit pressure falls to the saturation pressure of steam at T_c = 290^{o}C (Pressure approximately 8 MPa) as the hot legs are now empty. Temperature and pressure are still falling rapidly.

Initially, water in the RPV and SG inlet will flash to steam (as it is closest to the break). This can lead to the core in the RPV being partially (or fully) uncovered, or being covered by a wet, water/steam foamy mixture.

At this stage accumulators are used to provide additional water. Accumulators are at primary circuit pressure and containment temperature, and have pressure differential valves which release once primary circuit pressure drops. It is important to ensure that sufficient water can be provided and that this provision of water is not dependant on the integrity of all 4 inlet/outlet pipes. To this end, four accumulator tanks are positioned, one located on each inlet and outlet pipe, to provide additional water in the event of a LOCA (Figure 22). The amount of emergency coolant available in these tanks is calculated below.

Assuming primary circuit volume is 118.5 m^3 then 46% of this is 54.5 m^3. 4 x 20 m^3 tanks guarantees that 3 x 20 m^3 will be injected into the core, meaning 60m^3 of water is injected during a single leg large break LOCA. This ensures that in the short term, there is sufficient cooling water available to keep the core covered.

T = 10 s
Power = 28 MWth
Primary circuit pressure is now equalised with containment. Water temperature 100 ^oC
Volume of the primary circuit inventory is (very conservatively) around 50 m^3 and this is boiling rapidly. To prevent the core becoming uncovered the time taken to boil off water above core is key. The mass of water above the core and below the outlet pipe is calculated from the geometry in Figure 27.

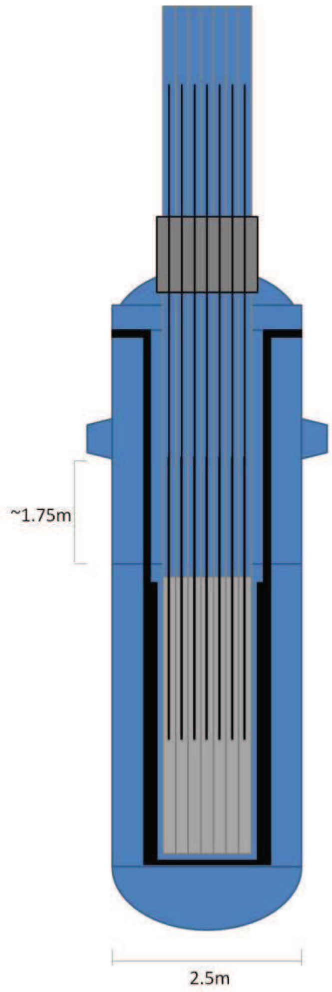

Figure 27. Dimensions of water above core and below outlet pipes.

Volume of water = 8.6 m^3, Mass of water = $8.6\text{x}10^3$ kg

The power required to vaporise this water in 1 second is equal to the latent heat of vaporisation multiplied by the mass of water:

$P_v= 2257\text{x}10^3 \text{ x } 8.6\text{x}10^3 = 1.94\text{x}10^{10}$ W

$P_{T=10s} = 25\text{x}10^6$ W, therefore 693 seconds of time must pass at this level of power to uncover the core. Or alternatively this can be expressed as $0.012m^3/s$ water lost as steam. If this state persists for 12hrs, then $475m^3$ of water is required.

The area required to be flooded during a refuelling operation (Figure 23) is 22m deep x 6m wide x 6m long (fuel pond end), 22m deep x 3m wide x 4m long (between core and pond) and 11m deep x 3m wide x 3m long above RPV. Minus the fuel pond volume of 11m x 6m x 6m.

The in-containment water storage tank (IRWST) required in order to fill this volume during refuelling must therefore be a minimum of 759m^3 in size. This is ~1.6 times the volume required for the 10s-12hrs cooling phase. Therefore gravity fed IRSWT injection can be used to 'top-up' the RPV during this phase. In actuality, the IRWST+ is designed to be larger, 1000m^3, to ensure that 250m^3 of water remains in the IRWST during refuelling, this is used as the normal operation residual heat removal system (the dark lines and u-tube heat exchanger shown to the left of Figure 22).

Water is evaporated to the top of the containment structure at which point it condenses on the cool steel shell. It then falls back down where it is collected around the RPV, using an annular trough around the inside of containment at a height level with the top of the steam-generators. Condensation mechanics suggest that the majority of condensing water will 'hug' the containment wall and flow down the insides of the shell, rather than 'raining' down (although 'rain' may take place in the centre of the dome). This mechanism allows water to be recycled into the IRWST+, further increasing the volume of water available to cool the core.

T = 12 hrs
Power = 4.5 MWth

Rate of water boil-off is now reduced to 1.9x10^{-3} m^3/s (approximately 15% of previous state). A final, 'hands-off' solution is required for residual heat removal from the containment structure itself, which has been accumulating heat for the duration of the time passed so far.

A passive solution at this stage is preferred, as thus far no operator intervention has been required. To date, the only plant to offer a fully passive solution is the AP1000 which uses its containment shell in combination with an external water 'drip' to transfer heat to the atmosphere. As this reactor is much smaller, and therefore of lower power, a passive solution which relies purely on air cooling is proposed by the author and investigated.

5.6.2. Passive Cooling

Figure 28 shows the newly proposed passive air cooling mechanism. The outer wall of the containment top dome section will be finned (much like the heatsink on a computer processor). Heat build-up at the top of containment will heat the mass of air in the middle 'chimney' section of the outer impact protection structure. This hot air mass will rise, 'sucking' air up from the side wall areas and through vents at the lower wall level. The gap between the side wall and containment shell is narrowed at the mid-sides of the containment shell which promotes a faster flow of air (Bernoulli principle) which aids in the cooling process.

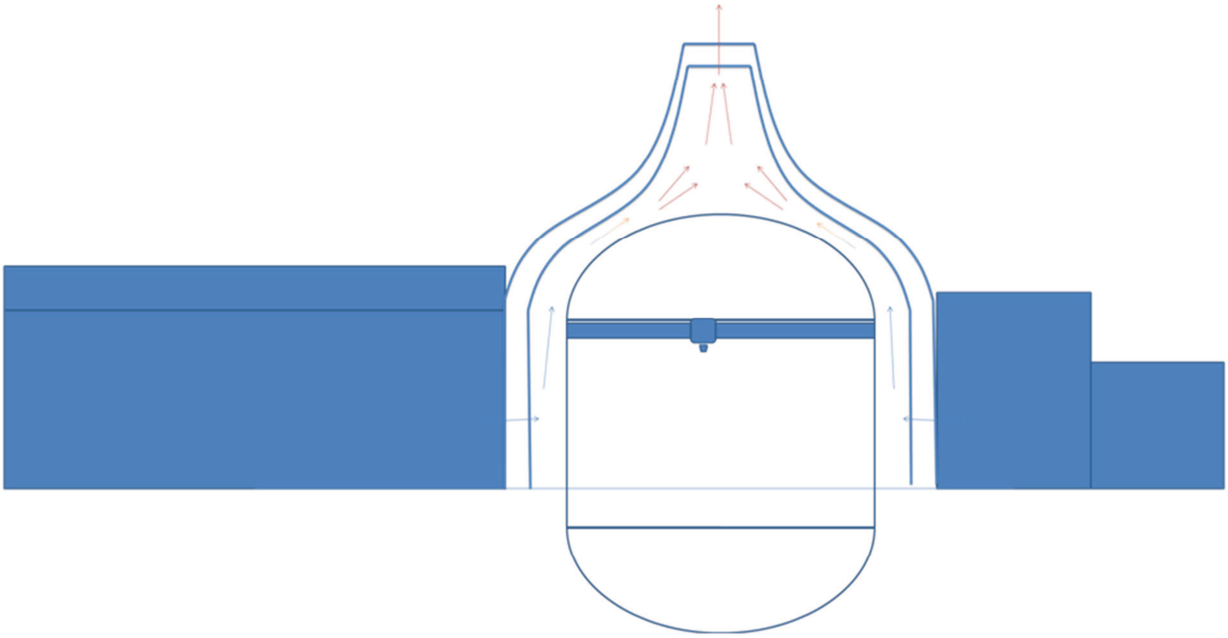

Figure 28. Side profile schematic showing proposed passive air cooling flow.

Calculating the heat transfer viability is complex and this document will only attempt to demonstrate basic process feasibility. At constant pressure, enthalpy (h) is determined in equation 14 (Zemansky and Dittman, 1997):

(14) $$h = c_{pa} + \chi([c_{pw}t] + h_{we})$$

c_{pa} = specific heat of air = 1.006kJ/kg

t = temperature

χ = vapour mass ratio in air = 0.0203kg/kg at 100% humidity

c_{pw} = specific heat of water vapour = 1.84kJ/kg at saturation

h_{we} = evaporation heat of water = 2501 kJ/kg

A 'worst-case' scenario exists whereby the ambient air temperature is very hot and also contains very little moisture. This does occur naturally in some places in the world, for example Riyadh (and surrounding areas) in Saudi Arabia have a record temperature of 52°C and humidity can be as low as 5% (NOAA, 2003). This example system is shown in Figure 29.

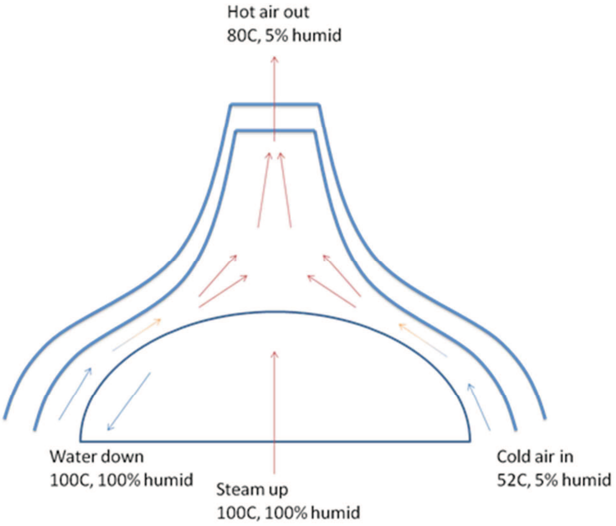

Figure 29. Passive cooling system setup

Δh_e = enthalpy difference between external cold air in and hot air out

Δh_i = enthalpy difference between internal hot steam up and hot water down

Using equation (13): Δh_e = 1.058 kJ/kg

From steam tables : Δh_i = 2257 kJ/kg

From earlier calculations on boiling rate we know that mass flow rate on inside is 1.3kg/s. Therefore we require 2773 kg/s air flow on outside (~2300 m^3/s). This would be difficult to achieve.

It would be easier to improve the heat transfer coefficient by (for example) adding water to the outer surface of the dome. This is how the Westinghouse AP1000 achieves this type of passive cooling (WEC, 2003). Also, in more humid environments the issue would be much less severe but this fact does not lend itself to a nuclear safety case for regulatory approval.

5.6.3. Active cooling system

Alternatively, a low power active system can be used. This is shown in Figure 30. The U-tube heat exchange tubes protrude from the IRWST into the top of the containment dome. As they are cold they promote condensation and allow steam which is accumulating in the dome to return to the IRWST as water, ready to be fed back into the primary circuit.

