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Coastal Flood Hazards			
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LIST OF ABBREVIATIONS

ALARP	As Low As Reasonably Practicable
BDBA	Beyond Design Basis Analysis
CD	Chart Datum
CEM	Coastal Engineering Manual
CMIP5	Coupled Model Intercomparison Project 5
DBA	Design Basis Analysis
DBE	Design Basis Event
Defra	Department for Environment Food and Rural Affairs
EA	Environment Agency
EIMT	Examination, Inspection, Maintenance and Testing
FEMA	United States Federal Emergency Management Agency
FFC	Flood Forecasting Centre
FRA	Flood Risk Assessment
GIA	Glacial Isostatic Adjustment
IAEA	International Atomic Energy Agency
IPCC	Intergovernmental Panel on Climate Change
JPM	Joint Probability Method
LC	Licence Condition
LIDAR	Light Detection And Ranging
NERC	Natural Environment Research Council
NRW	Natural Resources Wales
OD	Ordnance Datum (Newlyn)
ONR	Office for Nuclear Regulation
PSA	Probabilistic Safety Analysis
RGP	Relevant Good Practice
SAA	Severe Accident Analysis
SAP	Safety Assessment Principle(s)
SEPA	Scottish Environmental Protection Agency
SSC	Structures, Systems and Components
TAG	Technical Assessment Guide(s) (ONR)
UKCFF	UK Coastal Flood Forecasting
UKCP09	UK Climate Prediction 2009
UKCP18	UK Climate Prediction 2018
USNRC	United States Nuclear Regulatory Commission

GLOSSARY

Term	Description
Admiralty Chart	Admiralty Charts are nautical charts issued by the United Kingdom Hydrographic Office.
Backshore	The part of the beach between the foreshore and the coastline covered by water only during storms of exceptional severity.
Bathymetry	Bathymetry is the study of the "beds" or "floors" of water bodies, including the ocean, rivers, streams, and lakes
Bimodal sea	A sea which has two peaks or modes. Bimodal seas are characterised by the simultaneous arrival at the shore of steep irregular waves generated by the constructive interference of separate wave fields from local wind waves and more regular swell waves caused by more distant conditions.
Bulkhead	A vertical shoreline stabilisation structure that primarily retains soil, and provides minimal protection from waves
Capillary waves	Very small waves where the restoring force is surface tension of the water, rather than gravity, which is the restoring force for other waves.
Chart Datum	Tide heights in the UK are measured to Chart Datum (CD), which is a local datum from a specific Admiralty Chart. Tide heights in the UK are also measured to Ordnance Datum (OD) (also see Ordnance Datum).
Class A tide gauge network	The UK Class A tide gauge network averages sea level measurements over a 15 minute period. All sea level data from the UK Class A tide gauge network are available from the British Oceanographic Data Centre (BODC), which has a special responsibility for the archiving of sea level data from the network.
Coastal squeeze	Where a coastline is protected by engineering structures, increases in sea level result in a steepening of the intertidal beach profile, known as coastal squeeze
Credible maximum scenario	The credible maximum scenario is a peer-reviewed, high end, plausible, climate change scenario.
Equinox	The points at which the Sun will illuminate the Northern and Southern Hemispheres equally and when the Sun passes the celestial equator from the Northern to Southern Hemisphere (or vice versa) are known as the equinoxes. There are two equinoxes a year: the autumnal equinox in October and the vernal equinox in March.
Extreme sea level	The term ‘extreme sea level’ defines the results of a hazard analysis before wind–wave or other hazard effects have been combined. This may, but does not necessarily, include an allowance for climate change and the use of the word “extreme” should not be taken to imply that it does.
Fetch	Fetch is the distance of open water parallel to the wind direction that is available for wind driven wave action to develop. The greater the fetch, the larger the waves generated for a given wind speed, up to a maximum that is characteristic of the wind speed.
Flotsam	Flotsam is a type of marine debris associated with vessels. Flotsam is defined as debris in the water that was not deliberately thrown overboard, often as a result from a shipwreck or accident (see jetsam).
Glacial isostatic adjustment	The response of the solid Earth to mass redistribution during a glacial cycle. The movement of water over the surface of the Earth, both as water and as ice, during a glacial cycle acts as a load and the Earth deforms in response to this force; subsiding under the load of an ice sheet or full oceanic basin, and rebounding once the ice sheets melt or water is removed from the oceanic basin.
Gravity waves	Short period waves generated by winds acting on the sea surface and creating a disturbance via the action of viscous shear stress between air and water, where the restoring force opposing the viscous stress force is gravity (see capillary waves).
H++	H++ scenarios can be envisaged as a ‘high end’ range of a change in the frequency, intensity or magnitude of a particular climate metric or hazard, typically beyond both the likely range and 10th to 90th percentile range of climate futures as set out in UK Climate Projections such as UKCP09. The H++

