Programme Area: Nuclear

Project: Natural Hazards Phase 3

Title: Case Study 3: Hunterston

Abstract:

This document introduces the location and a demonstration of the hazard characterisation methodologies for:

- Marine biological fouling
- Space weather

Context:

The Natural Hazards Review project will develop a framework and best practice approach to characterise natural hazards and seek to improve methodologies where current approaches are inefficient. This is to improve energy system infrastructure design and the project is intended to share knowledge of natural hazards across sectors. The project will be completed in three stages. Phase one will focus on a gap analysis. Phase two will look at developing a series of improved methodologies from the gaps identified in phase one, and phase three will demonstrate how to apply these methodologies. Finally, phase 3 will develop a “how to” guide for use by project engineers.

Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies

Case Study 3:

Hunterston

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Preface

This document forms part of the Energy Technologies Institute (ETI) project 'Low Carbon Electricity Generation Technologies: Review of Natural Hazards', funded by the ETI and led in delivery by the EDF Energy R&D UK Centre. The aim of the project has been to develop a consistent methodology for the characterisation of natural hazards, and to produce a high-quality peer-reviewed set of documents suitable for use across the energy industry to better understand the impact that natural hazards may have on new and existing infrastructure. This work is seen as vital given the drive to build new energy infrastructure and extend the life of current assets against the backdrop of increased exposure to a variety of natural hazards and the potential impact that climate change may have on the magnitude and frequency of these hazards.

The first edition of *Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies* has been funded by the ETI and authored by EDF Energy R&D UK Centre, with the Met Office and Mott MacDonald Limited. The ETI was active from 2007 to 2019, but to make the project outputs available to industry, organisations and individuals, the ETI has provided a licence to the Institution of Mechanical Engineers and Institution of Chemical Engineers to exploit the intellectual property. This enables these organisations to make these documents available and also update them as deemed appropriate.

The technical volumes outline the latest science in the field of natural hazard characterisation and are supported by case studies that illustrate how these approaches can be used to better understand the risks posed to UK infrastructure projects. The documents presented are split into a set of eleven technical volumes and five case studies.

Each technical volume aims to provide an overview of the latest science available to characterise the natural hazard under consideration within the specific volume. This includes a description of the phenomena related to a natural hazard, the data and methodologies that can be used to characterise the hazard, the regulatory context and emerging trends. These documents are aimed at the technical end-user with some prior knowledge of natural hazards and their potential impacts on infrastructure, who wishes to know more about the natural hazards and the methods that lie behind the values that are often quoted in guideline and standards documents. The volumes are not intended to be exhaustive and it is acknowledged that other approaches may be available to characterise a hazard. It has also not been the intention of the project to produce a set of standard engineering 'guidelines' (i.e. a step-by-step 'how to' guide for each hazard) since the specific hazards and levels of interest will vary widely depending on the infrastructure being built and where it is being built. For any energy-related projects affected by natural hazards, it is recommended that additional site- and infrastructure-specific analyses be undertaken by professionals. However, the approaches outlined aim to provide a summary of methods available for each hazard across the energy industry. General advice on regulation and emerging trends are provided for each hazard as context, but again it is advised that end-users investigate in further detail for the latest developments relating to the hazard, technology, project and site of interest.

The case studies aim to illustrate how the approaches outlined in the technical volumes could be applied at a site to characterise a specific set of natural hazards. These documents are aimed at the less technical end-user who wants an illustration of the factors that need to be accounted for when characterising natural hazards at a site where there is new or existing infrastructure. The case studies have been chosen to illustrate several different locations around the UK with different types of site (e.g. offshore, onshore coastal site, onshore river site, etc.). Each of the natural hazards developed in the volumes has been illustrated for at least one of the case study locations. For the sake of expediency, only a small subset of all hazards has been illustrated at each site. However, it is noted that each case study site would require additional analysis for other natural hazards. Each case study should be seen as illustrative of the methods outlined in the technical volumes and the values derived at any site should not be directly used to provide site-specific values for any type of safety analysis. It is a project recommendation that detailed site-specific analysis should be undertaken by professionals when analysing the safety and operational performance of new or existing infrastructure. The case studies seek only to provide engineers and end-users with a better understanding of this type of analysis.

Whilst the requirements of specific legislation for a sub-sector of energy industry (e.g. nuclear, offshore) will take precedence, as outlined above, a more rounded understanding of hazard characterisation can be achieved by looking at the information provided in the technical volumes and case studies together. For the less technical end-user this may involve starting with a case study and then moving to the technical volume for additional detail, whereas the more technical end-user may jump straight to the volume and then cross-reference with the case study for an illustration of how to apply these methodologies at a specific site. The documents have been designed to fit together in either way and the choice is up to the end-user.

The documents should be referenced in the following way (examples given for a technical volume and case study):

ETI. 2018. *Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies,* Volume 1 — Introduction to the Technical Volumes and Case Studies. IMechE, IChemE.

ETI. 2018. *Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies,* Case Study 1 — Trawsfynydd. IMechE, IChemE.

1. Introduction

This case study illustrates the appropriate use of the derived methodology for Hunterston and its coastal infrastructure. Hunterston is located in western Scotland and is the site of energy generation and transmission infrastructure. The site was chosen as representative of a coastal site.

This case study assesses two different types of natural hazard:

- Volume 10 — Space Weather;
- Volume 11 — Marine Biological Fouling.

The location of Hunterston has been selected to illustrate the potential risks caused by these two hazards since this industrialised coastal site has been affected by past biological clogging events and is located at a northern latitude which makes it more likely to observe space weather impacts such as geomagnetic storms. Other natural hazard risks (such as extreme weather or flooding) at this location should still be considered more generally but are not the focus of this case study.

1.1 Geography and climate

Hunterston is located on the western coast of Scotland, in Ayrshire. The site includes infrastructure along the coast between Portencross and Fairlie as illustrated in *Figure 1*. The nearest town is West Kilbride. Glasgow is the nearest city and is located 60 km away. The climate is milder than on the eastern Scotland coast and is driven by maritime influences and the warm Gulf Stream. The yearly average maximum and minimum temperatures are 13.1 and 6.1 degrees Celsius (°C) respectively (computed by the Met Office on the climate period 1981 to 2010 using the climate station Largs which is the nearest weather station to Hunterston), and the yearly total average rainfall is 1346 millimetres (mm) (compared with London — Greenwich Park Station: 550 mm).

Figure 1. Map showing the location of Hunterston with respect to the rest of the UK (left) and zoomed in to show the local area (right). The red marker indicates the position of Hunterston. (Source: ©2017 Google LLC, used with permission. Google and the Google logo are registered trademarks of Google LLC)

1.2 Overview of natural historical hazard events

Scotland is occasionally inclined to severe storm and flood events. In particular, the 2002 Glasgow floods consisted of thunderstorms and an intense series of flash floods occurring in late July and early August 2002. The Boxing Day storm (on 26th December 1998) was characterised by wind speeds of 97 kilometres per hour (km/h) with gusts over 140 km/h during which northern England and Scotland lost access to electricity (*Ofgem, 1999*). Approximately 50,000 households were without electricity for 24 hours.