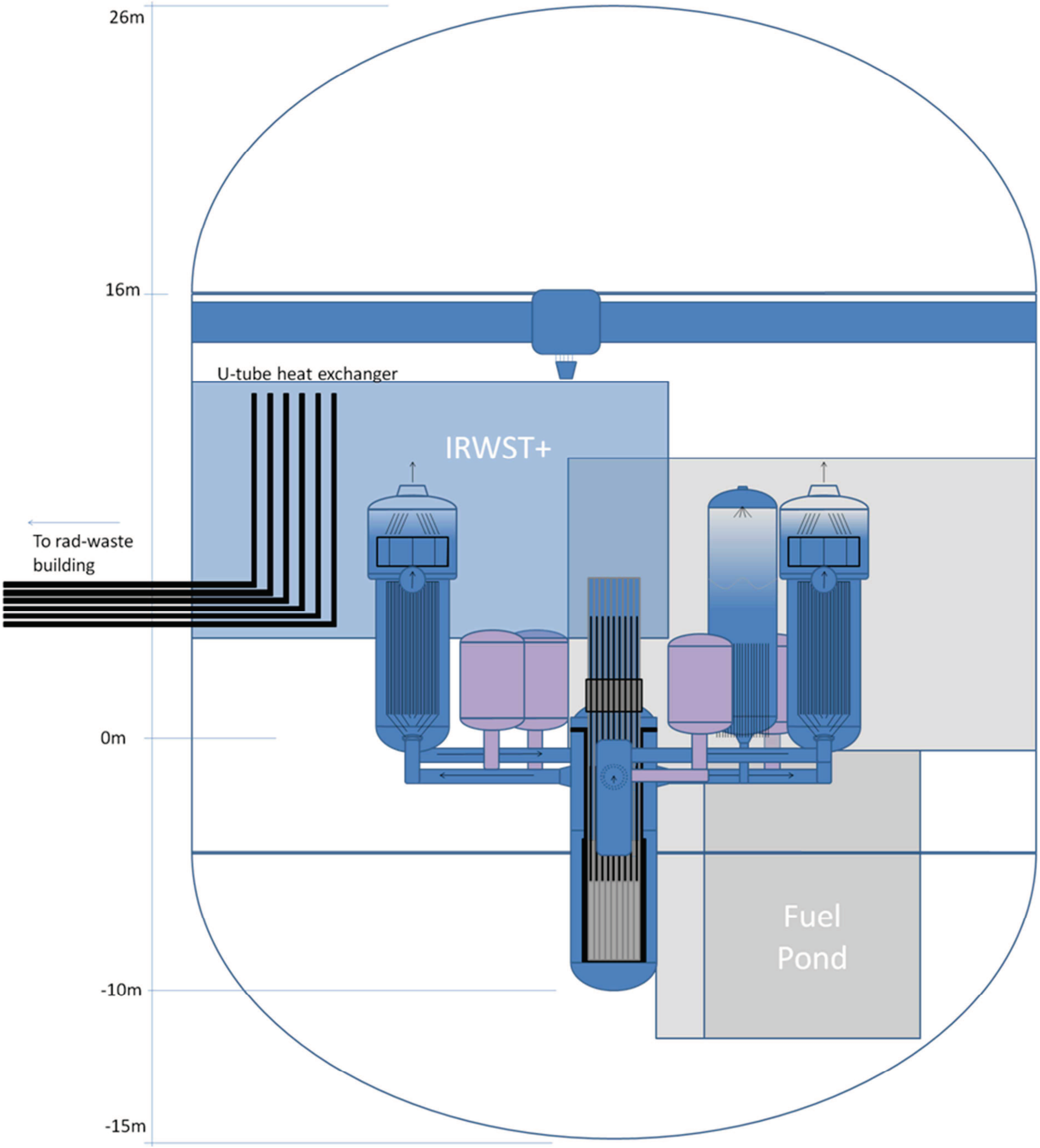

Figure 30. Active residual heat removal system. Accumulators (passive) are shown as pink. Values on the left side are height in relation to ground level.

A relatively low power pump is required for this residual heat removal loop. This loop ultimately dumps heat to the ultimate heat sink of choice at the site (sea or cooling towers). Alternatively, both passive and active solutions could be incorporated to provide additional buffer time (before off-site help can be applied) and defence in depth. Even with failure of this active residual heat removal system, the passive in-containment recirculation would be sufficient to cool the core for several days.

5.6.4. LOOP

In the case of a loss of off-site power (LOOP), there are two hardened buildings, either side of the containment structure (Figure 25) which each contain a gas-turbine (GT) generator set rated at around 4 MWe (at ambient temperature $T=\sim20^{o}C$).

When off-site power is lost the control rods immediately drop (by gravity), and the generator sets are started (this takes around 45 seconds) [calculations show that this is time taken to transform approximately 1% of primary circuit water into steam]. These generator sets are then able to provide backup power for emergency (reduced) instrumentation and control and the residual heat removal (RHR) system.

The GT generator sets and fuel are seismically mounted (earthquake resilient) around 15m above ground level. This provides a measure of protection against flooding and earthquake damage. Conventional backup diesel generators would need to be mounted on the ground as they are much heavier.

5.7. Steam-Generator Replacement

Steam generators tend to last around 30 years before needing replacement. If the plant is designed to last 60 years this means provision must be made to swap the steam generators. Figure 31 below shows how this would happen with this plant.

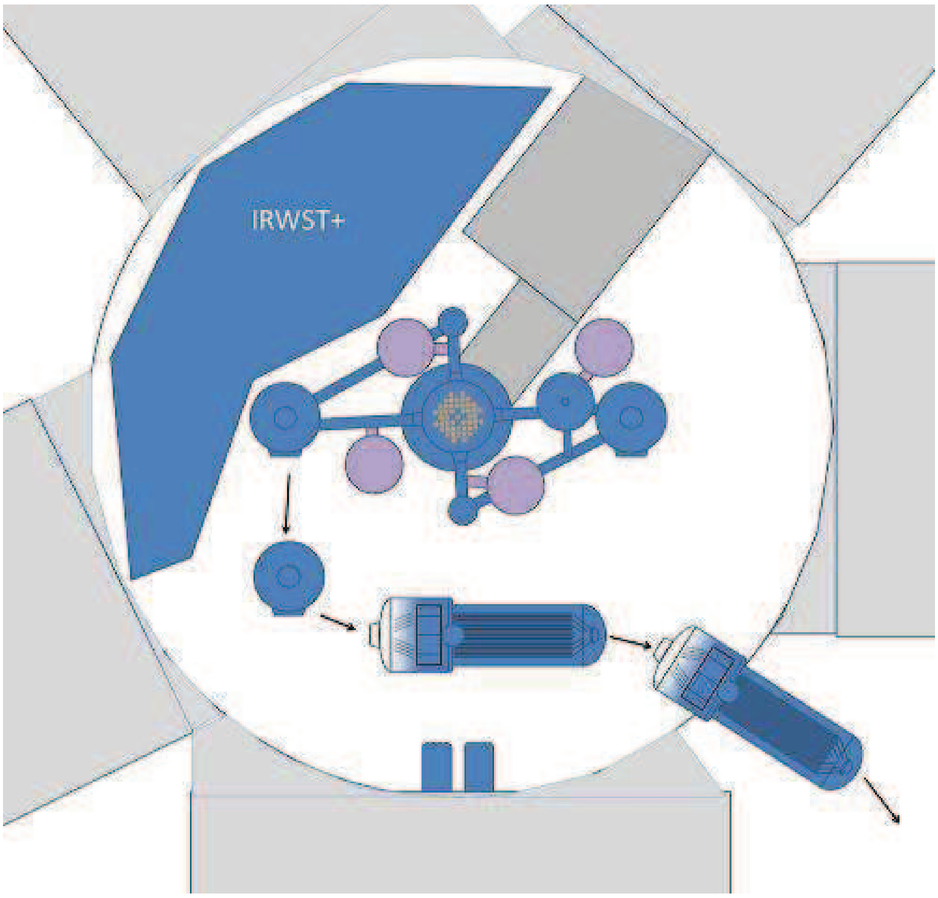

Figure 31. Showing route for removal of one of the two steam-generators. The plant benefits from the fact that both steam generators can be replaced without high-lifts over other components.

In this plant design, the base of the steam generators is actually 2 m below ground level. This means that they can be lifted laterally, rotated onto their side, and then lowered onto a trolley and then wheeled outside. Once outside, the trolley is drawn up a ramp by a tractor unit and the steam generator can be transported away from site.

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6. Commercial and Industrial Impact

6.1. Introduction

This section of the thesis is focussed on explaining the impact that the research project might have on both the industrial sponsor company, Rolls-Royce Plc, and the nuclear industry as a whole.

In spite of the Fukushima disaster, there remains some optimism that nuclear power generation will experience world-wide growth in the coming 20-50 years. Currently, there are over 60 reactors undergoing construction globally. Many are located in Asia (and in particular in China). The International Energy Agency (IEA), a division of the Organisation for Economic Co-operation and Development (OECD), analyses existing and future energy policy in its annual publication, 'World Energy Outlook' (IEA, 2011). In the 2011 World Energy Outlook, the IEA downgraded its New Policies Scenario (which is based on what will happen if countries carry through their future energy policy plans) from a 90% increase in nuclear power generation to a 60% increase, with much of the estimated increases being realised in countries outside of the OECD (mainly in China and the rest of Asia). However, not every observer is positive. Some critics point to the potential lack of Uranium to fuel such a large expansion of reactors, the inability of the nuclear industry to meet ambitious new build proposals and the calculations used to determine the real contribution made by nuclear energy to abate global warming (Guidolin and Guseo, 2012).

As a British based company, the first market for Rolls-Royce to exploit is its home market. The UK faces an upcoming 'energy gap' (as previously discussed in Section 2). This, combined with recent energy policy (DECC, 2012) put forward by the UK's coalition government makes it likely that some new nuclear power plants will be built in the UK in the next 10-15 years. At the time of writing, only one formal nuclear site license application has been submitted and granted in relation to new build in the UK. This was submitted by NNB GenCo (a subsidiary of the French utility EdF) who propose the construction of two Areva EPR units at the Hinckley Point site on the Bristol Channel (WNA, 2012c). The application was approved and license granted by the Office for

Nuclear Regulation (ONR), the UK's independent nuclear regulator, in late November 2012 (ONR, 2012). It is also likely that NNB GenCo will also submit a site license application to construct additional EPR units at the Sizewell site in Suffolk. Construction of reactors at the Hinckley Point site is now solely dependent on a financial decision to be made by NNB GenCo on whether to invest in the project. In turn, this investment decision depends on agreement of a 'strike-price' for nuclear electricity to be agreed between NNB GenCo and the UK Government. At the time of writing negotiations are on-going with no date for a final decision declared.

Horizon, a joint venture between German utilities RWe and EoN, had planned to build several new plants at both the Oldbury and Wylfa sites (WNA, 2012c). However, in 2011 Horizon's new build programmes were put on hold when RWe and EoN decided to exit nuclear new build and put the joint venture up for sale. In October 2012 it was announced that Hitachi had bought Horizon in a deal worth around £700m. Hitachi plan to bring their Advanced Boiling Water Reactor (ABWR) technology to the UK and construct plants at both Olbury and Wylfa; building up Horizon to be the owner/operator of the plants over time.

Finally, NuGeneration, a joint venture between Iberdrola and GdF Suez, plan on constructing two or three plants at the Sellafield site in West Cumbria. NuGeneration have yet to commit to a particular plant design.

6.2. Rolls-Royce Civil Nuclear

For over 50 years, Rolls-Royce has been active in providing nuclear power solutions to the UK's Royal Navy for use on its submarines. More recently, Rolls-Royce has decided to utilise its nuclear expertise in an expansion of its work on civilian nuclear power. Rolls-Royce civil nuclear activities are divided into three business units (as shown in Figure 32); Instrumentation and Control, Nuclear Services, and New Build Delivery (NBD). Instrumentation and Control and Nuclear Services are both mature business areas with a global presence. NBD is a new business which has grown organically since 2008. NBD aims to become a global leader in the manufacturing of high integrity nuclear components and a provider of internationally leading nuclear engineering support services. NBD has built relationships with many of the world's leading nuclear reactor vendors including Areva, Westinghouse, Rosatom and GE Hitachi. This has resulted in the business being involved in the signing of high-level working agreements and memorandums of understanding; for example, Prime-minister David Cameron and former French President Nicolas Sarkozy signing an accord on civil nuclear cooperation in February 2012 (BBC News, 2012).