	scenario has an evidential basis that cannot be ruled out based on current understanding and that may occur at some point in the future, and may or may not be tied to a specific time frame (e.g. 2020s, 2050s or 2080s).
Jetsam	Jetsam is a type of marine debris associated with vessels. Jetsam describes debris that was deliberately thrown overboard by a crew of a ship in distress, most often to lighten the ship's load (also see flotsam).
Joint Probability Methods	Joint Probability Methods (JPM) produce a probability distribution of extreme sea levels for a given location by combining statistically the separate distributions of tides and storm surges (and in some cases waves too)
Littoral zone	Coastal environments that extend from the extreme sea water level (or areas that are rarely inundated), to areas that are permanently submerged. This may extend beyond the intertidal zone.
Longshore drift	The tangential movement of beach material along coastlines.
Managed adaptive approach	The aim of the managed adaptive approach is to build flexibility into decisions of how best to protect infrastructure from the effects of climate change today, so that they can be ‘adjusted’ depending on what emerging research indicates may happen in the future.
Neap tides	Neap tides occur seven days after a spring tide where the gravitational effects do not coincide and the tidal range is reduced (also see spring tides).
Nearshore	The region extending from the land water interface (shoreline) to a location just beyond where the waves are breaking.
Ordnance Datum	Tide heights in the UK are measured relative to Ordnance Datum (OD) at Newlyn in Cornwall. Tide heights in the UK can also be measured relative to local Chart Datum (CD) (also see Chart Datum).
Overtopping	Water carried over the top of a coastal defence due to wave run-up or surge action exceeding the crest height.
Palaeoclimate	A climate prevalent at a particular time in the geological past.
Palaeoceanography	Palaeoceanograpic data are derived from many proxies found in deep-sea sediments including trace metal and isotopic composition of fossil plankton, species composition, and lithology.
Perigee	The point in the orbit of the Moon or a man-made satellite nearest to the Earth.
Pluvial	Pluvial flooding is defined as flooding that results from rainfall-generated overland flow before the water enters a river.
Seiche	A seiche is the resonant response of an enclosed or semi-enclosed body of water (eg a harbour) which has experienced a surface disturbance, such as from a seismic or meteorological cause, which then causes the body of water to oscillate at its natural frequency.
Semidiurnal tides	In general, most areas have two high tides and two low tides each day. When the two highs and the two lows are about the same height, the pattern is called a semi-daily or semidiurnal tide.
Significant wave height	The average height of the upper third of the wave heights in a wave record.
Skew surge	The difference between the height of the predicted astronomical high tide and the observed high water within a given tidal cycle.
Spring tides	At New Moon and Full Moon, the gravitational effects combine and high/low tides are a maximum/minimum (also see neap tides).
Still sea levels	Still sea levels are defined as sea levels after the short-term variations due to wind waves are averaged out.
Stochastic	Having a random probability distribution or pattern that may be analysed statistically but may not be predicted precisely.
Storm surges	Storm surge is the rise in seawater level during a storm, measured as the height of the water above the normal predicted astronomical tide. The surge is caused primarily by a storm’s winds pushing water onshore. The amplitude of the storm surge at any given location depends on the orientation of the coast line with the storm track; the intensity, size, and speed of the storm; and the local bathymetry.

Storm tide	Storm tide is the total observed seawater level during a storm, resulting from the combination of storm surge and the astronomical tide.
Storegga slide	Storegga slides, also called Storegga landslides, were a series of submarine landslides in the Norwegian Sea that occurred between approximately 8,400 and 2,200 years ago, causing a tsunami on the UK coast.
Tidal Bore	A tidal bore is a dramatic tidal feature in areas with a high tidal range (eg Bristol Channel) and occur only on a rising tide.
Tidal harmonic variables	In classic tidal harmonic analysis, tidal forcing is modelled as a set of spectral lines, ie, the sum of a finite set of sinusoids at specific frequencies, referred to as constituents
Tidal locking	Tidal locking refers to high tide preventing a river/sluice/etc. from draining effectively by submerging the outfall end of the drain.
Wave setup	Wave set-up is a small increase in the still water level (ie tide + surge + wave set-up) upon which the oscillatory surface waves sit. If waves are breaking then there is a spatial gradient in stress which causes sea levels to elevate by typically 5-10cm near the coast, therefore increasing the overall wave height, because it increases the still water level. A tide gauge cannot distinguish set-up from storm surge (or anything else); it just measures a level. However wave set-up can be determined with a wave model.
Wave run-up	The reach of breaking waves moving up the beach, or coastal topography is known as wave run-up, which can lead to water being forced to elevations higher than the crest height of the wave that caused it.
1% wave height	The average height of the upper 1% of the wave heights in a wave record.

1 INTRODUCTION

1. This annex outlines the main features of coastal flood hazards considered relevant to nuclear safety on nuclear licensed and authorised sites. It applies the general principles set out in the Technical Assessment Guide (TAG) head document [1][1] and provides guidance to inspectors in the application of the Safety Assessment Principles (SAPs) [2] to the assessment of coastal flood hazards. Coastal flood hazards include extreme sea levels due to the combination of high tides and weather induced storm surges (which together give rise to a storm tide), wind driven waves and coastal erosion. This annex also provides guidance on how the analysis of extreme sea levels will change due to long term changes in average (mean) sea level. The scope also includes tsunamis triggered either by earthquakes (see Annex 1 [3]) or submarine landslides. This annex is supported by one Expert Panel paper [4].

2. The Environment Agency (EA) has a major role in regulating coastal defence protection in England, with The Scottish Environmental Protection Agency (SEPA) and Natural Resources Wales (NRW) performing similar roles in Scotland and Wales respectively[2]. An explanation of the respective roles and vires of the EA and the Office for Nuclear Regulation (ONR) is provided by a Joint Advice Note [5]. Local authorities and other asset owners also play a significant role in coastal management and all parties cooperate as guided by the Flood and Water Management Act 2010.

[1] Section 2.1 gives an overview of the TAG 13 documentation structure.

[2] The EA and NRW provide advice to the Planning Inspectorate on the adequacy of flood protection measures for new nuclear sites in England and Wales respectively. Of particular interest to EH inspectors is that they assess the adequacy of the Flood Risk Assessments (FRAs) prepared by potential Licensees of new build sites. Inspectors should assure themselves that the claims made in FRAs are consistent with the claims on flood protection contained in nuclear safety cases.

2 HAZARD INFORMATION

3. Coastal flood hazard magnitude is a consequence of a number of separate factors, and their combinations:

- Tide
- Influence of weather (eg low atmospheric pressure and winds giving rise to storm surges)
- Wave conditions
- Influence of local shoreline and bathymetry
- Presence and performance of sea and coastal defences
- Long term sea level changes (including vertical land movement)
- Tsunami
- Seiches and tidal bores

4. Tide is the predictable variation of still sea levels on an approximately twice daily cycle. The shape and orientation of the local shoreline and sea bed can have a significant influence on both the dynamic response of still water levels due to tidal movement and the severity of wave motion. High air pressure serves to reduce still water level, but more importantly, low pressure weather systems can raise sea levels by up to around 4m ([4] Section 2.3) and is called storm surge. Waves are a consequence of wind action on open water and can enhance the potential for flooding above what would be expected solely from still water level. Since storms produce surge and high wind simultaneously, these factors are correlated, see Annex 2 [6]. High sea level can also be caused by tsunami.