More specifically related to the hazards analysed in this document, marine ingress events such as biofouling by ***sessile**** marine species have been recorded by Hunterston B nuclear power station (HNB) in the past; these are described in further detail in *Section 2.1.2*. Space weather impacts, such as geomagnetically induced current (GIC) generated by geomagnetic storms, can disrupt the high transmission power network. Several significant GIC effects on the UK electricity network were recorded during intense geomagnetic storm events on 14th July 1982, 13th to14th March 1989, 19th to 20th October 1989 and 8th November 1991, such as large ***reactive power*** swings on generators and

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*All technical terms marked in blue can be found in the Glossary section.

failure of two identical 400/132 kilovolt (kV) transformers at Norwich Main and Indian Queens (*Erinmez et al., 2002*). The location of Hunterston may be considered at risk of electric disruption if an extreme space weather event were to occur, since UK coastal sites are more likely to observe high intensities of GIC (*Kelly et al., 2017*).

1.3 Industrial history

Hunterston was an important site in the development of Scotland's oil and gas industry during the 20th century. This is due to its geography: the site is characterised by flat land adjacent to deep natural water. The construction yard site was used to construct the concrete offshore structure for British Petroleum's Harding Field and the gravity-based platform for the Maureen Field. The latter was dismantled and the construction yard is now empty. A coal-handling port that is located at Fairlie was opened in 1979. The main activity of the port is coal imports and, with 10% of the market, it is now the UK's largest in terms of volume (*Hunterston.eu, 2018*).

Hunterston includes energy generation sites: Hunterston A nuclear power station (a Magnox station in decommissioning phase) and Hunterston B nuclear power station (HNB). HNB consists of two advanced gas-cooled reactors, with a net output to approximately 930 megawatts (MW). It has generated electricity since 1976 and will be decommissioned around 2023 (*EDF Energy, 2018*).

The National Offshore Wind Turbine Test Facility (NOWTTF) at Hunterston is the UK's only onshore test facility for offshore wind turbines. It is an extension of SSE's Glasgow-based Centre of Engineering Excellence for Renewable Energy (CEERE). The wind conditions, the easy access to the grid and an adjacent jetty make the site ideal for turbine testing (*SSE, 2018*).

In terms of energy transmission, the Western Link has been built recently. The Western Link is a high-voltage (HV) direct current (DC) electrical link that connects the transmission network in Scotland with that in England and Wales. It includes a converter station in Hunterston; 385 km of undersea cable; 33 km of underground cable on the Wirral; and a converter station in Deeside, North Wales. The converter station at Hunterston transforms the DC that flows along the submarine cable into the alternating current (AC) that is injected into the HV electric network. It was commissioned in December 2017 (*Western Link, 2018*).

1.4 Development of the site

Hunterston Port and Resource Centre (Hunterston PARC, owned by Peel Ports) is currently in development. It includes the Hunterston Bulk Terminal, a functioning port facility, as well as the Hunterston Marine Yard which will be one of the largest dry docks in the UK, and two rail terminals. Further development will focus on future decommissioning of oil and gas structures as well as construction of assets for the renewable energy sector (*Peel Ports Group, 2016*).

2. Characterisation of the natural hazards

Two hazards are considered for Hunterston: marine biofouling and space weather. For each of them, a characterisation of the hazard is provided alongside a review of past events and examples of methodologies available to assess the hazards. For more detail about methods and data for characterising the different natural hazards, the reader should refer to the corresponding technical volumes:

- Volume 10 — Space Weather;
- Volume 11 — Marine Biological Fouling.

2.1 Marine biological fouling

2.1.1 Characterisation of marine biological fouling

Marine biofouling, or biological fouling, is the undesirable growth of marine organisms (both plants and animals) on man-made structures that are submerged for a sustained period; e.g. boats, buoys, jetties and piers, and the bases of offshore installations such as oil rigs and wind turbine foundations. The species which cause biofouling are perfectly adapted to colonising naturally-occurring hard ***substrates***, such as rocky seashores; so the accumulation of marine growth on man-made structures is to some extent inevitable, despite ongoing advances in anti-fouling paints and coatings.

The life histories of biofouling species are characterised by a free-swimming or planktonic juvenile phase, which drifts on the ocean currents until it comes into contact with a suitable hard surface to colonise. The subsequent adult form attaches firmly to this surface and extracts nutrients from the water column. Common biofouling colonisers include barnacles, mussels, tubeworms, anemones and seaweed. The colonisation of sessile (fixed/immobile) biofouling species then attracts mobile species such as fish and crustaceans.

Biofouling causes problems by increasing surface complexity, load and hydrodynamic drag on a structure. It can accelerate corrosion, compromise mechanical integrity and ultimately cause system failure. More than 4000 biofouling species have been reported globally (*Cao et al., 2011*). During the recent decommissioning of piled wind turbines, from the Solway Firth (UK), hard fouling of up to 300 mm thickness was observed on the upper 2 to 3 m of the submerged structure. On the North Sea oil platform, Montrose Alpha, 40 different species of sessile marine growth were recorded including seaweed and kelp, mussels, ***hydroids*** and ***bryozoans*** (*Forteath et al., 1982*).

Whilst biofouling may be a concern for engineers, the creation of 'artificial reefs' can be a positive outcome in terms of habitat creation and biodiversity. Before the onset of industrial fisheries, large areas of the southern North Sea were covered in natural reefs, many of which are now lost (*van der Stap et al., 2016*). In contrast, many thousands of artificial structures are now present in the North Sea in the form of shipwrecks, wind farms and oil and gas platforms; and thousands more will be installed in the near future.

Coastal power stations that utilise seawater in a *once-through* (i.e. open) *cooling water system* can also suffer from biofouling within the system. If untreated this will impede water flow and drastically reduce the efficiency of heat transfer condensers. However, the semi-enclosed nature of these systems allows the water itself to be dosed with anti-fouling chemicals. This is currently an effective solution which generally keeps the issue within manageable levels. However, future changes in environmental permitting of chemical discharges could make the current solution unavailable. New, alien or invasive biofouling species could be more resistant to even the current treatment. The control of fouling in water intakes, piping systems and desalination plants is estimated to cost over $15 billion per year (*Faimali, 2014*).

Nevertheless, due to the current availability and efficacy of chemical dosing treatments, once-through cooling water systems are currently more vulnerable to clogging by mobile (i.e. non-colonising) marine organisms such as jellyfish, fish and seaweed (that has broken away from the sea floor). This phenomenon may be interchangeably referred to as biofouling, biological clogging or marine ingress.