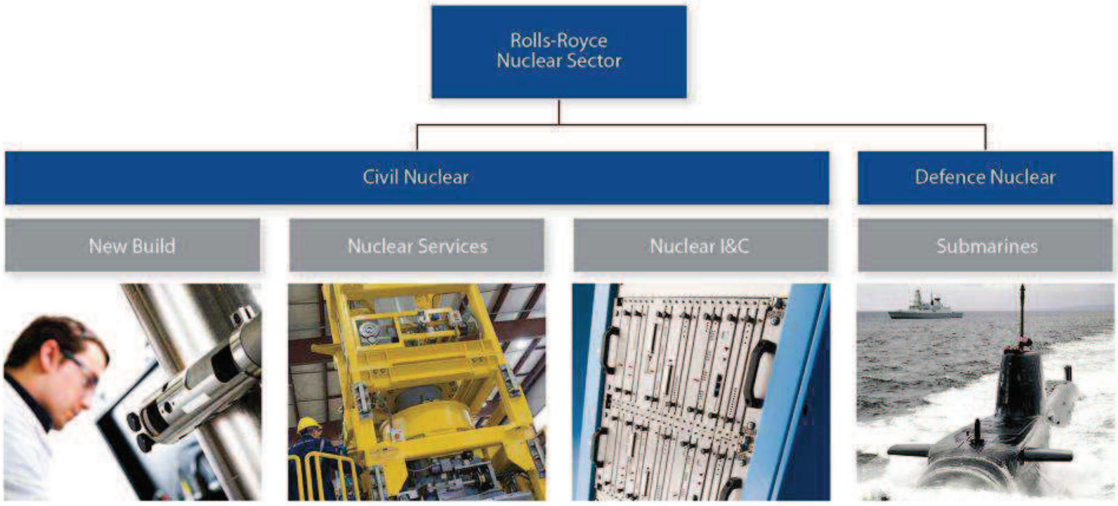

Figure 32. Breakdown showing the businesses that form the Rolls-Royce Nuclear Sector. New Build Delivery is shown alongside the Nuclear Services and Nuclear Instrumentation and Control businesses. (Figure courtesy of Rolls-Royce Nuclear)

NBD comprises around 100 members of staff. A significant proportion of this 100 are engineers, but other members of staff are employed in project management, business management, accounting and executive management roles. Human Resources, IT and other similar functions are centralised as part of the larger Rolls-Royce corporate structure. As a new and developing business unit, NBD was initially funded via the provision internal corporate funding. As time has passed, the burden of funding has transitioned from internal funding to external funding; through growth in work paid for by customers.

A major challenge for the nuclear industry in the UK is recruiting staff, both engineers and business related, who are suitably qualified and experienced. Cogent, the nuclear skills council, identified a shortage in the number of qualified 'nuclear' personal in its 'Power People' report of 2009 (Cogent, 2009) which largely results from an ageing workforce and a period of low industry recruitment during the 1990's and early 2000's. This shortage has constrained the NBD's ability to recruit new staff; as it has constrained every nuclear company for the last 15 years. Rolls-Royce does have the advantage that it can recruit from its internal talent pool, which is considerable. This is an on-going challenge that the business continues to address via training and development programmes.

The structure of the NBD organisation has evolved organically as the business has grown from around 20 employees in 2008 to over 100 in 2012. The business is located over three geographically separate sites, which increased the challenge of growing the business efficiently whilst maintaining lines of communication and responsibility. Monthly teleconference NBD briefings, instituted in 2011, are an example of how a direct line of two-way communication between management and workforce can be maintained successfully in these circumstances. These briefings also allow all teams within the NBD business to understand how the rest of the business is performing.

This research project was carried out whilst the author was based in the Civil Nuclear Advanced Concepts Team (ACT). For operational reasons, this team is based within the NBD division of Rolls-Royce Nuclear although its remit is much broader than components and services for new build. The ACT is responsible for new product and technology development across the full spectrum of civil nuclear applications including modelling and simulation, reactor design, component design and equipment to facilitate Nuclear Services. The work on-going within the ACT is intended for deployment anywhere between 1 and 10 years into the future. Being based in a forward looking, longer term development team has assisted with the execution of this research, which was always likely to have more long term impacts than shorter term ones.

The ACT pursues technology development based on both 'push' and 'pull' strategies. Pull comes from customer enquiries and develops from the existing and potential customer relationships that the customer facing side of the business is involved in. Push is generated by assessing the state of global civil nuclear technology and determining areas and technologies which Rolls-Royce has the expertise, or potential expertise, to develop. Both push and pull strategies are informed by the building of a coherent business strategy which is itself informed by communication between Rolls-Royce and the wider nuclear industry. Coherence is brought, in part, via the use of road mapping (Phaal et al., 2004) activities. There are a variety of processes in place to ensure that work being completed by the ACT is disseminated to the rest of the Civil Nuclear business in a timely and appropriate manner. The overriding aim for the ACT is to pursue and patent new technologies that move NBD up the 'value pyramid', as shown in Figure 33, ultimately resulting in an enhanced product range which is high value to customers, high margin to NBD and poses a high barrier to entry for competitors. To do this, Rolls-Royce pursues a strategy that involves the generation of intellectual property in key technology areas, for example nuclear component manufacturing. Such a strategy promotes competitive advantage through improved quality, improved processes and maximised efficiency.

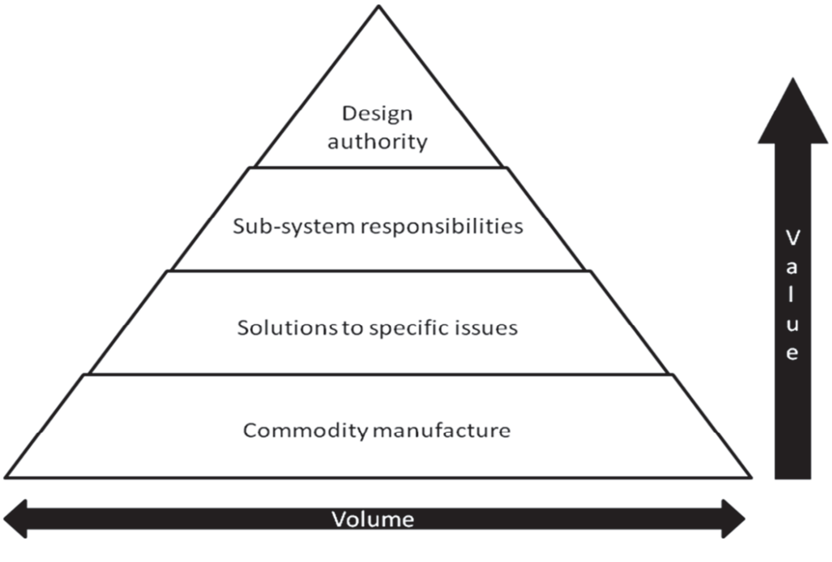

Figure 33. 'Value Pyramid' diagram showing the progression from basic commodity manufacture to plant design authority. Rolls-Royce has a desire to operate in the top sector of the pyramid; being involved in all aspects of design and manufacturing work.

Rolls-Royce also engages with the academic community through a network of University Technology Centres (UTC) that carry out joint research projects at the forefront of scientific development across a wide range of technical disciplines.

6.3. <u>The UK market opportunity</u>

Possible new build in the UK ranges from two to 13 new nuclear plants over the next 20 years, with each plant costing roughly £6 billion (at 2012 prices). The nuclear related components (also known as the nuclear island) are a minority part of the construction process, with earthworks and civil engineering dominating. However, the nuclear island incorporates many of the highest value components and is therefore attractive to companies interested in high-integrity manufacturing. Rolls-Royce Nuclear’s NBD business is aiming to capture a piece of that market for UK new build; worth at least several hundred million pounds and possibly several billion pounds. On a global level, over 60 reactors are currently under construction, with an additional 160 being planned (WNA, 2012a).

A significant risk to the continued growth of the NBD business in the UK is the timeframe for constructing the UK’s new nuclear plants. Negotiations between the energy utilities and the government over a ‘strike price’ for nuclear electricity and uncertainty surrounding the UK governments energy policy has led to concerns around the long term financial return on investment that investors in new nuclear plants would receive. In turn, this leads to uncertainty over when nuclear plants will be constructed. NBD continues to engage with its customers to ensure that once these issues are resolved it is in place to deliver the components and services it promises, on-time and to the highest levels of quality.

6.4. <u>Civil Nuclear growth strategy</u>

Rolls-Royce’s NBD business aims to be a global player involved in new build worldwide. In order to achieve this, NBD must build upon the existing reputation and credibility of the Rolls-Royce Nuclear brand, which has been producing nuclear reactors for submarines for 50 years. Starting in the UK, developing into Europe and then expanding beyond is the natural growth pattern for such an endeavour. However, as is the case with all good businesses, NBD closely monitors international developments so that if international opportunities present themselves it can capitalise on the skills and experience that the business possesses. This is particularly the case with engineering services and support operations, as they have significantly lower barriers to entry than hardware manufacture.

The geographical location of plants can limit the business opportunity available, as many nations will prefer their own indigenous suppliers to do the majority of the work (for economic and nationalistic reasons). However, there is still some scope for foreign investment, as organisations are usually keen to spread the risk burden of nuclear plant construction, which can be significant and run into billions of pounds. Any company looking to become involved in global nuclear new build must balance the desire to be involved and gain contracts with the inherent risk burden of new build. Large scale nuclear plant development is also a highly specialised industry, with stringent safety critical engineering goals. Experience and reputation play a significant role in earning sufficient trust to be awarded contracts for new build, with the majority of players in the marketplace having a long history in the industry. These factors can make entry into the market difficult. The lowest barrier to entry is in ones ‘home’ market, with manufacture for indigenous new build.

By fulfilling a significant role in the high-value components part of the nuclear island supply chain, the NBD business is able to maximise the amount of revenue generated whilst minimising its exposure to financial risk. Orders will only be received once the go-ahead for new plants has been granted, and therefore the risk of order cancellation is largely removed.

Beyond new build in the UK, NBD continues to develop links with reactor vendors and energy utilities around the world. These relationships are intended to allow the NBD business to gain contracts for manufacture for new build beyond the 2025 horizon for UK new build activities. As mentioned previously, the construction timeline for new nuclear plants is very long; it can take up to around 10 years to move from having a plan to actually carrying out work on the ground. It is therefore critically important that relationships between utility, vendor and supply chain are strong and maintained throughout this duration.

All facets of the new build scenario taking place in the UK at the moment that is described in this thesis are based on the construction of large nuclear plants, mainly of the light water reactor (LWR) type. This is likely to be the norm for the next 10-15 years. Beyond this, there are multiple disruptive technologies that may begin to have a significant impact on further new build. This includes small modular reactors (SMR), Generation IV reactors (such as those identified in the Generation IV International Forum (Generation IV International Forum, 2008)) and other approaches such as fast-breeder reactors and closed uranium/thorium fuel cycles (an approach being taken by India) (Kakodkar, 2002). Predicting which approaches will be successful at this stage is impossible, but every company engaged in the nuclear industry and associated supply chain needs to be abreast of developments so that they are in a position to be competitive as time passes and technology evolves. Partnering in research and development activities can assist in this process and Rolls-Royce Nuclear has close links with a number of academic organisations, in particular the University of Manchester and Imperial College London. Other research organisations such as National Nuclear Laboratories (NNL) Ltd and The Welding Institute (TWI) Ltd also provide research and development services that can complement in-house capabilities. Rolls-Royce's focus on high-value manufacturing and generating intellectual property can be used to place it in a position of competitive advantage if leveraged correctly in respect of these new technologies.

6.5. Impact within Rolls-Royce Civil Nuclear

The framework produced by this research is not of immediately deployable within Rolls-Royce Nuclear as the company is not currently a vendor of reactors for the civil nuclear market. However, the knowledge and expertise gained from researching this area has fed into a number of on-going projects that are focussed on sub-system and component design and has assisted in informing decision making on the direction taken in those projects. It has also helped to contextualise some of the external 'landscape' that civil nuclear finds itself within.

Following the presentation of the work contained in this thesis at conferences and events, contact has been made with a number of nuclear related companies and nuclear organisations who are interested in exploring how they might be able to apply the learning gained to their own activities. Such talks are currently in their early stages, but demonstrate that there is an appetite for understanding the issues discussed in this thesis and applying the learning gained within the nuclear industry.

An example of how this research has benefitted Rolls-Royce came in the wake of the Fukushima nuclear accident. The ACT produced a series of internal reports and updates after the Fukushima accident; to keep the business informed about on-going developments in Japan and the potential impact that different accident scenarios might have on the UK and global nuclear industry. A key part of assessing the impact of Fukushima was attempting to understand what the public reaction might be in different areas of the world and how this might influence changes to the nuclear industry and the market opportunities available to Rolls-Royce. Knowledge gained from this research project was able to directly contribute to this work.