5. Extreme sea level and / or wave energy can give rise to consequential hazards such as coastal erosion and / or damage to sea defences along with changes to local bathymetry. Ultimately, the hazard due to coastal flooding arises from overtopping / overflow of, or a breach of, flood defences leading to site inundation, water ingress to buildings and subsequent damage to structures, systems and components (SSCs).

2.1 Hazard Description – (SAPs EHA.1, EHA.12):

6. The TAG 13 head document introduces the notion of primary, secondary, consequential and correlated hazards (refer to [1] Section 5.2). The hazards that are considered for the analysis of Coastal Flooding are (with the exception of tidal effects) secondary hazards that arise from primary meteorological hazards (discussed in Annex 2 [6]), or other sources in the case of tsunami (such as seismic vibratory hazard discussed in Annex 1 [3]). Annex 2 Table 1 is adapted and extended for the purposes of coastal flood hazards as Table 1 in this annex.

7. The hazards that give rise to Coastal Flooding are briefly described below. Where additional information is necessary this sub-section is supported by Ref. [4] Section 2.

2.1.1 Tidal effects - *(primary hazard)*

8. Tides are periodic variations in the surface water level that result from the mutual gravitational attraction of the Earth, Sun and Moon, see [4] Section 2.5. Most places around the UK experience two high and two low tides each day (so-called semidiurnal tides). Any storm surge component (see above) is additional to the tidal level, so a storm tide can be up to several metres higher than the predicted tide in European seas. Atmospheric conditions can also affect the time of high water.

9. The tidal cycle is 12.4 hours long and is linked to the lunar day, so that successive high tides occur later on successive solar (24 hour) days by just less than an hour. A further two week cycle is evident based on the relative positions of the Sun, Earth and Moon. At New Moon and Full Moon, the gravitational effects combine and high / low tides are

a maximum / minimum (spring tides). One week later and their gravitational effects do not coincide and the tidal range is reduced (neap tides).

10. Some spring tides are higher than others. Tidal forces are strengthened if the Moon is closest to Earth in its elliptical orbit (perigee). Tide generating forces are also enhanced when the Sun and the Moon are directly overhead at the equator. For the Sun this happens on or around 21 March or September (the equinoxes). Spring tides are always higher at these times of year. Further tide cycles are evident over longer periods of years and decades, but their effect is less pronounced. Over 18.6 years the Moon's orbit slowly rotates around so it cuts through the solar orbit in a different place. This so-called nodal cycle has the effect of changing how far above or below the equator the moon can reach in its orbit. This leads to the greatest range between high and low tide and consequently, the maximum and minimum depth of water during the tidal cycle (although it is not possible to specify a simple rule for the absolute determination of extreme (high or low) tidal levels).

11. Tidal effects are very predictable and from a safety case perspective are deterministic. The following tide height definitions are in common maritime use and relevant to nuclear safety:

- *Mean High Water Springs*: The average (mean) tide height throughout the year of two successive high waters during a period of 24 hours when the range of the tide is at its greatest (springs).

- *Mean Low Water Springs*: The average (mean) height obtained by the two successive low waters during the same period.

- *Mean High Water Neaps*: The average (mean) throughout a year of the heights of two successive high waters during those periods of 24 hours (approximately once a fortnight) when the range of the tide is least (neaps).

- *Mean Low Water Neaps*: The average (mean) throughout a year of the heights of two successive low waters during those periods of 24 hours (approximately once a fortnight) when the range of the tide is least (neaps).

- *Highest Astronomical Tide*: The highest level that can be expected to occur under average meteorological conditions and under any combination of astronomical conditions.

- *Lowest Astronomical Tide*: The lowest level that can be expected to occur under average meteorological conditions and under any combination of astronomical conditions.

12. Tide times and tide heights can be predicted with reference to tidal harmonic variables. The UK Hydrographic office publishes times and heights for UK primary and secondary ports and also give relative datum for these ports. The timing and height of the tide varies around the coast and with the state of the tide. Interpolation or modelling is often needed to predict heights and times at locations without published conversion factors.

13. Tide heights in the UK are measured relative to Ordnance Datum (OD) at Newlyn in Cornwall and also to Chart Datum (CD), which is a local datum from a specific Admiralty Chart. Converting from CD to OD is straightforward, but is a potential source of error. For this reason, heights relative to sea level datum should specifically reference whether to CD or OD.

14. Tides lead to sea levels that can be deterministically calculated at any coastal location. For this reason, they can be protected against so that the consequences arising from high and low tides, eg overtopping of coastal protection / exposure of seawater intakes,

can be reduced for all practical purposes to zero. Tides contribute to other flood hazards by coincidental occurrence. They also contribute to other flood hazards in that, if damage has occurred to a sea defense due to an extreme event then flooding can occur at subsequent high tides.

15. Example consequential hazards / effects:

- High tidal effects contribute to overtopping of coastal flood protection.
- Low tidal effects can result in exposure of sea water intake structures.

2.1.2 Storm surge *- (secondary hazard)*

16. A storm surge is the regional increase in sea level due to passage of a storm as it tracks over the sea surface (see [4] Section 2.3 for more details). Storm surges can last from hours to days and span hundreds of square kilometres. They are caused by low atmospheric pressure effects on open water, often in combination with strong winds. The magnitude of any particular storm surge is influenced by many other factors such as the intensity and track of the weather system, the bathymetry of the sea bed and the shape of the coastline. The combination of a storm surge and tidal high water is commonly referred to as a storm tide; around the UK this can lead to sea levels up to several metres higher than due to tide alone. Individual storm tide levels can be predicted since tides are deterministic and storm surges can be modeled using winds and pressures from operational weather forecasts several days in advance[3].

17. Example Consequential Hazards:

- Overtopping of coastal flood protection. Wave overtopping occurs when waves run up the face of a seawall and pass over the crest of the structure or, in cases where the structure is vertical, the wave may impact against the wall and send a plume of water over the crest (see [3] Section 7 for more details).