2.1.2 Historical review of biological clogging events

The Hunterston industrial complex includes submerged and semi-submerged marine structures, both at the coal handling port and the operational power station, so biofouling by sessile (non-mobile or attached) marine species is relevant to this case study. The sea walls surrounding the NOWTTF and the construction yard will also be vulnerable to this form of biofouling. However, little historical information is available on this type of biofouling at the coal handling port, and on the sea walls surrounding the NOWTTF and the construction yard.

As for HNB, it largely avoids this particular problem by dosing its once-through cooling water system with sodium hypochlorite (a chlorine-based oxidant). Chlorination is the standard practice for the control of biofouling in the direct cooling water circuits of power plants, due to its proven effectiveness, limited environmental impact and acceptable capital and operating costs. The dosing regime at HNB is closely monitored to demonstrate compliance with a discharge consent regulated by the Scottish Environment Protection Agency (SEPA).

However, there are some elements of the cooling water system that are upstream of the dosing point, and therefore unprotected by the dosing. The cooling water intake, for HNB, is located at the end of a jetty, and surrounded by coarse (large aperture) steel screens designed to stop large objects from entering the cooling water system. The pier and the coarse screens are not protected by the chemical dosing regime, and are therefore subject to biofouling by sessile marine species. This issue was entirely predictable and well understood at the design stage, and the pier was therefore built to withstand this form of biofouling. It is routinely inspected for structural integrity, and repairs will be made where necessary.

The coarse screens are a different matter as, if left alone, they would accumulate sufficient marine growth that they would restrict the flow of cooling water, and ultimately become blocked. This problem has historically been addressed by removing individual screens in a regular, five-weekly cycle, and rotating them with spares. At any one time, there are ten operational coarse screens, in situ, plus two spares housed on top of the jetty. A screen, once removed, is subjected to a manual cleaning process, where the marine growth is scraped from screens. It can then be rotated back into service. Each screen is constructed from mild steel flat bar and is 3.67 m (12 ft) high by 2.38 m (7ft 8 in) wide (*Figure 2*). The manual cleaning process is a highly labour-intensive task, often undertaken in foul weather.

In 2014, HNB trialled an additional method for dealing with this problem. The two spare coarse screens were sent to a specialist engineering company, where they were shot-blasted, re-profiled, and coated with an anti-fouling agent. The screens with the new coating were tested against untreated screens, and showed a considerable improvement in terms of the amount of biofouling by sessile organisms (*Figure 2*). It is understood that, on this basis, the new coating was subsequently applied to the remaining ten coarse screens, thus reducing the requirement for labour-intensive manual cleaning.

Figure 2. HNB coarse screens after five weeks in situ during normal operation. Screen with new coating on the right; untreated screen on the left. (Source: EDF Energy)

Moving on to the separate issue of biological clogging by mobile macro marine organisms, this is an important challenge for HNB, but is not considered a problem for the rest of the Hunterston industrial complex.

HNB continuously abstracts a high volume of seawater (up to a maximum of 28.48 cubic metres per second), primarily required for efficient operation of its turbine generators. It is inevitable that this high volume of seawater will contain some marine life so, in common with the rest of the current operating UK nuclear fleet, HNB operates a set of rotating drum screens, designed to filter out marine debris, and thus allow an unrestricted flow of cooling water. However, the system was inevitably designed and built to cope with a certain maximum rate of material arrival. Most of the time this system operates well within these constraints. However, there are occasions when the system is overwhelmed by exceptionally high densities of material. *Figure 3* shows the number of marine ingress 'events' recorded in HNB Operational Experience (OPEX) logs. It is not advisable to read too much significance into any observable trends in this data, as individual OPEX records are not necessarily comparable to one another (some recorded events will be much more severe than others). Nevertheless, a trend of events increasing over time is clearly observable, and this is the current understanding at EDF Energy.

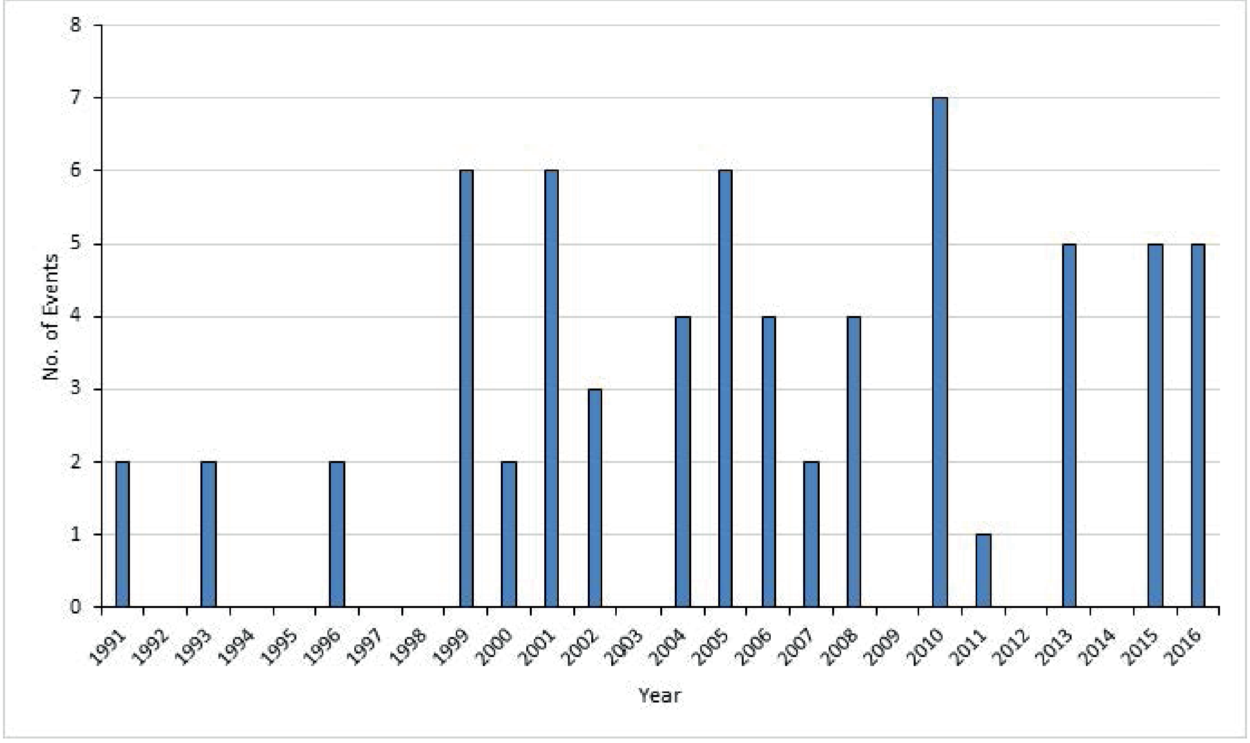

Figure 3. Marine ingress 'events' recorded annually at HNB. (Source: EDF Energy)

Several theories have been considered to explain the increasing trend, but there is currently no clear answer. Problematic ingress events at HNB are caused by both seaweed and jellyfish. Schooling fish (sprat and herring) cause ingress problems elsewhere in the UK, but have never been a problem at HNB. Severe seaweed and jellyfish ingress events occur under very different circumstances, so it is worth considering them separately. Severe seaweed ingress events happen during storm conditions, when wave energies are high enough to rip seaweed from the seabed. For severe jellyfish ingress, there must be the perfect combination of circumstances to allow a jellyfish bloom (e.g. calm weather and abundant food) and then the right currents to transport the bloom, intact, to the station's cooling water intakes.