Rolls-Royce has an on-going obligation to ensure that its activities are carried out to the highest ethical, moral and regulatory standards. An Environmental Advisory Board (EAB) meets regularly as a part of the corporate governance process to ensure that this takes place. As quoted on the Rolls-Royce website, the role of the EAB '*is to review and make recommendations on the environmental aspects of the company's activities, including business, product and operational strategies. Board members are drawn from academia and external organisations and are respected authorities in their fields*' (Rolls-Royce Plc, 2012). The work of this research project has been presented to the EAB and to the rest of the Civil Nuclear business as part of the continuing effort to fulfil these obligations.

Rolls-Royce has a wide-ranging suite of engineering processes that have been written and implemented to ensure the quality and integrity of the products that it manufactures. As part of the on-going evolution of these processes it is possible that the work presented in this thesis may be incorporated into nuclear specific (or even general) system design processes at a future date. It was not possible to achieve this during the timeframe of the project due to the immaturity of the framework until the end stages of the project and the time taken to integrate a new method into the processes.

6.6. Wider Potential Impact on the Nuclear Industry

The framework proposed by this project is significantly different to standard approaches to design that are currently in use in the nuclear industry. As discussed in Section 4, the principle impact that incorporating a public view of design might have is to increase the diversity of designs (particularly if groups of people in different geographical locations express a variety of views on nuclear design options). This increase in the diversity of designs would appear to counter the existing trend towards standardisation and single, larger, ‘one size fits all’ nuclear power plants.

Nuclear plant design has classically been an evolutionary process. Most current designs can trace their roots back to the origins of nuclear power. A ‘family tree’ of nuclear plant design evolution is shown in Figure 34.

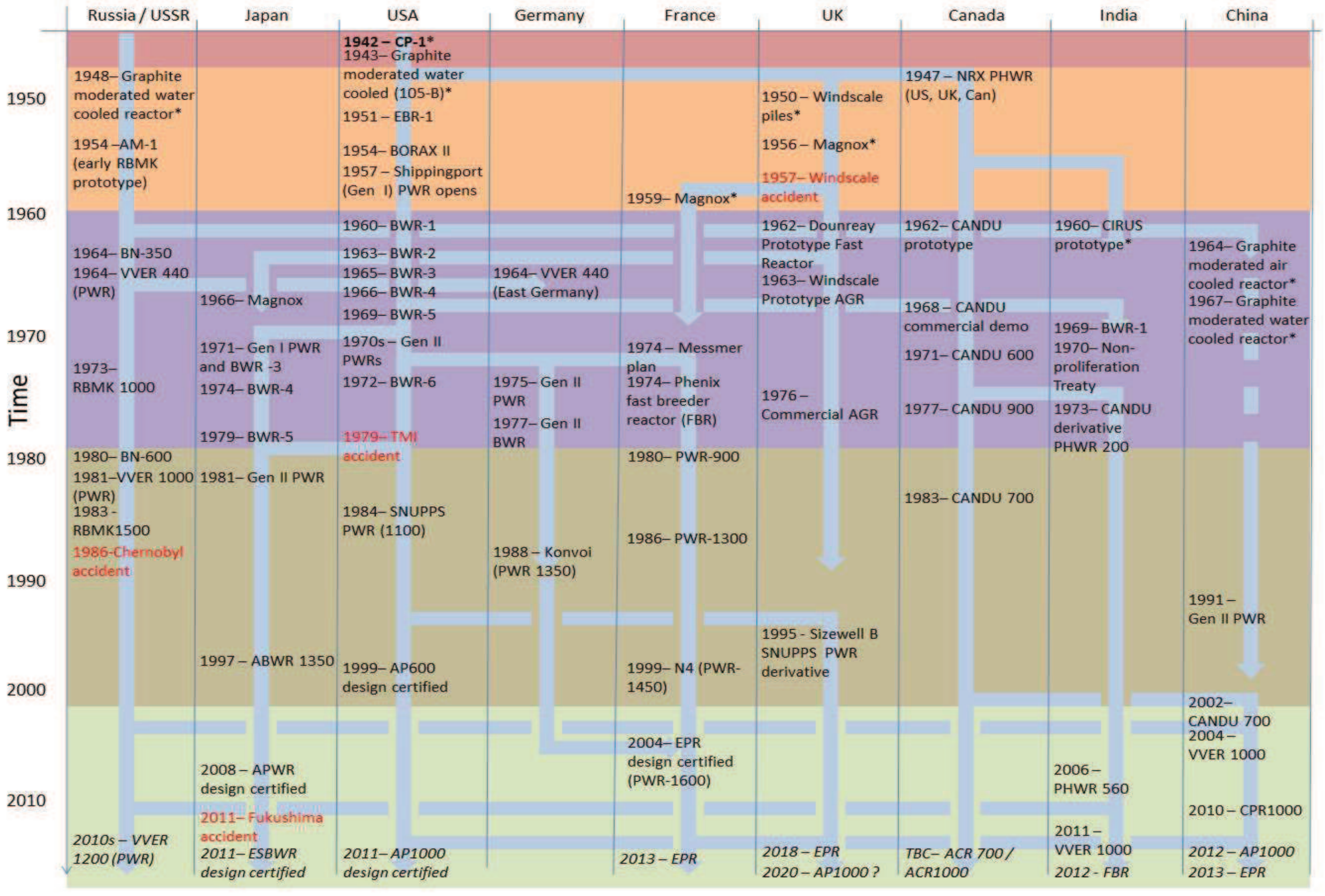

Figure 34. A combined lineage of nuclear power reactor design; dates shown are certification or commissioning date. Information sourced from (Char and Csik, 1987; NEI, 1997; Lamarsh and Baratta, 2001; Cummins et al., 2003; Bajaj and Gore, 2006; Nelson, 2008; AREVA, 2011; WNA, 2011; DOE, 2011; Wallenius, 2011; Candu Energy Inc., 2012)

As designs have evolved there has been a trend towards maximising the economy of scale of nuclear plants. This is most apparent in the design of AREVA's EPR which is the largest PWR to have been designed to date (AREVA, 2005). Such designs push manufacturing processes to their limit; only a handful of companies exist in the world with the capability to manufacture ring-forgings of the size required by the EPR, such as Japan Steelworks based in Muroran, Hokkaido (JSW, 2012). Whilst the theory of maximising the economy of physical plant scale is attractive, these manufacturing limits begin to reduce the economic benefits due to production capacity being reached. Single-sources for high value items also have the potential to drive premium pricing in the supply chain.

One solution to some of these 'large-scale' issues is to modularise sections of the nuclear plant so that they can be constructed separately in a factory environment and then assembled on location. Westinghouse are leading proponents of this approach, and their AP1000 is designed in a highly modular way (Cummins et al., 2003). AECL have also adopted modularised system design in an attempt to reduce the cost of their proposed ACR-700 reactor type (Torgerson, 1999). By simplifying construction, the time taken to construct the plant can be reduced. In turn, this reduces the capital cost of the plant. Modularisation of plant designs must be carefully optimised to gain the most benefit. Logic dictates that using too many small modules will increase the amount of time taken to build a plant, as the difficulty of managing the build sequence is increased. However, if properly leveraged, there is significant potential for cost savings from factory-based module production. However, factory-based production involves the capital cost of designing, building and commissioning a factory and this will have to be paid for over the course of the production lifetime of the factory. The return-on-investment of such a facility will depend on the demand for nuclear plant components and this may introduce uncertainties into the business case for the construction of such a factory. A way to reduce these uncertainties is to provide a strong service offering to customers using your components and systems. This can 'smooth out' the revenue stream between the peaks of plant-to-plant component manufacture.

A key point to note is that whilst every plant has a 'base' design, more often than not each plant of the same type that is constructed will differ slightly from its 'siblings'. This is often due to the geography of the different sites that the plants are located on, or differences in the regulatory system in different nations where the plants are constructed. Many existing nuclear plants are one of a kind, with differences between similar plants varying from minor to major. However, these differences are often significant enough to prevent learning gained from constructing and operating one plant being carried over to the others. This effect flows down through much of the supply chain. In turn, this means that ‘first of a kind’ (FOAK) costs are often recurrent with multiple similar plants, and often the savings that could be made from fleet deployment are lost.

There has been recognition within the nuclear industry that this situation must change in order to increase the economic competitiveness of nuclear power (Ingersoll, 2009; Carelli et al., 2010). Although entities such as CORDEL (WNA, 2012b) have been instituted to facilitate such change, and new designs such as that for the EPR and AP1000 are more standardised, the varied regulatory environment encountered in different nations precludes full global standardisation of plants at this time.

This prompts a question, ‘Is the proposed design framework, which logically results in a more diverse range of designs, compatible with the enduring goal of design standardisation?’ A solution may lie in standardisation of components and sub-systems which are then treated as discrete modules which can be interchanged as the system requirements vary site-by-site or nation-by-nation. This would result in a reactor vendor having a suite of standardised sub-systems and components that it could integrate together into different plant configurations to provide a range of solutions as required by customers and other stakeholders in different places. The standardised sub-systems and components could also then be manufactured in factories and transported to site as finished units (size permitting). This would also allow for continued adherence to the high integrity manufacturing approach required by nuclear codes such as the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Codes (section 3) (ASME, 2010) and RCC-M (Baylac and Grandemange, 1991); although some modification of construction and commissioning regulations might be required.

This approach lends itself particularly well to the production of fleets of smaller reactors. Rather than an economy of physical scale being exploited, the economy of production scale can be maximised. To exploit this economy of production scale, it is important that the reactor vendor has a mature supply chain in place with the required expertise (and confidence) to increase production capacity. Presumably, this would also have to take place in response to increased acceptance of SMR technology and demand for larger quantities of reactor plants to be constructed within years (rather than decades) of each other. Engendering this confidence prior to actually achieving these levels of production would be a significant challenge for the nuclear industry. An additional risk is posed by 'step-change' technologies, such as might occur with a transition to Generation IV sodium cooled fast reactors which would require similar but different components.

The demand for large numbers of smaller reactors is not a current 'pull' from energy utilities. In spite of renewed interest in building new nuclear plants, demand may never be high enough for large scale fleet production to be viable, regardless of reactor size. However, the concept of achieving this kind of scalable, modular, customisable nuclear fleet is not unprecedented if one looks at other complex products. Womack et al. (1990) described an evolution of this type in automotive manufacturing, as shown in Figure 35.

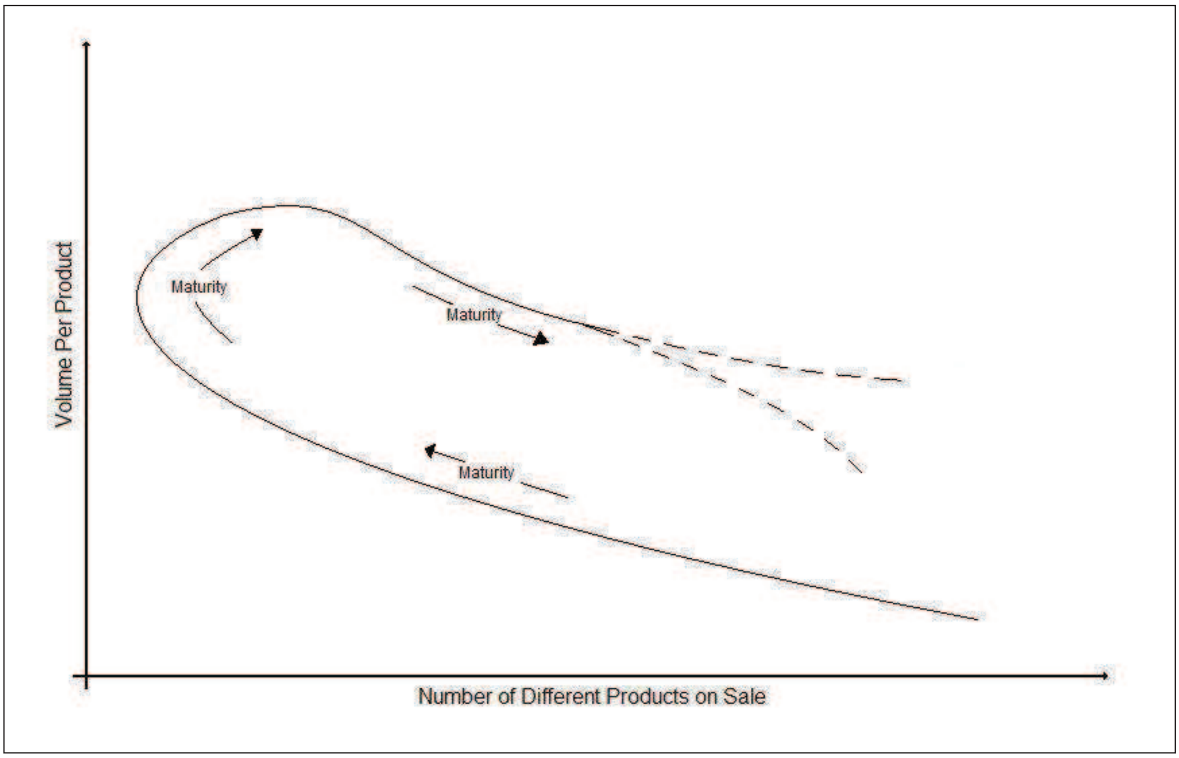

Figure 35. This figure demonstrates how a multitude of products in an emerging sector (lower right) are consolidated into fewer products as mass production becomes commonplace (left). As manufacturing techniques mature increased customisation results in a wider product range (centre top). In the future it may be possible to have cost-effective production of customised options (lower dashed line) or the level of customisation possible may plateau (upper dashed line). Adapted from Womack et al. (1990)

In the initial stages of the development of the automobile many different models were available, but in low quantities (many were one-off). As technology and production techniques were consolidated the range of cars available decreased but the quantities increased. This leads to the ‘turning-point’ shown on the graph which might be considered by using the example of the Model ‘T’ Ford, with the apocryphal quote; ‘you can have any colour so long as it is black’.