2.1.3 Wind driven waves – *(secondary hazard)*

18. Relatively short period waves are generated by winds acting on the sea surface and creating a disturbance via the action of viscous shear stress between air and water, see [4] Section 2.4 for more details. This transfers wind energy to the water that manifests itself as surface wave motion with characteristic features, such as wave height and wave length, that depend on the windspeed, the duration over which the wind action exists, and the available fetch. Such waves typically have periods of less than 10s. Within a surface wave, individual molecules of water follow an elliptical orbit but there is no mass transport of water in the direction of propagation. In practice, both wind speed and direction vary about long term steady state values (gusts), so that a spectrum of waves is observed of varying periods up to a maximum characteristic of the steady state wind speed. Wind driven waves are also called storm waves, or referred to colloquially as “sea”.

19. *Swell waves*: Once wind action on the sea surface has ceased, any wind driven waves will persist, sometimes for many days after. Such waves will attenuate in height as they move away from the storm location. Short wavelength (high frequency) waves attenuate far more quickly that long wavelength (low frequency) waves. It is for this reason, that “swell” waves (relatively long waves typically with periods of approximately 10 – 15s) can be observed a long way from the storm giving rise to them (and several days after the waves were originally formed). Swell waves can travel the full width of ocean basins (ie thousands of kilometres). Swell waves and wind driven waves may be observed as separate wave fields with differing directions of propagation, and it should

[3] A coastal flood warning system operates under the auspices of the UK Coastal Flood Forecasting (UKCFF) partnership. A suite of forecast models for storm surges and waves runs four times a day on Met Office supercomputers and delivers coastal forecasts to regional warning centres.

be noted that swell waves carry more energy than wind driven waves of the same wave height.

20. *Shoaling and breaking waves*: As waves approach a coastline from deep water and as depth decreases, wavelength and wave speed decrease, and wave height increases. This is known as shoaling. Shoaling normally continues until a point of instability is reached when the top of the wave overtakes the base and the wave breaks. At this point, the energy of the wave is transferred into a horizontal movement of water mass in the direction of propagation and turbulence. Breaking waves can inundate land beyond the existing water margin. The reach of breaking waves moving up the beach, or coastal topography is known as wave run-up, which can lead to water being forced to elevations higher than the crest height of the wave that caused it.

21. *Seiches*: A seiche is the resonant response of a semi-enclosed body of water (eg a harbour) which has experienced a surface disturbance, such as from a seismic or meteorological cause, which then causes the body of water to oscillate at its natural frequency. The seiche period of a typical harbour is a few minutes and seiche amplitudes are of the order 10-50cm. Seiching is often observed in tide gauge records after earthquakes even when those seismic disturbances were not powerful enough to cause tsunamis.

22. *Tidal Bores*: A tidal bore is a dramatic tidal feature in areas with a high tidal range (eg Bristol Channel) and only on a rising tide. As noted above, tides are caused by the gravitational effects of the Earth, Sun, Moon system and are manifested as coherent ocean waves that affect most locations twice every day. A rising tide inundates areas of coastline as this wave advances. Some funnel-shaped estuaries offer a restriction to the natural progression of the tidal wave which effectively backs up until a point is reached where the difference is relieved by a step change in water level (a hydraulic jump). The result is a single or small group of waves that form the bore, which moves rapidly upriver with the appearance of a moving yet continuously breaking wave.

23. Example consequential hazards / effects:

- Increased likelihood of overtopping of coastal flood protection.

2.1.4 Tsunamis (earthquake-triggered & landslide-triggered) – *(secondary hazard)*

24. Tsunamis are a series of travelling waves of long wave length and period (eg from kilometres to hundreds of kilometres and several minutes to tens of minutes), see [4] Section 2.7.

25. Tsunamis can arise from a variety of causes eg submarine earthquake (the most frequent source), submarine landslides, volcanic eruption, sudden meteorological effects, and meteorite impact.

26. It should be noted that whilst the size of the tsunami waves postulated for the UK (see [4] Section 2.7) may be comparable to those in typical storm surges, certain characteristics of tsunamis (the number of waves, the range of wavelengths) are likely to create sea conditions very different to those during a storm surge. Therefore, it should not be assumed that the impact of a tsunami would be comparable to that of a storm surge simply on the basis of a similar wave height. The very long wave length is especially relevant in this respect, since when tsunami waves approach coastline they can develop into shorter (but still relatively long) waves with substantial crest height. When such waves eventually break they can force large volumes of water hundreds of meters inland, inundating large areas of coastline and causing severe damage to settlements and infrastructure. In doing so they may destroy natural and artificial sea defences or change their state profoundly.

27. Example consequential hazards / effects:

- Overtopping or failure of coastal flood protection.
- Inundation of inland areas adjacent to the coastline.
- Inhibit personnel movement on- and off-site.
- Wide-ranging damage to infrastructure.

2.1.5 Coastal morphology and erosion – *(secondary hazard)*

28. The movement of sea water can change the shape (morphology) of and erode coastlines – therefore changes to coastal morphology and erosion are secondary hazards arising from water movement. When a large quantity of water moves at speed, as can be the case in storm conditions and most tidal conditions, it carries with it enormous amounts of momentum and energy (water has a density of about 1 tonne/m^3). So when it interacts with natural and man-made coastal structures, large forces are produced. Morphologically, in the absence of engineered defences, coastal areas can be classified in to high, medium and low energy environments, with coastlines exposed to the open sea being high energy and protected estuaries and mudflats classed as low energy.

29. Tidal movements combined with waves set up circulation patterns in coastal waters that can transport large quantities of sea bed material, scouring it from some areas and depositing in others. In this way offshore banks are created. These can evolve over seasons, years and decades and can certainly change over the lifetime of nuclear sites (and offshore banks themselves can potentially change very quickly due to an extreme storm event). A further feature is the tangential movement of beach material along coastlines known as longshore drift.

30. The shore is strongly shaped by wave-driven processes, coupled with tidal movement and sea level change. In general terms, the shore form is maintained by these hydrodynamic drivers working on the in-situ geology and mobile sediments. Stabilising feedback processes may allow the shore form to persist even if the coast is retreating or advancing. Changes in the hydrodynamic drivers, sediment availability or underlying geology can lead to a progressive change in form or a sudden change in state (perhaps the breach of a natural sea defence, such as a dune or barrier beach). Such changes may be caused by coastal management interventions, such as the construction of a seawall or revetment. Structures that prevent erosion and the release of sediments may lead to lowering of shore platforms and beaches locally or along connected coasts. Such trends reduce the intertidal width (a process known as ‘coastal squeeze’), increase water depths (and therefore wave activity) and may destabilise the coastal structures.