Figures 4 and *5* show the same marine ingress OPEX events, but with separate graphs for seaweed and jellyfish. When viewed separately, the previously observed trend is less clear.

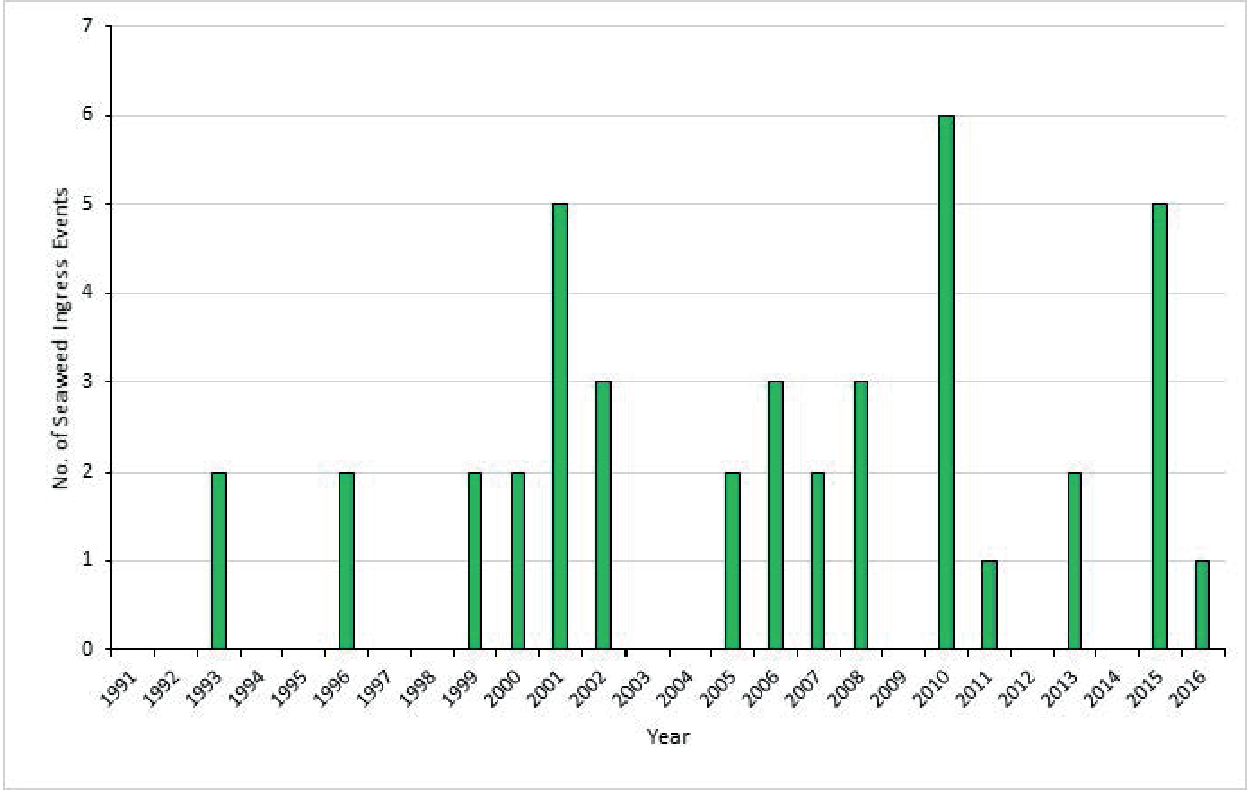

Figure 4. Seaweed ingress 'events' recorded annually at HNB. (Source: EDF Energy)

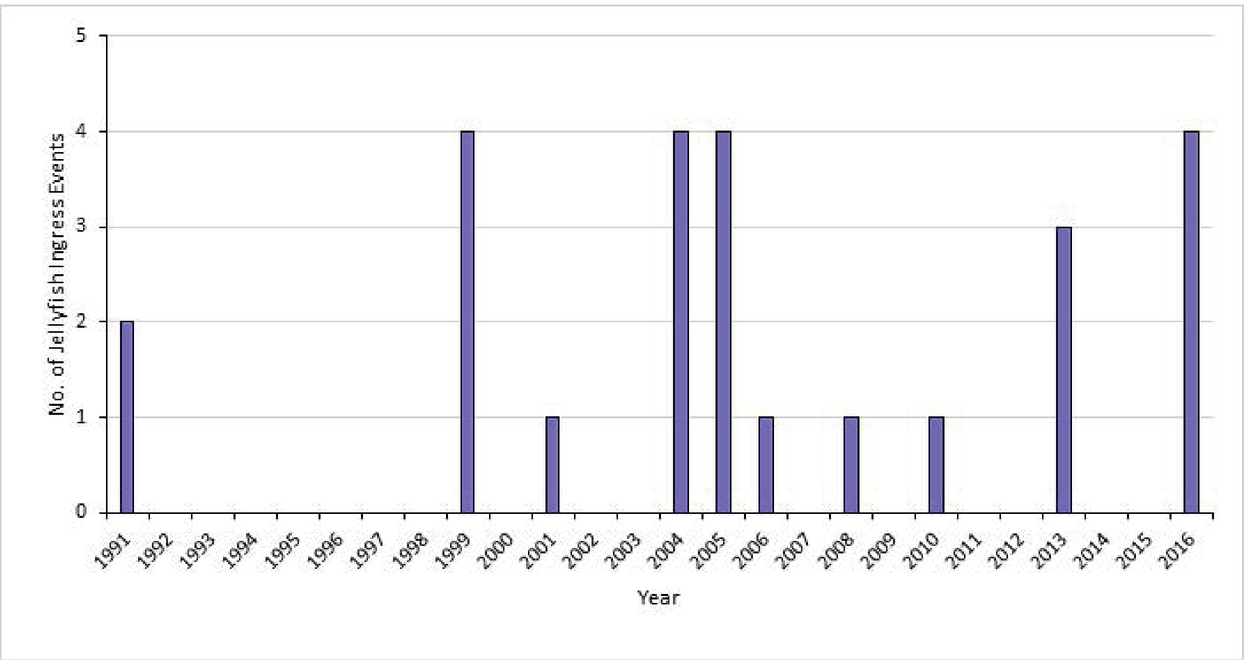

Figure 5. Jellyfish ingress 'events' recorded annually at HNB. (Source: EDF Energy)

2.1.3 Assessing the hazard

In Volume 11 — Marine Biological Fouling, a literature review of the biological species responsible for biofouling and clogging has been undertaken, along with their functional traits, larval duration, settling behaviour and any other information which might identify likely proliferation conditions. The spatial distribution of each species was mapped using the

International Council for the Exploration of the Sea (ICES) statistical areas, and all the above information was entered into a database. In all, 62 species were identified in nine main groups. Some have been previously recorded as providing nuisance to existing power assets, whilst others are considered sufficiently likely to cause nuisance. This new dataset, published in 2016, is the most comprehensive and up-to-date tool for characterising this natural hazard.