The turning point comes when components begin to be standardised across the whole industry, rather than simply within individual manufacturers. As this industry wide standardisation grows, the cost associated with assembling different combinations of the standard parts declines. Manufacturing techniques become standardised and shared learning is possible, reducing the level of defects and the time of manufacture. Outsourcing of component manufacture becomes more economic and more reliable.

These factors mean that higher volumes of customised product required can be manufactured at economically viable costs. In recent years in the automotive industry, consolidation of components has been extended to take place between different manufacturers who are competing against each other; an example of this is the Citroen C1, Toyota Aygo and Peugeot 107, which all share numerous components (Brondoni, 2008). It might seem fanciful to imagine a future where Areva, Westinghouse and Rosatom plants use identical steam-generators, turbines, or core-volume makeup systems (for example), but the same could likely have been said 15 years ago about the idea of three major car manufacturers sharing components and technology on competing products.

It is important to recognise that the current situation in automotive was not arrived at through a single unanimous choice to take this path. It evolved from market demands that required a diversity of product offerings which were safe, cost effective and provided a certain level of comfort and performance. Nor was the transmission smooth, the progress to this level of 'industrial maturity' (using the terminology of Womack et al. 1990) was made at the expense of a significant number of national and international manufacturers, who for various reasons could not compete effectively in the evolving marketplace.

The nuclear industry still has some way to go before standardisation of designs and regulations is achieved. It may be that achieving the levels of 'standardised customisation' discussed in this section may only be possible following such standardisation efforts, as was the case in the automotive industry. However, the potential benefits that a 'standardised customisation' approach might bring to the nuclear industry are significant and it is possible that certain aspects of plant design may be amenable to such an approach before complete standardisation is achieved. Further research is required to determine if this is the case.

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7. Future Work

7.1. Introduction

In this section future research and development opportunities will be discussed. Ten key areas have been identified for future research, covering three broad themes; refining and developing the method, understanding how to deploy the framework and understanding the impact that such deployment might cause. This is highlighted in Table 20, with each area being discussed in more depth in the remainder of this section. Rather than being full project proposals they should be read as initiators to inspire further work; both as academic research and industrial development.

Table 20. Proposed future research areas and themes.

<table>
<tr><th colspan="3">Future Research Area</th></tr>
<tr><th>Method</th><th>Deployment</th><th>Impact</th></tr>
<tr><td>1. Measuring the success of changes made</td><td></td><td></td></tr>
<tr><td>2. Comparison with engagement on waste disposal</td><td></td><td></td></tr>
<tr><td>3. Sensitivity of the design framework (cost issue)</td><td></td><td></td></tr>
<tr><td>4. Multi-staging of engagement process</td><td></td><td></td></tr>
<tr><td colspan="2">5. Integration of various data collection methods</td><td></td></tr>
<tr><td colspan="2">6. Public engagement in different cultures</td><td></td></tr>
<tr><td></td><td>7. Reacting to public demand vs. standardisation vs. implementation timescales (and regulatory context)</td><td></td></tr>
<tr><td></td><td colspan="2">8. Real world deployment / technology roadmaps</td></tr>
<tr><td></td><td></td><td>9. The MIT automotive model applied to nuclear (‘standardised customisation’)</td></tr>
<tr><td></td><td></td><td>10. Understanding why background views on nuclear power don’t appear to influence preferences on nuclear design</td></tr>
</table>

7.2. How to measure the success of changes made

The logical end point for this research would be to empirically determine the level of impact that a modified design has on a populations acceptance of a proposed new nuclear plant. To do this additional extensive research on public requirements for a nuclear plant would need to be carried out, the design framework followed through and then an experiment would need to be conducted to test whether the new design was more or less publicly accepted than a control design. In practice this could be very difficult to achieve, in particular because arriving at a 'definitive' publicly informed design is some way beyond what has been achieved with the framework so far.

Assuming publicly informed designs are beneficial, it would also be useful to test a range of designs which incorporate the public view to a greater and lesser extent. This could help to inform design engineers how much influence the public views need to have to make the optimum amount of difference. This (potential) gain would need to be offset against the amount of design change made and the various implications that more novel designs create; such as lack of operating experience, additional cost and regulatory issues.

When all of the above is assessed it may be that the greatest benefit of the framework is not in determining customised designs that are demonstrably more publicly acceptable, but is in showing that the nuclear industry is ready and willing to engage with the public, over the long term, in a fair and unequivocal way. Understanding when, and if, this is the case would be an ultimate long-term goal of any further work on the framework.

7.3. Comparison with engagement on waste disposal

As has been stated previously within this thesis, there is no record of two-way engagement of the type described here ever having taken place in relation to the design of a nuclear power plant. However, engagement processes are currently taking place in the UK in relation to the location and development of nuclear waste disposal facilities. West Cumbria: Managing Radioactive Waste Safely (WC:MRWS) is a partnership organisation comprising of a range of different local organisations who represent the local public; this includes local councils and trade unions along with tourism and environmental organisations (WC:MRWS, 2012). The aim of WC:MRWS is to engage with the public and provide a clear view on their feelings and thoughts in relation to the area volunteering to host a geological disposal facility for long-lived nuclear waste. Three stages of consultation have taken place, and the area has a right to withdraw from the process if it decides that it does not want to proceed.

The progress made so far is much more positive than previous experiences from 10-20 years ago when the government tried to impose a similar facility on the area. In that instance, Nirex Ltd, the company charged with moving the project forward, encountered significant resistance which ultimately resulted in the project being abandoned (Folger, 1993).

It would be useful to understand in detail any similarities and differences between the approach proposed in this thesis (which largely stems from participatory design processes used outside the nuclear industry) as compared to the approach taken by the WC:MRWS partnership. Such a study could assist in refining this framework (and possibly both frameworks).

7.4. Sensitivity of the design framework

A full sensitivity analysis of different types of requirements is yet to be carried out on the modified QFD process included in the framework. Whilst the normalised weighting system is relatively straightforward and does not inherently bias any given requirement this may not actually be a fair reflection of the reality of designing and building a new nuclear plant.

A good example of this arises when one considers cost requirements. As was mentioned in earlier sections, cost is treated (at least in the EUR documents (EUR, 2011)) as an ‘essential’ requirement. However it is not treated as more or less ‘essential’ than a wide range of other ‘essential’ requirements. Therefore, when it is processed via the modified QFD its weighting is currently the same as many other requirements. Once this has been normalised and analysed what it results in is cost actually only playing a small part in a large design space. It is debatable whether this is a true reflection of the economic reality of building new nuclear power plants, particularly in liberalised energy markets. Much more analysis is required, with a wider range of plant requirements, to determine the best way of dealing with cost and associated economic issues within this design framework.

Another issue relates to the use of restrictive and prescriptive requirements. As nuclear energy suffers from technological lock-in (Section 2), and because of various other political factors that may influence energy utilities when they choose their reactor type (such as nationalistic concerns), the design space that is available for the framework to operate within can be severely restricted. This may hamper innovation and the ability of designers to reflect accurately what the public requirements are requesting. In order to resolve this issue future work would likely require engagement with energy utilities and reactor vendors to determine both current and future requirements that may alter the design space, in turn providing a means to meet public requirements.

7.5. Multi-staging of engagement process

The current research was carried out with only a single method and stage of engagement, the wide-scale research questionnaire. A future development could be to stage the process, such that initial investigations can be carried out to determine for a given population, which aspects of design were the most important to the public. A second stage of investigation might then ‘drill-down’ into these areas in more depth, using complimentary techniques, to determine the public’s specific requirements.

7.6. Integration of various data collection methods

As discussed previously (Section 4), if the framework was to be deployed in the ‘real world’ then it would be important to understand which groups of people should be asked what questions, and at what stage of the engagement process different methods should be used. So called ‘mixed-methods’ research has developed in the social sciences over the last few years (Johnson et al., 2007). Applying such approaches to the public engagement stages of the proposed framework has the potential to improve both the understanding of the public's views on nuclear design, but also the understanding of how best designers can meet the requirements of the public along with the other stakeholders involved. Work needs to be carried out, which could tie in to the work detailed in section 6.2, to determine the optimal approach for determining public design requirements.

7.7. Public engagement in different cultures

The proposed framework has been conceived and designed to work in the UK. As was discussed in Sections 2 and 3, cultural differences exist when issues such as risk perception are considered, and it would seem likely that similar issues would exist in terms of public preferences for nuclear design. In addition to differences in design preferences, it is also possible that different groups would require different approaches to engagement in order to elicit 'true' responses on design preferences.

One of the key findings of this work was that it appears that the public, in the UK, can be asked basic questions about the design of nuclear plants and respond with an answer. However, how this translates into other areas of the world with different levels of basic education is an area that needs to be investigated. Additionally, familiarity with the technology may also impair people's ability to engage in such participatory processes.

Finally, there may be issues with deploying such participatory processes in cultures where either the government has no history of any form of public engagement, or in cultures where experts are revered. In the latter, asking for a public view may actually undermine public confidence in design processes, rather than bolster it. For example, it would be interesting to have carried out the same questionnaire in a different culture (such as Japan or China) to see what, if any, differences arose. Much further work is required to inform these areas.

7.8. Reacting to public demand vs. standardisation

As was identified earlier in Section 4, the current trend in nuclear design is for larger plants that are being standardised for global deployment. This contradicts the localised, participatory approach suggested by the framework. Several means to reconcile this difference were suggested in Section 0 but there is much more work that should be done to understand how practical such schemes would be.

In particular, understanding how the varying regulatory regimes around the world would deal with standardised components, as well as plants that comprised of standardised components in different configurations, requires further investigation.

7.9. Real world deployment (technology roadmaps)

Dissemination of the framework around industry is a challenge that remains to be faced. Realistically it is unlikely that companies would be interested in integrating the framework into their design practices until some of the work detailed in this section is completed and the framework better refined and wider deployment tested.

Technology roadmaps for future nuclear deployment may provide a means to begin integrating the approach suggested by this framework. Globally, the guidelines laid out by the International Atomic Energy Agency (IAEA) are an example of how the framework might be presented in a non-prescriptive way.

7.10. The MIT automotive model applied to the nuclear industry

Section 6 of this thesis presented a brief discussion of the application of the MIT model, for automotive manufacturing maturity, to the nuclear industry. The discussions are largely based on hypothesis derived from an informed view of nuclear design, past and present. There is significant potential for further investigations in this area to expand and adapt the MIT model to the nuclear industry in an effort to understand where future design trends may lead. A key difference between the automotive and nuclear industries is the volume of production. Understanding how the model adapts in the high-cost, low volume nuclear industry should be a cornerstone of this future work. The adapted model might then be applied to other high-cost, low volume industries, such as ship building or other power plant technologies. Rationalising such a model in industries where empirical data is hard to come by may pose a significant challenge. However, the benefits gained from this increased understanding could be very useful, particularly in an industrial context, for determining priorities for technology development and financial investment.