31. The most damaging short-term erosion processes are due to wave action during storm conditions. There is evidence of severe storms having re-shaped sections of coastline to an extent that changes the nature of the coastal environment over a single storm event. A further feature of storm systems highlighted in Annex 2 [6] is the ability of certain atmospheric conditions to lead to successive storms affecting the same area over a period of days or weeks. This provides an additional erosion challenge to coastlines. Long term effects should be considered over the lifecycle of the site through to final decommissioning.

32. Examples of other related consequential hazards / effects include:

- Undermining of site flood defences by loss of foundation support
- Enhanced likelihood of overtopping of site flood defences due to changes in water depth, local bathymetry and / or shoreline geometry.
- Settlement or differential settlement.
- Blockage of drainage paths by sediment / flotsam / jetsam.

2.2 Issues Affecting Extreme Sea Levels Around the UK – (SAP EHA.11, EHA.12)

33. Due to changes in global mean sea level, there is evidence of a slow increase in extreme water levels around the world, including the UK. The projected rise in globally averaged sea level for the year 2100 has been made by the Intergovernmental Panel on Climate Change (IPCC). On the basis of observed data over the past century, sea level rise around the UK is consistent with global averages, [4] Sects. 2.1 & 2.6.

34. For this country, the UK Climate Prediction 2009 (UKCP09) [7] report predicts an increase that varies around the UK coastline and is subject to considerable uncertainty depending on the greenhouse gas emissions scenario selected; indicative values for the UK are given below[4].

35. The most recent published projections of sea level change for the UK (UK Climate Projections 2009) provide a range of estimates for UK mean sea level rise of between 0.3m and 0.5m by the decade 2090-2099, depending on the greenhouse gas emissions scenario. Because of the many uncertainties involved in making projections of sea level into the future, the UK Climate Projections 2009 have also provided upper bound scenarios (so-called 'H++') to aid contingency planning. These low probability, high impact scenarios are required by some government agencies for contingency planning and vulnerability testing. The H++ figure for sea level rise by the year 2100 is 1.9m and is a value consistent with limiting physical constraints on glacier movement in polar regions, see [4] Section 6.

36. It should be noted that an update is currently in progress (UK Climate Prediction 2018 - UKCP18) that will supersede UKCP09. This is planned for release in November 2018.

37. On the basis of UKCP09 projections, the Department for Environment, Food and Rural Affairs (Defra) and the EA have produced sector-specific flood and coastal risk guidance documents [8]; for further information see [4] Section 3. ONR's expectations are set out in paragraphs 92 and 93.

38. It should be noted that the UK projections must be considered together with local measurements of vertical land movement due to Glacial Isostatic Adjustment (GIA)[5]. When vertical land movement is included then larger sea level rise projections are obtained in southern parts of the UK where land is subsiding and smaller increases are obtained for more northern parts of England and Scotland. Even with no change to the storm climate of northern Europe the rise in mean sea level will increase the frequency of extreme water levels (since storm surges and waves will be superimposed on a higher mean sea level); any particular threshold will be exceeded more often.

39. Modelling studies suggest that changes in tidal range due to climate change will be in the order of plus or minus 10% of the changes in mean sea level. Although small in comparison to the mean sea level changes, altered tidal ranges could enhance coastal flooding at some locations [4]. Changes in tides therefore need to be considered in future assessments of extreme sea level change and coastal flooding.

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[4] Taking vertical land movement into account gives slightly larger sea level rise projections relative to the land in the more southern parts of the UK where land is subsiding, and somewhat lower increases in relative sea level for the north. For example, UKCP09 project sea level rises for the period for 1990–2095 of approximately 21–68cm for London and 7–54cm for Edinburgh. This is based on the outputs for the medium emissions scenario and for the 5th to 95th percentile [7] (UKCP09 UK Climate Projections science report: Marine & coastal projections — Lowe et al. Chapter 3, 21-35, June 2009).

[5] During the last ice age, the mass of the ice sheets caused deformation that resulted in vertical movement of the Earth's crust throughout Europe. Melting of the ice sheets removed this load and allowed the crust to rebound, called GIA. In terms of present vertical land movement in the UK, GIA processes dominate over the negligible vertical component of plate tectonics. GIA is typically modelled with a global geophysical model that includes details of the Earth's vertical structure.

40. Further detail on the impact of climate change on extreme sea level and tidal amplitude along with the various projections obtained from climate modelling is provided in [4] Section 3. An overview of climate models themselves is provided in [9] Section 5.

41. Other factors independent of climate change require consideration. These include changes in the physical geography of a drainage basin, including the estuaries, and changes to the offshore bathymetry, coastal profile and catchment areas. These changes can be natural or as a result of a change in management practice (for example a managed retreat of a defended shoreline) or maintenance regime (such as the dredging of a navigation channel).

42. For river basins and estuaries the design basis coastal flooding event is, to a great extent, dependent on the physical nature of the basin. This can change over time as a result of changes in the geography or other changes such as the construction of storm surge barriers. The continuing validity of the design basis coastal flooding event and the assumptions used can be checked by making periodic surveys of the shoreline and local bathymetry.

2.3 Hazard Data Sources – (SAP EHA.2, EHA.11, EHA.12, AV.3, AV.7)

43. A site-specific hazard analysis for coastal flooding including tsunami for major nuclear facilities requires the compilation of available information that may be pertinent. All such data relevant for assessing the potential for coastal flooding including tsunami hazard is expected to be compiled in catalogues specific to the site.

44. For tsunami, Licensees are expected to refer to published work by Defra and any up-to-date research relevant to the site in question, see [4] Section 8.

45. A brief overview of data sources is given below, but more detail regarding some of these data required for a site-specific analysis of coastal flooding hazards is given in [4] Section 4.