To undertake such a hazard assessment, it is necessary to combine the species-specific data, from the database, with information on the planned infrastructure and its local environment. For Hunterston, 45 of the 62 species in the database have been identified as occurring in the same ICES statistical area. The next step is to consider the settling and proliferation requirements for each of these 45 species, and whether they will be met by the planned infrastructure and its location/environment, e.g. depth, temperature, salinity, wave energy levels and currents.

For example, the blue mussel (*Mytilus edulis*) spawns (produces larvae) between April and September. The larvae spend 30 to 81 days as zooplankton, drifting passively in the water column, so the settling period is May to December (temperature permitting). Once settled, the blue mussel thrives at depths between 0 and 10 m, and at temperatures between 5 and 20 °C. It requires a minimum salinity of only 5 Practical Salinity Units (PSU), so it can survive in estuaries and other low salinity environments. If the location of the planned infrastructure meets these requirements, colonisation by the blue mussel should be expected, with growth rates of up to two mm per month, and a life expectancy of 18 years. In contrast, the kelp species, *Laminaria hyperborea*, tolerates a wider depth range (between 3 and 47 m) but requires a higher minimum salinity (30 PSU), so will not survive in estuaries. Where the environmental conditions are right, it can grow at a rate of up to 30 cm per month, and survive for 20 years.

The database of biofouling species is a useful tool to start assessing the risks of marine biofouling to new marine or coastal infrastructure. However, this work should be considered as a snapshot of the information available at the time of publication (2016). The marine biological environment is inherently dynamic and future changes to water temperatures and circulation patterns, e.g. as a result of climate change, are expected to alter both native and non-native species distributions. Various observations have been made with respect to previously more southerly distributed species gradually extending their ranges northward as sea temperature averages increase. It is hoped that emerging power technologies will build upon this work, and that future experiences of how fouling organisms affect new designs will add further useful information to the hazard dataset.

2.2 Space weather

Space weather deals with processes that originate from the Sun which can impact the terrestrial environment and infrastructure at ground level. Geomagnetic storms and the associated geomagnetically induced current (GIC) for extreme cases will be the focus in this section. Space weather encompasses several large-scale processes occurring in the region between the Sun and the Earth, the environment surrounding the Earth (inside the ***magnetosphere***, magnetic shield of the Earth) and the upper part of the atmosphere (ionosphere). Hence, terrestrial and regional impact analyses are difficult to carry out. In this case study, characteristics of space weather processes are mentioned, followed by examples of historical space weather events and techniques available to simulate GIC risk for electrical infrastructure along with the geographical and infrastructural specificities of Hunterston. Other technological disruptions related to space weather events are also briefly outlined.

2.2.1 Characterisation of space weather processes

Space weather concerns the processes related to solar activity. Solar activity includes solar flares, coronal mass ejections, and solar energetic particles (SEPs). The main cause of solar activity is related to the continuous evolution of the solar magnetic field. The space weather processes of interest are the following (more information is provided within Volume 10 — Space Weather):

- *Coronal mass ejections* (CMEs) are large ***plasma*** clouds, containing electrons and protons embedded in magnetic field lines. CMEs can be ejected from the Sun in any direction. Only the ones directed towards the Earth can cause an impact at ground level.
- *Solar flares* are intense bursts of radiation. They can be observed through photons that are released over a wide frequency band.
- *Solar energetic particles* are released during solar flares and occur due to shocks at the front part of CMEs.

These phenomena create different types of disturbances on Earth:

- Grid outages can be observed during severe geomagnetic storms. Depending on the intensity and the direction of the magnetic field contained in the CME, the magnetosphere may be disturbed, i.e. the topology of the magnetic field lines is modified. Bursts of particles are then injected into the upper part of the atmosphere (the ionosphere) toward the higher latitudes, creating higher currents in the ionosphere. Finally, inductive effects will generate current in the lithosphere. GIC tends to follow less resistive paths such as high transmission lines.

- Geomagnetic storms and flares which disturb the ionosphere can disrupt radio and satellite communications including Global Positioning System (GPS) signals.
- SEPs can increase the level of radiation on Earth; this is called ***ground level enhancement*** (GLE) (*RAE, 2013*). Ionising radiation can trigger soft, firm or hard failures in modern microelectronics.

2.2.2 Historical severe geomagnetic storms

Different severe space weather events occurred in the past and led to damage specifically in North America, Sweden and South Africa. The most severe and recent space weather occurred in March 1989 which produced a blackout in Quebec (*Bolduc, 2002*) and damaged two transformers in the UK (*Erinmez et al., 2002*). The geomagnetic storm observed in 1859 by Lord Carrington (commonly named the Carrington-type event) is often taken as a reference for an extreme geomagnetic storm. This solar eruption damaged the telegraphic system at that time. On 28th August and 2nd September 1859, ***auroras*** (a natural appearance of coloured light in the sky, usually seen in the latitudes close to the poles) were observed down to the 18° latitude (in Panama).

The intensity of a geomagnetic storm is deduced from the variation of the magnetic field measured at ground level by a magnetometer. More specifically this is the rate of change of the horizontal plane magnetic component, $\frac{dB_h}{dt}$ (*Viljanen et al., 2001*). Three magnetometers are located in the UK (at Hartland, Eskdalemuir and Lerwick). The largest measured value in the UK is 1100 ***nanotesla*** per minute (nT/min), recorded in 1991. Different geomagnetic indices such as *Kp* and disturbance storm time (*Dst*) index derived from a network of geomagnetic observatories are also used by space weather forecasting centres to analyse at the earth scale the intensity of the geomagnetic storms (see Volume 10 for more detail). *Dst* values of −589 nT and −800 nT are associated with the 1989 event and the Carrington-type event respectively (a geomagnetic storm is defined as intense when *Dst* is lower than −200 nT).

The return frequency associated with the occurrence of a Carrington-type storm is difficult to estimate. Past studies analysed the 50-year *Dst* index dataset (recorded from 1957) using different statistical methods: extreme value analysis (*Tsubouchi and Omura, 2007*), power law or log normal statistical distributions (*Riley, 2012*; *Love, 2015*). The return period from these studies spans from 80 years to 40,000 years. Based on these results and catalogues of past aurora observations (*Willis et al., 2005*), it could be assumed that the return period is less than 1000 years. However, these analyses do not take account of the local variation in the magnetic field that depends on the latitude. *Thomson et al. (2011)* performed an extreme value analysis of the horizontal component of the magnetic field (B_h) observations at different geomagnetic latitudes in Europe to understand how extreme geomagnetic storms can be. Due to the latitude of the UK, this region has a tendency to observe enhanced magnetic field activity during a geomagnetic storm event. For a 1-in-200 year event (i.e. an annual exceedance probability of 1/200) the equivalent values are 1000 to 6000 nT/min; these values are the minimum and maximum extremes associated with specific stations in Europe and illustrate the range of plausible values.