7.11. Nuclear design preferences and background views on nuclear power

An important finding, from the questionnaire documented in Section 3 of this thesis, was that expressed preferences relating to the design of a nuclear plant do not appear to be connected to background views on nuclear power. This was in contrast to how expressed preferences relating to nuclear waste and transport did seem to be connected to background views on nuclear power. The questions asked, and the form in which they were asked, in this research were very limited. This prevents the resolution of this dichotomy with the data that is currently available. Future work should explore this area in more depth to validate the findings of this research and then, if required, understand what is driving public design preferences and why it appears to be independent of their background views on nuclear power.

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8. Concluding Remarks

This thesis has described a new design framework which is intended to allow a wider range of stakeholders to engage in the process of designing new nuclear plants. The original goal of this research was to understand if the public reacted to the parts of a nuclear plant in different ways in terms of their perception of risks and the acceptability of plant designs. Section 2 presented a wide ranging literature review which included elements of nuclear design, calculated nuclear risk levels, psychology, sociology and the current state of nuclear new build. This paper highlighted the multidisciplinary nature of trying to understand complex socio-technical interactions, such as the public’s understanding of nuclear related risk. It also suggested that some form of participatory design process might facilitate improved public acceptance of nuclear plant designs, whilst also reducing inflated risk perceptions of nuclear plants. Two key questions were raised; could the public contribute design preferences in a meaningful way, and could such views be integrated into the design of a nuclear plant. This research set out to answer these questions. Ultimately this thesis presents a proof of concept that both of the above questions can be answered. Public participation in the design of nuclear plants appears to be achievable, though with a degree of difficulty.

In an attempt to understand the public‘s preferences relating to nuclear design, a questionnaire was conceived to probe both background views relating to nuclear power and the public’s views on 12 aspects of nuclear design (Section 3). Although a nationally representative sample of the UK public was surveyed, the questionnaire and associated analysis can only be considered a first step in understanding the full depth of the public’s views on nuclear design. This is because of the multitude of possible underlying factors that might influence design choices, along with limitations in the questionnaire method for understanding reasons behind expressed preferences. For example, statistical analysis suggests that whilst issues relating to nuclear waste and material transport are driven, in part, by an individual’s background views on nuclear power, design preferences are not. Further research is required to confirm such findings and determine the root cause of observed phenomena.

As trust is identified strongly as a means to reduce inflated risk perceptions, it was determined that a transparent and bi-directional engagement process might facilitate improved public acceptance of nuclear power plants. A framework for the system level design of a nuclear plant was developed which allows for the integration of stakeholders' views, as determined by means such as research questionnaires, focus groups, interviews and written consultations (Section 4). This framework utilises a modified Quality Function Deployment (QFD) process that enables a wide-range of different requirement inputs to be interpreted by the designer and converted into matching system level specifications. QFD is a visual systems design method which assists in ensuring that traceability of requirements can be maintained within the system level design. This ensures that contributing stakeholders retain visibility of how their input is being considered and used within the design process, facilitating the building of trust between stakeholders and designer.

The framework was demonstrated by means of creating an example nuclear plant using abridged sets of plant design requirements from a range of stakeholders; including a 'customer' energy utility set, a public set and a governmental set. The UK regulatory principle of ALARP was used to guide design decision making, although such a principle has a relatively subtle effect at the system level. Determining full adherence to any regulatory regime, prescriptive or goal-based, requires a deeper understanding of elements of detailed design than was explored within this research. The example plant produced by the framework was subtly different to existing 'real' plant designs in that it was much smaller (around ¼ of the size of most modern PWR plants), and incorporated additional elements that were strongly driven by the public input gained from the research questionnaire. An outstanding issue, which could be addressed with further research, was 'calibrating' the weightings of various requirements such that the output of the QFD process was a fair reflection of 'reality'. Calibrating the weighting of cost related requirements is a significant challenge, particularly in light of continuing difficulties experienced by reactor vendors in determining the cost of nuclear power plants.

The industrial context of this work was presented and specific reference made to the challenge inherent in allowing for stakeholder driven design customisation (which might vary significantly from one location to the next) whilst addressing ongoing efforts towards standardising both nuclear plant design and regulation (Section 6). ‘Standardised Customisation’ is proposed as a means to address this issue and the theoretical background of this concept is briefly discussed. The relevance of this work to ongoing developments within Rolls-Royce’s Nuclear business was also described.

Ten strands for future work were presented in Section 7. These are divided into three categories which relate to the methods used in the framework, deployment of the framework and the impact that the framework might have on the wider nuclear industry. These ten areas were briefly described such that they can be used as initiators for future research proposals. At the time of writing two areas are being actively investigated for future research relating to engagement activities and the application of the ‘standardised customisation’ design ethos.

By demonstrating that a wider range of stakeholders could be brought into the process for designing nuclear power plants, this research has laid a foundation for future work which can improve and refine the proposed framework and our understanding of how the lay-person interacts with the complex and often controversial technology that is nuclear power. Such work requires a range of skills across a variety of scientific disciplines. Developing this framework to a state where it could be used in the design of a new nuclear power plant requires further effort. It will also be a challenge to gain support within the nuclear industry for what is a relatively radical change in approach to the design of nuclear plants. However, the framework proposed in this thesis has the potential to be enable public engagement in an area (nuclear plant design) where previously this has not been achieved. The framework could provide a step-change in the nuclear industry’s ability to engage with the public; in turn, providing the public with an unprecedented opportunity to gain control and influence in an area that has previously been out of reach. There is also nothing that limits the application of this framework to the nuclear industry. Other areas that have been subjected to public opposition, such as wind farms or petrochemical plants, could be designed with this approach with the potential for similar benefits to be realised.

9. APPENDIX A – Data Tables

The full data tables from the questionnaire, as described in Section 3, can be found on the attached CD/DVD in IBM SPSS, Adobe PDF and Microsoft Excel format. They are not contained here due to their considerable size.

10. APPENDIX B – Plant Requirements

This appendix contains tables which show the origin of the stakeholder requirements taken into account when designing the reactor proposed in this thesis. The requirements used are by no means full, representative or exhaustive and were used only to facilitate the demonstration of the framework in action. These tables can also be found on the attached CD/DVD in Microsoft Excel format.

Table 21. The requirements of the different stakeholders accounted for in the example plant design.

Category	Utility (EUR, 2011)	Public (Goodfellow et al., 2013)	Other (Government etc.) (DTI, 2006, DECC, 2012)
Co-location	U- no mirroring layout U- no shared safety facilities		
Design Ethos	U- latest proven technology based on LWR	P- novel (modern) approach	
Safety System	U- Defence in depth U- passive preference	P- blend of active and passive systems	
Physical Plant Characteristics	U- single turbine output		
Site Selection	U- The plant should cope with site in a wide range of locaitons / conditions	P- the plant should be located away from people	G- the plant should be on an existing site
Aircraft Impact	C- The plant should have visible strong hard outer impact dome	C- The plant should have visible strong hard outer impact dome	
I&C	C- A modern digital I&C approach should be taken	C- A modern digital I&C approach should be taken	
Weapons Reprocessing	C- The ability to use mixed oxide fuel (MOX) should be included	C- The ability to use mixed oxide fuel (MOX) should be included	
Waste Storage	U- minimum of 10 years storage capacity available	P- Waste stored on site pending ultimate disposal	
Nuclear Transport	C- Movement minimised	C- Movement minimised	
Waste Form	U- Standardised		
Containment	U- minimal release in extreme event		
Social Impact			G- bring jobs
Proliferation Resistance			G- minimise proliferation
Capital Cost	U- £1300 per kW		G- Non-subsidised
Natural Hazard Protection	U- Resistant to DBA		
Grid Connection	U- able to cope with LOOP		
Power Performance	U- 600MW-1800MW U- Load following capable	P- multiple small reactors preferred	
Fuel Efficiency	U- 12-24 month cycle		
Availability	U- 90% or greater		
Design Life	U- 40 (60) year lifetime		

Table 22. Expanded list of stakeholders’ design requirements. ‘Definitive Outcome’ shows areas where requirements are prescriptive or agree on a design option.

#	**Category**	**"Goal"**	**EUR "State"** (EUR, 2011)	**Utility** (EUR, 2011)	**Public** (Goodfellow et al. 2013)	**Regulator** (HSE, 2002, 2006)	**Government** (DTI, 2006, DECC, 2012)	**Definitive Outcome?**
1	Site Selection	The plant shall be located at X	shall	(1.4.2.2) Plant shall operate under a range of extreme design conditions (2.4.1.4.1)	The coast away from cities	ST1, ST2, ECE4	Existing site	Existing Site
2	Aesthetically sympathetic	The plant should X the local surroundings	should	(2.11.1.1.7) and (4.3.1.3) "The Designer should bear in mind that some of the plant buildings will be part of the landscape for a long period, through to the end of dismantling. Appearance is therefore very important." compliant with local legal requirements	Blend in			
3	Ultimate Heatsink	The plant must have an output to dump heat to/by X	Shall	Available under all circumstances (1.2.11)	Fan-assisted towers (low visibility means?)	EHT1, EHT3		
4	Co-location	The plant shall consist of X	Shall	(2.11.1.1.4) No mirroring, Sharing of safety related facilities not desirable	Multiple smaller reactors	ST6, EES4		
5	Design Ethos (new/old)	The plant should be based on X technology	Should	LWR and Proven design philosophy (1.2.3), Standardised (2.12.1)	Novel (modern?) tech	EKP1		
6	Aircraft Impact	The plant shall be protected against aircraft impact by X	Shall	(1.4.2.5) Based on PSA of the risk	Hard outer dome	EHA8		Outer Impact Dome
7	Safety Systems	The plant shall employ X style safety system	Shall	Defence in Depth (1.3.3) Passive preferred (2.0.2.2.7) All of Vol2 Chap1, Negative Void Coef (2.2.3.5)	Active and passive	EKP3, EDR2, EDR3, EDR4, ERL3, ESS19, A SS is required to act in response to a fault, including passive, not interfere with normal operation, single fail criteria, redundance above		

						10x-2 allowed events		
8	Control System	The plant shall us X type I&C system	Shall	All Vol2 Chap10, and 10x-3 failure requirement, Digital (1.2.10)	Digital I&C	ESR4, ESR5		Digital I&C
9	Fuel Reprocessing	Nuclear fuel shall be X	Shall	Up to 50% MOX loading (2.2.3.1)	Recycled	RW2		MOX capable
10	Weapons reprocessing	Nuclear weapons shall be X	should?	Up to 50% MOX loading (2.2.3.1)	Recycled		Recycled(?)	MOX capable
11	Long term waste disposal	Nuclear waste shall be X	Shall	Provide 10 years of capacity on site (15yrs for MOX) (1.5.7.1, 2.2.2.2, 2.2.5.1)	Stored on site pending	ENM6, RW1, RW3 (minimised on site)		
12	Transport of material to and from	Nuclear transport should be X			Minimised	ELO3 (minimised)	*Minimised*	Minimised transportation
13	Waste form	The output of used material shall be X	Shall	(1.5.5.2, 1.5.7.2, 1.5.7.3) within standardised fuel rods / assemblies		RW(X)		Standard fuel assemblies
14	Containment	The plant shall X in the event of an accident	Shall	All Vol2 Chap9, and (1.2.8, 2.1.9, 1.3.4.4, 2.0.2.2.12) Minimal release in the event of a severe accident		ECV4	*Not explode*	Strong Outer Containment
15	Physical Plant Characteristics	The plant shall have a footprint of X	Shall	All Vol2 Chap11, All Vol4 Chap3, single turbine, layout up to designer to minimise risk and maximise safety		ELO1, ELO2, access restricted and controlled	Existing site	Minimised Footprint
16	Social Impact	The plant should X to the local community	Should?				*bring jobs*	

17	Proliferation Resistance	The plant should X the production of materials that could be used in a weapon	should?				*Minimise*	
18	Capital costs	The plant should cost X	Should	(1.6.2) £1300 per kw			non-subsidised market price	Cost effective
19	Natural Hazard protection	The plant shall be X to natural hazards	Shall	(1.3.3.4) Should be included for all nuclear island and safety related structures		EHA1, EHA2, EHA3		Resilient to natural hazards
20	Grid connection	The plant shall X to the grid	Shall	All Vol2 Chap3, no single unit bigger than 2GW (2.3.1.1), cope with connection loss (4.2.4.10)				Robust grid connections
21	Staffing	The plant shall have X personnel	Shall?			EHF8		Optimised personnel
22	Power performance	The plant shall achieve X performance characteristics	Shall	600-1800MWe (1.2.2), Load following (2.2.3.8), no single unit bigger than 2GW (2.3.1.1)			*As per planned share of national requirement*	Total output 1800MW
23	Fuel efficiency	The fuel shall last for X period in the reactor	Shall	12-24 month fuel loading cycle (1.5.5.2, 2.2.3.2)				>12 month refuelling cycle
24	Availability	The plant shall be up at least X% of the time	Shall	(1.5.3) 90%				90% up time
25	Design life	The plant shall be able to run for X years	Shalll	(1.5.2) 40 (60) years				40 (60) year lifetime

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11. APPENDIX C – Modified QFD Sheet

This appendix contains the full view of the modified QFD sheet. The sheet itself is very large and does not transpose well onto an A4 page. It is shown here for completeness and is available in Microsoft Excel format on the attached CD/DVD.