2.3.1 Instrumental data and other scientific data sources

46. *Sea level data*: Instrumental data on UK sea levels is provided by tide gauge networks. All sea level data from the UK Class A tide gauge network are available from the British Oceanographic Data Centre, which has a special responsibility for the archiving of sea level data from the network. Daily checks are kept on the performance of the gauges and the data is downloaded weekly. These are then processed and quality controlled prior to being made available for scientific use. The network includes 43 gauges, most of which are related through the national levelling network to Ordnance Datum Newlyn. Data is collected, processed and archived centrally to provide long time-series of reliable and accurate sea levels which are then suitable for statistical analysis of extreme sea levels. Processed data from the Class A tide gauge network from 1915 to December 2015 are available free of charge. Other sea level datasets for certain locations are held by the EA and by Port Authorities. In order to measure sea level accurately, most tide gauges will average measurements over a 15 minute (or sometimes longer) period to remove noise. This internal averaging which is essential for long term sea level measurements and accurate tidal measurement has the side effect of removing any measurement of wind waves.

47. Another useful data source is the UK wide systematic database of extreme sea level and coastal flooding that has been compiled, covering the last 100 years[6]. Using records from the UK National tide gauge network, all sea levels that reached or exceed the 1 in 5 year return level have been identified at the time of writing. These were attributed to 96 distinct storms, the dates of which were used as a chronological base

[6] This can be found at www.surgewatch.org.

from which to investigate whether historical documentation exists for a concurrent coastal flood. For each event the database contains information about:

- the storm that generated that event;
- the sea levels recorded during the event;
- the occurrence and severity of coastal flooding that resulted.

48. This database is continuously updated. It should be noted that this database will fail to capture the most extreme storm surge if it happened to occur on a neap tide (since then the total water level may not have proved hazardous).

49. In addition to the above, many existing nuclear sites have installed and maintained their own instruments for monitoring sea levels and wave heights. Data recorded from such instruments is expected to be considered and, if appropriate, used to augment the data catalogue. Particular care should be taken to ensure that any local instrumental records have employed good quality control, especially regarding sampling period and datum control. For instance, the UK Class A tide gauge network averages sea level measurements over a 15 minute period which is optimum for tidal and mean sea level studies but will not always reveal records of tsunamis (where sea level oscillates over shorter periods). For this reason it is difficult to identify tsunamis from UK instrumental records.

50. Processed instrumental data is also available via many assessments of extreme sea levels for the UK that have been implemented using varying statistical methods. The need for national consistency and improved estimates, combined with the increase in available sea level data over the past few decades, led to the recent production of a UK database of extreme sea levels which is available from the EA (the full background on this data is provided in [4] Section 5). This uses a joint probability method (JPM) for combining the deterministic tidal distributions with stochastic storm surge distributions.

51. *Other scientific data*: There are many other forms of modern data acquisition relevant to the analysis of coastal flooding. Of particular importance is baseline data that describes the morphological and geological behaviour of the coastline and nearshore, for a particular site. This would normally involve the collection and assessment of charts and surveys, examples of which are given below, without detailed discussion, and is intended to give inspectors the opportunity to challenge Licensees on the completeness of their data collection.

52. Examples of charts and surveys:

- Aerial photographic surveys
- Topographic surveys, including LIDAR (light detection and ranging)
- Bathymetric (depth) surveys including Admiralty and other navigational charts, as well as bespoke bathymetric surveys
- Historic maps giving an indication of morphological changes to the coastline over time.

2.3.2 Historical accounts / records

53. Historical and anecdotal accounts of coastal flooding events and tsunami in written literature can provide useful context for the more accurate instrumental records, and in some cases provide important and otherwise unavailable information for improving the comprehensiveness of the data record, extending back in time for several hundred years (depending on socio-cultural factors such as population density, the availability of printed media and ease of transport across the region). Such accounts are obtained by searching information sources such as newspapers, official historical cultural information sources, personal narratives and film or video records. Such records could, for instance, indicate a severe flooding event not seen in the relatively short instrumental record. Whilst historical data cannot always accurately quantify extreme

events, they can provide an indication of more extreme conditions than contained in short instrumental records. An example of this is the Bristol Channel floods of 30 January 1607 which historical accounts say drowned many people and destroyed a large amount of farmland and livestock.

2.3.3 Palaeological data

54. Palaeoceanography and palaeoclimate data is derived from many proxies found in deep-sea sediments; examples include trace metal and isotopic composition of fossil plankton, species composition, and lithology. Such data sources have significant uncertainties and historically have not routinely been investigated for use in hazard analyses. However inspectors should be aware that these data sources could be considered where available as useful background to inform the hazard analysis. As with historical or anecdotal data they can sometimes indicate the occurrence of an extreme event not present in the modern instrumental record. For Coastal Flooding hazards this data source is most useful for indicating the occurrence of past tsunamis that may have affected the coastline and can help deduce the tsunami source parameters eg the tsunami caused by the Storrega slide. For further information please refer to [4] Section 4.2.

2.3.4 Previous coastal flooding & tsunamis hazard studies

55. As part of the documentation of a site-specific hazard assessment it is expected that the Licensee or prospective Licensee conducts a detailed review and assessment of previous hazard studies for the site, for any other sites in close proximity, as well as regional and national studies encompassing the site. Depending on the authority of previous studies, these can provide useful information on hazard levels at the site. Although of interest, the usefulness of regional and national hazard studies may be limited for site-specific applications, since the hazard maps they produce may be considered too coarse and approximate for site-specific use.

56. The potential sources of tsunami that could affect the UK were reviewed by the UK government following the Sumatra earthquake of 26 December 2004 and the devastating tsunami that followed. This study considered possible tsunamigenic sources, past events and the propagation of tsunami waves to the coast. Further information on this and more recent studies is provided in [4] Section 8, including a review of the evidence for other tsunamis and the sources that may have impacted the UK historically (eg the Storrega submarine landslide). Such distant sources are credible because tsunamis can travel huge distances with minimal energy loss, so that the entire North Atlantic and North Sea constitutes a potential source region for the UK.

57. With regard to flood modelling, the EA has the most extensive collection of studies, however there are many other sources that may provide useful information eg Local Authorities, developers, land managers, infrastructure owners etc.