2.2.3 GIC modelling methodology

Assessing the risk posed by GIC to power grids requires the investigation of several elements such as the rate of change of the magnetic field, the conductivity or resistivity (inverse of the conductivity) of the ground, and the characteristics of the electrical network (*Beamish et al., 2002*). In the case of assessing the risk at the transformer level, other information (such as transformer type) is needed. GIC modelling requires different steps — the determination of the geoelectric field at the surface of the Earth, and the calculation of GICs in the grid. Note that GIC can propagate along the gas and oil distribution network (*Fernberg, 2011*). This situation does not apply at the case study site as no major pipelines cross the Hunterston area (*National Grid, 2018*). The following subsections describe the fundamental elements that are required to simulate GIC across the electrical supply network.

Ground conductivity structure

The first step for simulating GIC requires the calculation of the intensity of the geoelectric field at the surface; this calculation is dependent on the ground conductivity. The geoelectric field penetrates the upper mantel of the Earth. The resistivity models take into account layers down to a depth of 1000 km. The upper layer, down to 100 km, is generally different across the UK. Below a depth of 100 km, the mantle is fairly uniform. *Figure 6(a)* illustrates the complexity of the geological structure in the UK. Each rock possesses different conductivity properties. A one-dimensional conductivity model is often selected (see GIC studies such as *Beggan et al. (2013)*, *Kelly et al. (2017)*). The European Risk for Geomagnetically Induced Currents project (EURISGIC, FP7 Project — European Risk for GIC) developed a model that consists of several blocks of conductance (*Viljanen et al., 2012*), as illustrated by *Figure 6(b)*. This model is characterised by a upper resistivity of 100 ohm.metre. *Figure 6(c)* represents the conductance of the top 3 km of the crust at Hunterston (1 km resolution). The saline water is highly conductive and slight variations in the conductivity can be observed on the land. Hunterston is situated between the conductive sea and non-conductive igneous volcanic rocks. The site itself sits on relatively conductive sandstone by the shore. Thus, an enhanced electric field is observed in this area due to the 'channelling' effects of the coastline and the hard rock. Note that generally a conductive layer reduces the intensity of regional GIC in geophysical terms. However, locally, a conductive layer could reduce the transformer's earthing resistance, thus increasing its susceptibility to GIC.

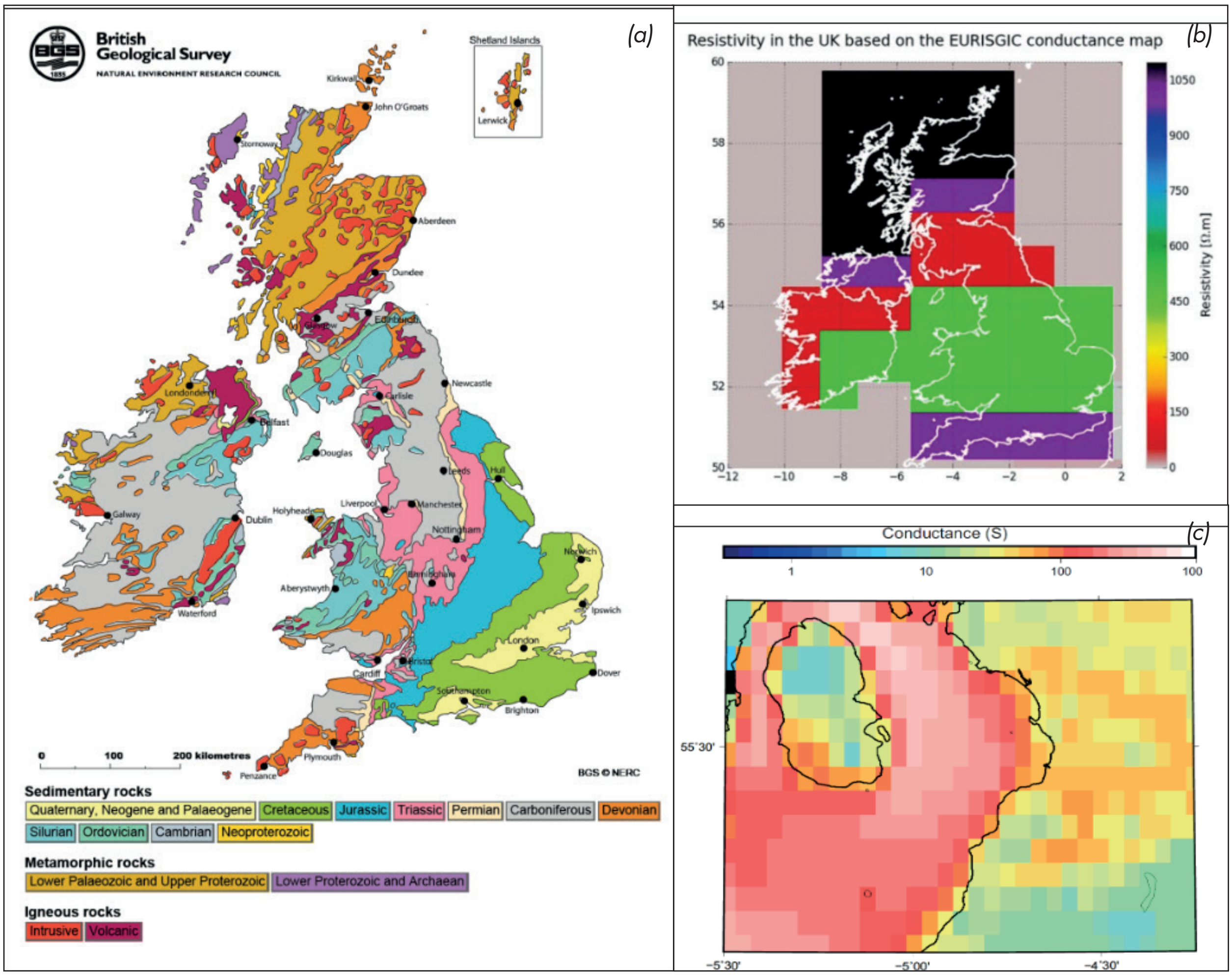

Figure 6. (a) Geological map of the UK © NERC. (b) Ground block resistivity map of the UK based on the FP7 European Project EURISGIC; the scale colour indicates the surface layer resistivity (Viljanen et al., 2012). (c) Conductance map of Hunterston area (1 km resolution, in siemens (S)); the sea is highly conductive © NERC.