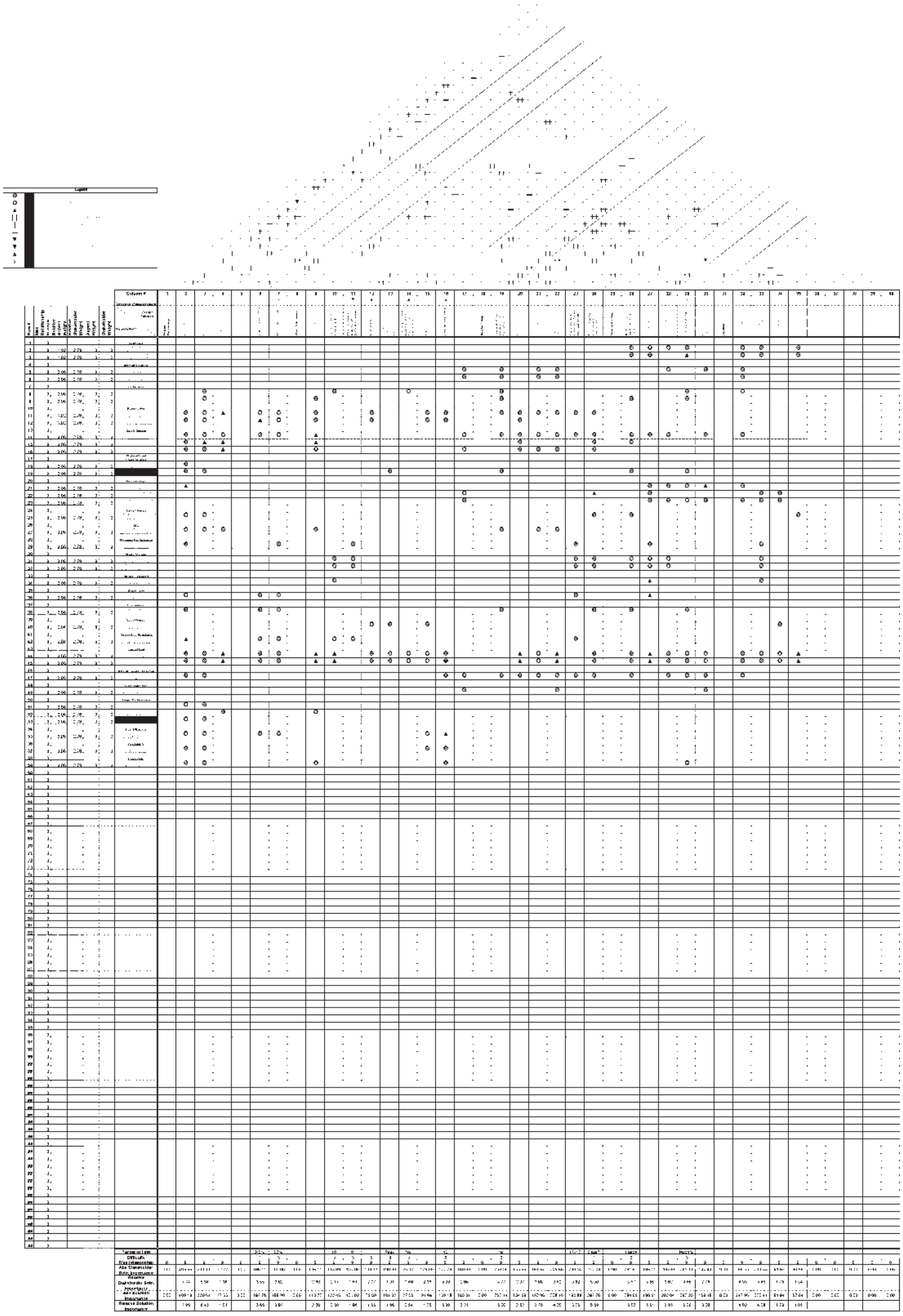

Figure 36. The full system level QFD sheet. Please access the attached materials to view the functional QFD sheet properly.

12. APPENDIX D – Pugh Matrices

This appendix contains the various Pugh matrices that facilitated the system level design of the reactor proposed in this thesis. The tables are also contained on the attached CD/DVD in Microsoft Excel format. The tables are presented as used in the design process without in depth explanation and justification for individual design decisions and scoring.

Table 23. Pugh Matrix for determining Reactor Type (2 pages)

Requirement and benchmark	Weighting		Dispersed PWR	Integral PWR	BWR	HTGR	CANDU
U- latest proven technology based on LWR	⊖	9	5	2	3	1	3
Latest approved design			*2012*	*none but is LWR*	*none but is mature LWR*	*none*	*GDA suspended*
P- novel (modern) approach	⊖	9	3	5	2	5	3
Design research activity judgment			*Evolutionary*	*Lots of extra efforts*	*not much*	*China*	*Evolutionary*
U- Defence in depth	⊖	9	3	4	3	3	4
resilience to failure			*standard*	*less rhr*	*standard*		*standard*
U- passive preference	⊖	9	4	3	2	3	2
Judgement on passive prevalence			*AP1000 exists*	*smaller size more amenable*	*no passive BWR design exists*	*standard (low core density)*	*tubes?*
P- blend of active and passive systems	⊖	9	4	5	3	3	3
Can be designed to use both			*AP1000 exists*	*smaller size more amenable*	*No design exists*	*No design exists*	*No design exists*
U- single turbine output	⊖	9	3	3	3	3	3
Single generator output			*equally*	*applicable*	*to*	*all*	*designs*
P- multiple small reactors preferred	⊖	9	4	5	2	4	2
			Small PWR exist	*smaller size more amenable*	*No small BWR designs*	*AGR is smr?*	*scalable but none exist*
U- The plant should cope with site in a wide range of locations / conditions	▲	1	5	5	4	4	4
			Current plants on many sites	*Can be designed for many sites*	*Current plants on many sites*	*Current plants on many sites*	*Current plants on many sites*
C- The plant should have visible strong hard outer impact dome	○	3	5	5	5	4	5
			Existing Designs	*Can be achieved*	*Existing Designs*	*Existing Designs*	*Existing Designs*
C- A modern digital I&C approach should be taken	○	3	5	4	5	4	5
			In service	*Can be achieved*	*In service*	*Can be achieved*	*In service*
C- The ability to use MOX should be included	⊖	9	5	3	5	3	4
			In service	*Can be achieved*	*In service*	*Can be achieved*	*Certified but not used*
U- Standardised waste form	○	3	5	5	5	5	5
			Standard fuel form	*Standard fuel form*	*Standard fuel form*	*Standard fuel form*	*Standard fuel form*
U- minimal release in extreme event	⊖	9	5	5	3	4	5
			TMI example	*Can be achieved*	*Fukushima?*	*Nitrogen purge outpour*	*Calandria plus tubes*
G- minimise proliferation	▲	1	3	3	3	3	3
			Standard fuel form	*Standard fuel form*	*Standard fuel form*	*Standard fuel form*	*Standard fuel form*
U- £1300 per kW	⊖	9	4	2	4	2	4
			Based on what is being built	*Based on what is being built*	*Based on what is being built*	*Based on what is being built*	*Based on what is being built*
G- Non-subsidised	⊖	9	3	3	4	2	3
			Based on what is being built	*Based on what is being built*	*Based on what is being built*	*Based on what is being built*	*Based on what is being built*

Requirement and benchmark	Weighting		Dispersed PWR	Integral PWR	BWR	HTGR	CANDU
U- Resistant to DBA	Θ	9	4	4	4	4	4
			Can be achieved	*Can be achieved*	*Can be achieved*	*Can be achieved*	*Can be achieved*
U- 600MW-1800MW	O	3	5	3	5	2	4
			ATMEA-EPR	*Hard to upscale*	*BWR-1 - ABWR*	*AGR and GenIV in works*	*Can be achieved*
U- 12-24 month cycle	O	3	5	5	5	5	5
			18mth in service	*Can be achieved*	*18mth in service*	*Can be achieved*	*18mth in service*
Standard Enriched Fuel	3.68	3	4	3	4	4	4
			In service	*Some designs use higher*	*In service*	*In service*	*In service*
DUPLICATE MOX loading capable	3.90	0					
On-site Used fuel storage ponds	2.40	3	4	4	4	4	4
DUPLICATE Minimise usage and production of proliferable material	1.98	0					
Modular design	1.56	1	3	4	3	3	2
			AP1000 only	*can be achieved*	*ABWR only*	*can be achieved*	*not*
Utilise economy of scale (modular/phased build)	1.98	1	3	5	3	4	3
			AP1000 only	*smaller designs facilitate*	*ABWR only*	*can be achieved*	*tube/calandria design helps*
Internal layout allows ease of access to maximise online maintenance	0.54	1	5	1	3	4	5
			Large with spaces	*Internal components*	*maintenance of gensets harder*	*Large with spaces*	*Large with spaces*
Long-life components	3.12	3	4	2	4	3	4
				Internal components		*higher temperatures*	
Independent safety systems in non-mirrored layout	5.03	9	4	3	4	4	4
				Internal components			
DUPLICATE Fuel in standard assemblies that last into used storage	3.78	0					
DUPLICATE Strong containment structure around reactor core	5.63	0					
DUPLICATE Hard outer impact dome over primary containment	5.57	0					
Concrete basemat	5.23	9	4	4	4	3	4
						Larger structure	
			625	570	541	507	557

Table 24. Pugh Matrix for determining Reactor Size (2 pages)

Requirement and benchmark	Weighting			200MWe	600MWe	1200MWe	1600MWe
U- no mirroring layout	Θ	9		2	3	4	5
				too many small units			
U- no shared safety facilities	O	3		3	3	3	3
U- latest proven technology based on LWR	O	3		3	4	5	5
							Big plants more common
P- novel (modern) approach	O	3		4	3	2	3
				SMR trend?			
U- Defence in depth	O	3		4	4	4	4
U- passive preference	▲	1		4	4	4	4
P- blend of active and passive systems	Θ	9		4	4	4	4
P- multiple small reactors preferred	Θ	9		5	4	2	1
				Size			
C- The plant should have visible strong hard outer impact dome	O	3		3	3	3	3
C- A modern digital I&C approach should be taken	O	3		3	3	3	3
U- £1300 per kW	Θ	9		2	1	4	5
				economy of production			*economy of scale*
G- Non-subsidised	Θ	9		4	4	3	2
							Big increases investment risk
U- Resistant to DBA	Θ	9		3	3	3	3
U- 600MW-1800MW	Θ	9		2	3	3	3
				Too small?			
U- 12-24 month cycle	O	3		3	3	3	3
U- 90% or greater	Θ	9		3	3	3	3
U- 40 (60) year lifetime	Θ	9		3	3	3	3