2.3.5 Statistical data processing

58. Before a site-specific dataset can be used to derive the hazard via statistical analysis methods the data may need to be processed to ensure the format is compatible for the intended end use (eg if the data is intended to be used as an input to a design code then the data format will need to be compatible). An example is ensuring that any additional tide or wave monitoring gauges are correctly calibrated and correspond to the appropriate datum (OD or CD).

59. In some cases the data catalogues may appear to contain exceptional values or outliers. It is expected that these values are investigated and where practicable explained prior to the data values being either retained or removed from the dataset.

60. The hazard data is likely to be used as input to the analysis of shoreline interaction, flood modelling and, in some cases, physical modelling and testing. In such cases the data processing is expected to take account of the characteristics of the facility to ensure its use is consistent with SAP EHA.4 and leads to a conservative estimate of the design basis. For more details see [4] Section 5.

2.4 Notable Aspects of Response of Structures to Coastal Flooding & Tsunami Hazards – (EQU.1, EAD.2, ELO.1, ELO.4, ECE.5, ECE.6, EMC.7, TAG 017 [10])

61. The impacts of coastal flooding hazards on nuclear sites are many and varied and it is not possible to provide comprehensive guidance on every aspect an inspector may encounter. General guidance is provided below based on applicable regulatory experience gained from UK sites over recent years.

2.4.1 Overview

62. Coastal Flooding hazards usually consist of varying combinations of wave and extreme water level that often occur in combination with storm systems that bring various other meteorological hazards such as wind and precipitation. Therefore these combined events may simultaneously affect all exposed structures, systems and components important to safety on a nuclear site. This could lead to the risk of common cause failure for systems important to safety, such as the emergency power supply systems, with the associated possibility of loss of off-site power and other vital systems. The potential for common cause effects and damage across the site is an important consideration when analysing possible implications for a site, including for the incorporation of new, upgraded or appropriately located safety related systems. These considerations are more important when a multi-unit or multi-installation site is under consideration, and in particular if SSCs are shared between units.

63. Coastal Flooding hazards may also affect the communication networks and transport networks around the nuclear site. Their effects may jeopardise the implementation by operators of safety related measures, and may hinder emergency response by making escape routes impassable and isolating the site in an emergency, with consequent difficulties in communication and supply of resources from off-site.

64. Overtopping of flood defences by wave action generally leads to varying degrees of flooding to the area of the site local to the defence barrier itself and to low lying areas that are connected by drainage to overland flow routes. Often sea walls are provided with overtopping drainage via channels and pipework through the defence itself, which returns the overtopping volume back into the sea. If such drainage is overwhelmed, then flooding of the site will increase progressively as overtopping rates and durations increase. Return drainage is often fitted with non-return flap valves on pipe outfalls; if these fail open, say through lack of maintenance, blockage or damage, then the local area may be at an increased risk of progressive flooding. If sea levels submerge drainage outfalls (called tidal locking) then water cannot be drained from the site during submergence. Wind strength and direction at the site can be influencing factors during an overtopping event – potentially increasing the volume and extent of overtopped water.

65. Tidal influence can change sea level substantially during a flood event so that tidal locking and overtopping potential is more likely around high tide and less likely around low tide. Licensees may claim that the overtopping, or the duration over which drains are tide-locked, is limited in time around the high tide point. In such cases, inspectors should assure themselves that the duration claimed is reasonable, and takes account of pluvial inputs [6] and repeat events.

66. Direct breach of the sea defences may lead to the inundation of the local area and the site that may in turn lead to restricted movements on and around site, flooding of basements and low lying areas, backing up of drainage systems, flooding of plant

areas and potential to breach containments, potential shorting and damage of electrical equipment and other SSCs.

67. Wave action can progressively cause damage to flood defences directly leading to breaches. Coastal erosion and / or changes in local morphology can lead to the undermining of the site platform and offshore structures (seawater pipework, intakes, and outfalls). In addition, changes in local morphology could lead to changes to circulation patterns that may reduce cooling efficiency derived from seawater abstraction. Storms can also stir up large volumes of sediment and other material eg seaweed that could clog intakes and adversely affect outfalls.

68. Coastal flood hazards can occur at the same time as high rainfall, or high river input [6], on to a site. In this case site drainage may be challenged to remove high volumes of rainfall in addition to coastal flood water such as wave overtopping. Inspectors should consider the adequacy of claims made on surface water drainage during periods of coastal and pluvial flooding [6], since these often route water through sea defences and in to the sea[7], and may be less effective than claimed if the outfalls are tide locked.

69. *Provision of coastal flooding information*: Coastal flood warnings and forecasts in the UK are via the Flood Forecasting Centre (FFC) and the EA, along with meteorological information provided by the UK Met Office. Such warnings can be used by the Licensee to inform operational decisions such as taking precautionary flood protection measures, or limiting activities on-site. These warnings are advisory and the Licensee should have a decision-making process to inform any operator actions based on them. On-site (or near site) monitoring can augment such warnings and assist Licensee decision-making.

2.4.2 Overview of coastal defences

70. Coastal flood defences take many forms and exist across all parts of the coastal zone, from the offshore region to the coastal hinterland. Defences generally have two main functions; to limit coastal erosion and reduce wave overtopping rates to acceptable levels.

71. Offshore defences can take the form of natural features such as rock outcrops and sand banks, or man-made structures such as offshore breakwaters or harbours. These structures reflect and diffract waves, reducing wave energy at the location behind the defence. These offshore structures can be subject to significant wave forces as they are situated in deeper water.

72. Nearer to the shore, detached breakwaters can be constructed within the littoral zone and influence the movement of sediment and the shape of the beach (through the creation or enhancement of beaches).

73. The nearshore and backshore are also functional in coastal flood defence. Beach width and volume are key to wave energy dissipation and these parameters can be artificially maintained though beach recycling / recharge / nourishment to meet local and regional objectives. Some areas of coastlines are also vulnerable to littoral drift which can be mitigated through the construction of groynes (typically made of wood or rock armour units) which limit longshore movement of sediment. Natural features such headland and rock outcrops can also perform this function. Where sediments are controlled through groynes or hard structures there is often a marked response to beach behaviour away from these controlled zones.