High-voltage transmission network

The simulation of GIC is obviously highly dependent on the characteristics of the HV transmission network. In the UK, the HV transmission network is owned and maintained by regional companies. SP Energy Networks (part of the ScottishPower group of companies) is responsible for the transmission of electricity in southern (including Hunterston area) and central parts of Scotland. National Grid Electricity Transmission plc (NGET) is the UK system operator, responsible for operating the national electricity transmission system (NETS) in England, Wales and Scotland.

Characteristics of the network including number of substations, transformer resistances, ground resistance line systems activated, and line resistance, must be taken into account when simulating GIC. Approximate UK models can be built using publicly available documentation such as the National Grid Electricity Ten Year Statement (ETYS) (*National Grid, 2017*) in which transformer names, short code, connection-to nodes line length and line resistances for the 400 kV and 275 kV networks are included. The 132 kV network in Scotland is also included as managed by NGET (but not for England and Wales). Some important information is missing such as the location of the transformer, type of transformer and earthing resistances. It is important to highlight that the network is not static; its configuration can vary day-to-day.

The HV transmission system network in the Hunterston area is characterised by the presence of five substations (Hunterston, Hunterston Converter Station, Hunterston North, Hunterston East, Hunterston Farm), connected to the 400 kV, 220 kV and 132 kV networks. The site also contains a converter station that converts the DC, flowing through the marine cable from Hunterston to Flintshire Bridge, to AC which can be used by the electric transmission system. Underwater DC connectors are not affected directly by GICs, though the AC-DC converters may be affected by additional harmonics (*RAE, 2013*). *Figure 7(a)* presents a simplified HV transmission network, modelled using ETYS data, along with the network architecture zoomed in at Hunterston *(Figure 7(b)*).

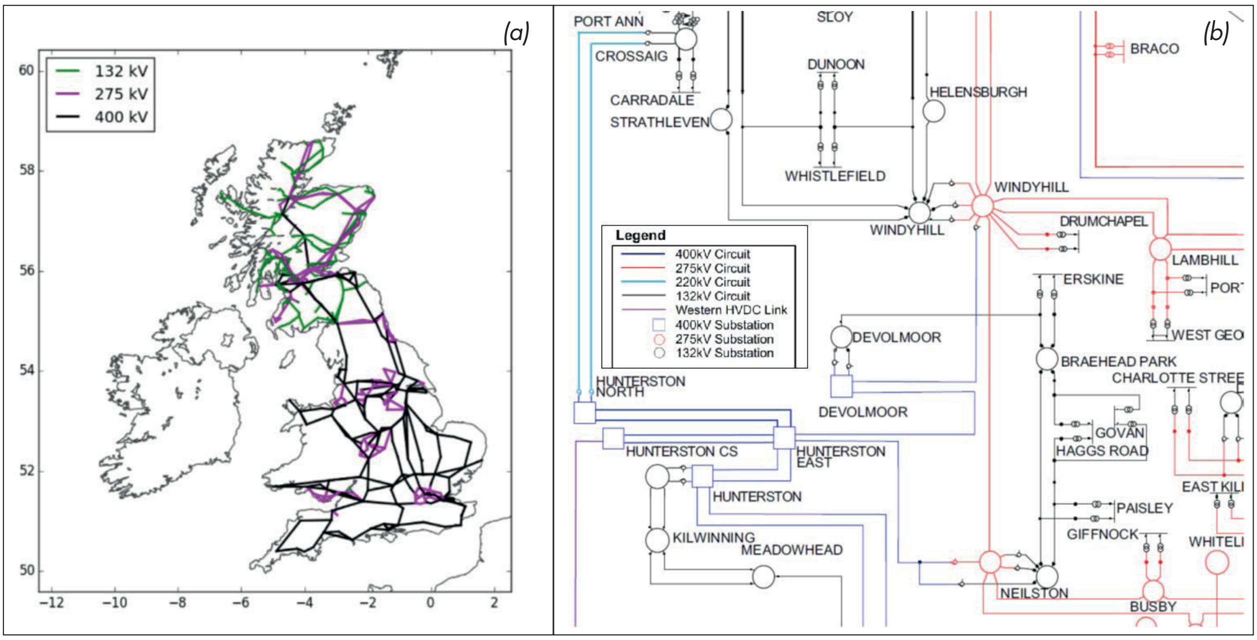

Figure 7. (a) Simplified HV network (132 kV, 275 kV, 400 kV) built using ETYS 2017 data © NERC. (b) HV electric transmission network zoomed in at Hunterston © National Grid plc, all rights reserved.

General methodology

The surface electric field is computed by combining the ground conductivity model with the spatial and temporal measurements of the horizontal magnetic field. The surface electric field response can be calculated using a thin-sheet modelling code (*Vasseur and Weidelt, 1977*) that permits the determination of the surface electric field arising at a frequency from the conductivity models. Alternative techniques exist, such as transfer function analysis (*Ingham et al., 2017*). Finally, GIC entering and exiting the earthed high-voltage can be calculated using the approach of *Lehtinen and Pirjola (1985)* with the Ohm's and Kirchoff's law:

$$I_e = (1+Y_n Z_e)^{-1} J_e$$

where J_e is the geovoltage between nodes, Z_e is the earthing impedance matrix including the earthing resistances of the system. Y_n is the network admittance matrix and I_e is the GIC at each node.

GIC tendency

This section does not contain specific GIC results for the Hunterston area. Due to the sensitivity of results produced by the configuration of the power network (*Kelly et al., 2017*) and the lack of availability of information regarding the transformer technology used in the different Hunterston stations, we advise the reader to use up-to-date conductivity and power network data. GIC models currently have weaknesses such as lack of shallow structure and lateral variations in conductivity models and lack of coast effect; there is ongoing research in this area, such as the NERC-funded Space Weather Impacts on Ground-based Systems (SWIGS) project (*UKRI, 2018*).

In the UK, typical ground-level electric field strengths are of the order of 0.1 V/km during quiet space weather, but may rise to ~5 to 10 V/km during severe space weather (for example during the October 2003 storm) (*Thomson et al., 2005*). *Winter et al. (2017)* presented a method for creating a realistic Carrington-type event magnetic field model at UK latitude, they estimated the range of maximum electric field values of 4 to 20 V/km, with a GIC peak around 300 Amperes (A). In *Beggan et al. (2013)*, ten nodes across the UK which experienced the largest GICs during their 200-year return period (scenario close to a Carrington-type event) were used to estimate induced currents; values in the range from 131 A to 384 A were obtained. *Kelly et al. (2017)* estimated the GIC peak observed at any point in the network in the UK of 290 A for a Carrington-type event, based on the scaled March 1989 event.