Requirement and benchmark	Weighting		200MWe	600MWe	1200WMe	1600MWe
Standard Enriched Fuel	3.68	3	3	3	3	3
On-siteUsed fuel storage ponds	2.40	3	3	3	3	3
Modular design	1.56	1	4	4	3	2
					bigger modules more management	*bigger modules more management*
Utilise economy of scale (modular/phased build)	1.98	1	5	4	2	1
			Easier			
Internal layout allows ease of access to maximise online maintenance	0.54	1	3	3	3	3
Long-life components	3.12	3	3	3	3	3
DUPLICATE Independent safety systems in non-mirrored layout	5.03	0				
Strong containment structure around reactor core	5.63	9	3	3	3	3
DUPLICATE Hard outer impact dome over primary containment	5.57	0				
Concrete basemat	5.23	9	3	3	3	3
			418	417	423	424

Table 25. Pugh Matrix for determining Ultimate Heatsink

Requirement and benchmark	Weighting		Natural Draught Cooling Towers	Fan Assisted Cooling Towers	The Sea	A River
U- A reliable UHS must be available	Θ	9	4	3	5	3
Reliability						
P- The UHS should be low visibilty and managed	Θ	9	1	3	4	4
Visibility						
U- Defence in depth	O	3	4	3	4	2
				power failure		drought/flood
P- blend of active and passive systems	O	3	4	4	4	4
P- the plant should be located away from people	O	3	4	4	4	2
						Settlement
G- the plant should be on an existing site	Θ	9	2	2	4	1
					UK standard	
U- Resistant to DBA	Θ	9	4	3	4	2
			quake?	power failure	Flood	drought/flood
U- able to cope with LOOP	Θ	9	4	2	4	4
				power failure		
			171	150	225	150

Table 26. Pugh Matrix for determining Passive Safety Systems

Requirement and benchmark	Weighting		Passive Containment Cooling	Passive Feedwater system	Core Catcher	Passive Emergency Power	Accumulators
U- latest proven technology based on LWR	⊖	9	2	5	4	1	5
			AP1000 untested	*standard*	*standard*	*not commonly used*	*standard*
P- novel (modern) approach	⊖	9	3	3	3	5	3
						novel	*common*
U- Defence in depth	⊖	9	3	3	3	3	3
U- passive preference	⊖	9	3	3	3	3	3
P- blend of active and passive systems	⊖	9	3	4	5	4	4
			Requires mainly passive?		*It's a concrete chute*		
U- £1300 per kW	▲	1	2	4	4	3	4
			complex			*complex*	
G- Non-subsidised	▲	1	2	4	4	3	4
U- Resistant to DBA	⊖	9	3	4	5	4	4
			Easy to undermine?		*It's a concrete chute*		
On-site Used fuel storage ponds	2.40	3	4	4	0	4	0
					has no effect		*has no effect*
Independent safety systems in non-mirrored layout	5.03	9	3	3	3	3	3
Strong containment structure around reactor core	5.63	9	4	3	5	3	3
			required for pressure build up		*It's a concrete chute*		
Hard outer impact dome over primary containment	5.57	9	3	3	3	3	3
Concrete basemat	5.23	9	3	3	3	3	3
			286	326	341	306	314

Table 27. Pugh Matrix for determining Active Safety Systems

Requirement and benchmark	Weighting		Low Pressure Injection System	High Pressure Injection System	Residual Containment heat Removal System	Chemical SCRAM system	Control Rods
U- A reliable UHS must be available	Θ	9	0	0	3	0	0
			has no effect	*has no effect*		*has no effect*	*has no effect*
P- The UHS should be low visibility and managed	Θ	9	0	0	3	0	0
			has no effect	*has no effect*		*has no effect*	*has no effect*
U- latest proven technology based on LWR	Θ	9	5	4	4	4	5
			all	*are*	*in*	*current*	*use*
U- Defence in depth	Θ	9	4	4	4	4	4
P- blend of active and passive systems	Θ	9	2	2	4	3	4
			Very active	*Very active*	*can be semi passive*		*can be semi passive*
C- A modern digital I&C approach should be taken	Θ	9	3	3	3	3	3
U- £1300 per kW	O	3	4	2	3	2	4
				Costly		*Costly*	
G- Non-subsidised	O	3	4	2	3	2	4
U- Resistant to DBA	Θ	9	3	3	3	3	3
Independent safety systems in non-mirrored layout	5.03	9	2	2	3	3	5
			mirroring	*mirroring*			
Strong containment structure around reactor core	5.63	9	2	2	3	3	5
			Size issue	*Size issue*			
Hard outer impact dome over primary containment	5.57	9	3	3	3	3	3
			240	219	315	246	312

Table 28. Pugh Matrix for determining Backup Power Systems

Requirement and benchmark	Weighting		Diesel Gensets	Gas Turbine Gensets
U- A reliable UHS must be available	Θ	9	5	5
P- The UHS should be low visibilty and managed	Θ	9	5	5
U- latest proven technology based on LWR	Θ	9	5	3
				Not in common use
U- Defence in depth	Θ	9	5	5
P- blend of active and passive systems	Θ	9	5	5
C- A modern digital I&C approach should be taken	Θ	9	5	5
U- £1300 per kW	▲	1	3	4
			Unit	Cost
G- Non-subsidised	▲	1	3	4
			Unit	Cost
U- Resistant to DBA	Θ	9	2	4
			Heavy	light
U- able to cope with LOOP	Θ	9	5	5
Long-life components	3.12	3	5	5
Independent safety systems in non-mirrored layout	5.03	9	5	5
Hard outer impact dome over primary containment	5.57	9	5	5
			444	446

Table 29. Pugh Matrix for determining Secure Site

Requirement and benchmark	Weighting		Outer Fence	Guard Patrols	CCTV	Moat
U- Designer should bear in mind that the plant is going to be there for a while	O	3	2	4	4	3
			unsightly			*space requirement*
P- The design should blend in to local surroundings	Θ	9	2	3	4	3
			unsightly		*subtle*	
U- Defence in depth	Θ	9	3	3	3	3
U- The plant should cope with site in a wide range of locaitons / conditions	Θ	9	4	4	4	3
						Geology
P- the plant should be located away from people	Θ	9	4	2	4	4
				needs people		
G- the plant should be on an existing site	Θ	9	5	4	3	1
			Already exists	*Trained*	*may need installation*	*unlikely to be in place*
C- The ability to use MOX should be included	Θ	9	5	4	5	4
				dosage?		*disables access*
U- minimum of 10 years storage capacity available	O	3	4	4	5	3
					easily scalable	*limits expansion*
P- Waste stored on site pending ultimate disposal	O	3	3	3	3	3
C- Movement minimised	▲	1	3	3	3	3
U- Standardised waste form	▲	1	3	3	3	3
U- £1300 per kW	▲	1	4	1	3	2
			Cheap	*costly*		*costly*
G- Non-subsidised	▲	1	4	1	3	2
			Cheap	*costly*		*costly*
On-siteUsed fuel storage ponds	2.40	3	3	3	4	2
					easily scalable	*limits expansion*
Minimise usage and production of proliferable material	1.98	1	3	3	3	3
Internal layout allows ease of access to maximise online maintenance	0.54	1	3	3	3	3
Independent safety systems in non mirrored layout	5.03	9	4	3	4	2
			scalable		*scalable*	*limits expansion*
			299	263	309	229

Table 30. Pugh Matrix for determining Defence vs. Flood (2 pages)

Requirement and benchmark	Weighting		Sea Walls	Sand Dunes / landscaping	Drainage infrastructure	On Site flood barriers
U- Designer should bear in mind that the plant is going to be there for a while	Θ	9	3	3	3	3
U- A reliable UHS must be available	O	3	4	4	4	3
						removal once deployed?
U- Defence in depth	Θ	9	3	3	3	3
U- The plant should cope with site in a wide range of locaitons / conditions	Θ	9	3	2	3	4
				shingle/cliffs?		*install anywhere*
G- the plant should be on an existing site	Θ	9	4	4	4	4
U- minimum of 10 years storage capacity available	O	3	3	4	4	4
			limits expansion			
P- Waste stored on site pending ultimate disposal	O	3	3	3	3	3
U- £1300 per kW	Θ	9	2	4	3	3
			costly	*may naturally exist*		
G- Non-subsidised	Θ	9	2	3	3	3
U- Resistant to DBA	Θ	9	5	4	3	3
			solid	*solid*		
Independent safety systems in non mirrored layout	5.03	9	3	3	3	3

Requirement and benchmark	Weighting		Sea Walls	Sand Dunes / landscaping	Drainage infrastructure	On Site flood barriers
Strong containment structure around reactor core	5.63	9	4	3	3	4
			solid			*solid*
Concrete basemat	5.23	9	4	3	2	4
			enhances		*undermines*	*enhances*
			327	321	303	336

Table 31. Pugh Matrix for determining Robust Grid Connection

Requirement and benchmark	Weighting		Ground based connection	Suspended cable connection
U- A reliable UHS must be available	Θ	9	3	3
U- Defence in depth	Θ	9	3	3
U- The plant should cope with site in a wide range of locaitons / conditions	▲	1	4	3
				unsightly
G- the plant should be on an existing site	Θ	9	3	3
U- £1300 per kW	O	3	3	2
				cost
G- Non-subsidised	O	3	3	2
				cost
U- Resistant to DBA	Θ	9	3	3
U- able to cope with LOOP	Θ	9	3	3
Independent safety systems in non mirrored layout	5.03	9	3	3
			184	177

Table 32. Pugh Matrix for determining Site Location

Requirement and benchmark	Weighting		Existing Coastal Site	Existing Rural (non-coastal) Site	New Coastal Site	New Rural (non-coastal site)
U- Designer should bear in mind that the plant is going to be there for a while	Θ	9	5	4	3	2
proximity and 'unspoilt'						
P- The design should blend in to local surroundings	Θ	9	4	4	3	3
unspoilt						
U- A reliable UHS must be available	Θ	9	5	3	5	3
			Sea		*Sea*	
P- The UHS should be low visibilty and managed	Θ	9	5	3	5	3
			Sea		*Sea*	
U- no mirroring layout	O	3	3	3	3	3
U- Defence in depth	Θ	9	4	3	4	3
			Sea		*Sea*	
U- The plant should cope with site in a wide range of locaitons / conditions	Θ	9	3	3	3	3
G- the plant should be on an existing site	Θ	9	5	5	1	1
			Yes	*Yes*	*No*	*No*
U- £1300 per kW	Θ	9	4	4	3	3
Infrastructure costs						
G- Non-subsidised	Θ	9	4	4	2	2
Infrastructure costs						
U- Resistant to DBA	Θ	9	3	4	3	4
			Flood		*Flood*	
			387	342	297	252

Table 33. Pugh Matrix for determining Connecting Infrastructure

Requirement and benchmark	Weighting		Road	Rail	Boat
U- Designer should bear in mind that the plant is going to be there for a while	Θ	9	3	4	4
Longevity and maintenance					
P- The design should blend in to local surroundings	Θ	9	2	3	4
			Multiple	*Singular*	*Dockside*
P- the plant should be located away from people	Θ	9	1	3	4
			Roads = people		
G- the plant should be on an existing site	Θ	9	4	4	2
			already exists	*already exists*	*may exist*
C- The ability to use MOX should be included	Θ	9	2	3	4
				Arrives via rail	*Arrives by boat*
U- minimum of 10 years storage capacity available	O	3	2	3	4
Capacity of transportation			*Truck*	*Train*	*Boat*
P- Waste stored on site pending ultimate disposal	Θ	9	2	3	4
Capacity of transportation			*Truck*	*Train*	*Boat*
C- Movement minimised	Θ	9	3	3	3
U- £1300 per kW	Θ	9	4	3	2
			Low cost		*High Cost*
G- Non-subsidised	Θ	9	4	3	2
			Low cost		*High Cost*
Standard Enriched Fuel	3.68	3	3	3	3
MOX loading capable	3.90	3	3	3	3
DUPLICATE On-siteUsed fuel storage ponds	2.40	0			
Modular design	1.56	1	2	3	4
			small modules		*large modules*
Fuel in standard assemblies that last into used storage	3.78	3	3	3	3
			260	300	304

Intentionally blank