2.2.4 Other space weather hazards

Ground level enhancement and impact on microelectronic equipment

Cosmic rays and solar particles impact the upper atmosphere and create particles, mainly protons, in the upper atmosphere which can directly affect satellites. Secondary particles generated in the atmosphere can lead to an increase in neutron irradiation at ground level which can interfere with microelectronic equipment. Sudden increases of neutron fluences can be observed during solar energetic particle events (*RAE, 2013*). This may cause single event effects (SEE) in microelectronic components. This can lead to disruption, performance degradation and complete system failure. The impact of SEPs at ground level has not yet been extensively studied.

Disruption of satellite (including GNSS positioning) and radio communication

Global Navigation Satellite Systems (GNSS), GPS and other similar systems are used in many devices, providing navigation and positioning services. During an intense space weather storm, these satellites may be disrupted by the impact of SEPs. In addition, *solar radio bursts* may cause radio noise interference. Finally, CMEs arriving a few hours after these bursts can cause direct *ionospheric scintillation* (random fluctuations in phase and amplitude of an electromagnetic wave in response to a varying refractive index of the medium in which the wave is propagating), disturbing radio and satellite communication (*Hunsucker and Hargreaves, 2003*; *Ippolito, 1999*). Any degradation to satellite communication or navigation in the UK will likely depend on the location of the satellites to which signals are transmitted or from which they are received. However, GPS and Galileo satellites with their 55° orbital inclination, can at times be in locations where the signals to and from a given satellite are affected by scintillation. Severe scintillation conditions can prevent a GPS receiver from locking on to the signal and can make it impossible to calculate a position. Less severe scintillation conditions can reduce the accuracy and the confidence of positioning results.

Terrestrial commercial communications in the UK are resilient since they are not reliant on GPS. However, solar radio bursts can disturb the signals, but only for parts of the network facing the Sun at dawn and dusk (*RAE, 2013*).

3. Conclusion

In this document, elements of guidance for characterisation of marine biofouling and space weather events (mainly GIC) have been applied at the Hunterston site. This document does not contain specific risk estimates since both hazards are emerging as key topics of research and, as such, characterisation of these hazards in the future will require extended databases and analysis. However, this document has highlighted the main areas to focus on when designing future infrastructure.

The risks associated with marine biofouling events have been illustrated through past extreme events encountered at Hunterston B nuclear power station. It has been shown that several different species need to be considered when undertaking a risk analysis for marine biofouling, and the occurrence and intensity of events will depend on several site-specific factors. The current work provides a snapshot of species that could affect a site, but it is clear that this is an evolving context and the number of marine biofouling events may be increasing with time. However, there is no clear explanation regarding this tendency. Volume 11 — Marine Biological Fouling contains a database of biofouling species in the UK and this is a starting point to assessment of risk to any new marine or coastal infrastructure.

The space weather hazard was added to the National Risk of Civil Emergencies in 2011 (*HM Government, 2017*). Disruptions related to intense events (such as the Carrington event observed in 1859) on ground-based infrastructures (power grid, microelectronics, GNSS/telecommunication systems) could be important. Hunterston, and more generally the UK, is vulnerable during an extreme event due to its high geomagnetic latitude, deep earth conductivity structure and proximity of the coast line to much of the power grid infrastructure. Risk assessment requires the simulation of extreme GIC events on the power system network with a more refined analysis of the system response (calculation of GIC at each transformer, transformer reactive losses and transformer thermal assessment). It may also be necessary to carry out an assessment of single event effects vulnerability due to ground-level events for sensitive devices and for systems requiring GNSS or satellite communication. Mitigating these events requires the ability to forecast them. Space weather forecast centres deliver essential information, but the prediction of the severity of the geomagnetic storms that is needed for GIC evaluation (i.e. variation of the magnetic field at ground level) remains challenging. Monitoring systems (GIC sensor or neutron monitor) also play an important role for benchmarking simulation or developing alert systems. Finally, engineering systems may be designed to reduce vulnerabilities at the system level.

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Aurora

Sporadic radiation emission, appearing as streamers of light, that usually occurs in the northern or southern sky regions of the Earth. It is caused by charged particles that precipitate into the upper atmosphere during periods of Earth's magnetic field disturbances.

Bryozoans

Colonies of microscopic animals; the colonies of different species take different forms.

Coronal mass ejection (CME)

Generated from the outer solar atmosphere, the corona, that is structured by magnetic fields. Plasma can be confined inside these fields and suddenly be released into the interplanetary medium. Larger CMEs can contain a billion tons of matter with an average speed of 400 km/s. They may be directed into the Earth, impacting the extra-terrestrial environment.

Ground level enhancement (GLE)

Sudden increases in the count rates of neutrons due to SEP events recorded by ground-based detectors at ground level.

Hydroids

Colonies of microscopic animals (polyps, or inverted jellyfish) attached to a feather-like base, often mistaken for plants.

Ionopsheric scintillation

The rapid modification of radio waves caused by small-scale structures in the ionosphere.

Magnetosphere

An area of space, around a planet, that is controlled by the planet's magnetic field. It is formed by the interaction of the solar wind with the planet's magnetic field.

Nanotesla

The tesla (T) is the derived unit of the magnetic flux density. It is equal to one weber per square meter. 1 nanotesla = 10^{-9} tesla.

Once-through cooling water system

Extracts cold water from the environment, circulates it through pipework and condensers to absorb heat from other systems, e.g. steam turbines, and then discharges the warmed-up water back to the environment. The opposite of a closed system, in which the water is recirculated.

Plasma

A state of the matter in which the atoms are ionised.

Reactive power

The power required to maintain adequate voltage in the system.

Sessile

Fixed in one place; immobile.

Solar energetic particle (SEP)

A high-energy particle coming from the Sun. It can be a proton, electron or heavy ion with energy ranging from a few tens of mega to giga electronvolt.

Solar flare

An intense burst of radiation (covering large parts of the spectrum) that follows the release of magnetic energy associated with sunspots.

Solar radio burst

Radio waves that cover a broad waveband created by a solar flare.

Substrate

The surface or material on which an organism lives and grows.

Abbreviations

AC	Alternating current
CEERE	Centre of Engineering Excellence for Renewable Energy
CME	Coronal mass ejection
DC	Direct current
Dst	Disturbance storm time
EURISGIC	European Risk for Geomagnetically Induced Currents
ETYS	Electricity Ten Year Statement
GIC	Geomagnetically induced current
GLE	Ground level enhancement
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
HNB	Hunterston B nuclear power station
HV	High-voltage
ICES	International Council for the Exploration of the Sea
NERC	Natural Environment Research Council
NETS	National Electricity Transmission System
NGET	National Grid Electricity Transmission
NOWTTF	National Offshore Wind Turbine Test Facility
OPEX	Operational Experience
PARC	Port and Resource Centre
PSU	Practical Salinity Unit
RAE	Royal Academy of Engineering
SEE	Single Event Effect
SEP	Solar energetic particle
SEPA	Scottish Environment Protection Agency
SWIGS	Space Weather Impacts on Ground-based Systems
UKRI	UK Research and Innovation

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