[7] Licensees may make various assumptions about the operational status of drainage systems during extreme storm events. A common approach is to assume that all underground drainage is blocked by debris that would inevitably be carried by storm water. Another is that roads and other suitable topographic features are able to act as surface water drains.

74. A range of hard coastal defences can be constructed within the foreshore zone. Two common types are revetments and sea walls. Revetments typically comprise rock armour slopes founded with a toe to cater for beach or foreshore lowering. Sea walls are typically constructed close to vertical, again with suitable toe protection. In some instances a wave return wall is constructed at the top of the wall in order reduce wave overtopping.

75. Inspectors should ensure that Licensees have considered not only the sea defences in place on the seaward side of nuclear sites but have also taken into account the potential for a flooding contribution from elsewhere. Licensees need to consider the potential for flooding of the site via what is known as “outflanking”. This involves a broader consideration of the landscape and sea defences in the area of the site.

76. Natural features such as shingle ridges and dune systems along the backshore also offer a defensive function although these features can be relatively fragile during extreme events. Should these items be claimed in a safety case then expert advice should be sought and the principals of engineering substantiation outlined with the ONR SAPs should be used to assess claims made by the Licensee. Secondary flood walls and drainage are often used to provide a more economic and less intrusive line of defence against wave overtopping within the hinterland. Generally these defences are not exposed to direct wave impacts, but in combination with drainage and storage systems manage the overtopped seawater back to the sea. The advantage of secondary walls is that they can be lower than a primary defence as they are not exposed to the full wave energy. Gates and access are often needed through secondary walls, which can introduce structural and operational weaknesses in defences.

2.4.3 Ownership of sea defences

77. It is usual for the Licensee to own and maintain the sea defences immediately fronting its site; these defences should protect the site area up to the design basis flood level plus margin. But for the regional area surrounding the site, if protected at all, it is likely that the flood defences are owned and maintained by third parties, such as the EA, or local land owners. Third party defences are unlikely to provide a design basis level of protection, or be maintained to the same standards as Licensee owned defences.

78. Much of the UK’s foreshore has some form of national or international environmental designation that can affect how it is managed. Similarly land and marine planning requirements can also influence how a site’s foreshore can be managed. Also there may be environmental or planning constraints that could influence the maintenance of a sea defence both now and in the future. This is particularly important where potentially mobile beaches form part of the sea defence or could affect access (onshore and offshore) or the cooling water system.

79. ONR would not normally accept safety cases claiming protection from third party sea defences, but if this is the case, inspectors should assure themselves that the Licensee has arrangements in place to ensure that adequate substantiation is in place to demonstrate that such claimed protection can be maintained and delivered[8]. This includes sea defences on neighbouring nuclear sites. Although they are likely to be on a maintenance schedule, it is important that this is scrutinised and not assumed, particularly in cases where the projected lifecycles of the sites differ significantly. Particular consideration should be given to claims made on protection from adjacent sites that are under decommissioning or have been decommissioned as their safety case and Examination, Inspection, Maintenance and Testing (EIMT) requirements may have been substantially reduced.

[8] Advice from the EA is that they would be unlikely to accept any responsibility for claims made by nuclear Licensees on their coastal protection assets (TRIM: 2018/312066).

80. A common situation is where third party defences protect immediate off-site areas such as access roads. In such cases, the Licensee's emergency / operational arrangements should be cognisant of the enhanced potential for loss of access for example, even at flood levels below the design basis. If safety case claims are made on the accessibility of these off-site areas then inspectors should satisfy themselves that adequate substantiation is in place to demonstrate that these areas will remain accessible as required.

2.4.4 Monitoring

81. It is possible to provide monitoring of local sea state at or immediately offshore from the site, eg from tide gauges. These can be used to provide data to control rooms and can be used, normally in conjunction with flood forecasts, to initiate precautionary measures, such as closing flood gates and erecting temporary or demountable defences around exposed plant. Such monitoring can also be valuable as a means of validating wave transformation models, if these have been used as part of the coastal flood hazard analysis of a site.

82. Post-event monitoring is also needed to examine any sea defences or other SSCs that may have been damaged by an extreme event. The purpose of post-event monitoring is to ensure that any damage is noted and repaired as soon as reasonably practicable, and preferably in advance of the next tide cycle. If damage is present and cannot be repaired quickly, the Licensee will need to ensure that adequate additional temporary protection measures are in place.

83. The maintenance schedule should include the requirement for checks after events that may challenge the defences (as well as before such events if they have been forecast). The Licensee should also be monitoring the situation as appropriate during the event if it is safe to do so.

2.4.5 Ageing and maintenance

84. Plant response and its ability to withstand Coastal Flooding hazards can be significantly affected by physical changes to the defences and local area for example, concrete degradation or corrosion, coastal erosion / undermining of defences induced by ageing and poor maintenance. Therefore the impact of ageing and the adequate definition of EIMT are expected to be included in any assessment and captured by the Licensee's arrangements under Licence Condition (LC) 28. This is especially important on older facilities, but it should also be taken into account during the design or modification of nuclear plant.

85. A particular issue at coastal sites is the presence of salt laden moisture that can promote corrosion of metalwork especially. The Licensee should have in place adequate inspection and maintenance arrangements to ensure that flood protection equipment subject to salt spray, or salt water inundation, eg the flap valves on return drains through sea walls, remains functional. Storm conditions can also transport quantities of debris posing a blockage hazard to this equipment. See also Annex 2 Section 2.4 [6].

2.4.6 Housekeeping

86. Finally, the potential for coastal flooding hazard induced plant faults can be reduced by good housekeeping. This may involve restraining items of temporary equipment that may become buoyant eg storage containers, and may become a missile or secondary hazard to primary safety plant, or block access routes that are needed for safety significant operator actions.

3 SAFETY ANALYSIS – (FA.1)

87. The sub-sections below reflect those in TAG 13 Section 5.1 [1] and provide advice to inspectors on the application of the general principles to Coastal Flooding hazards specifically.

3.1 Hazard Identification, Characterisation and Screening – (SAPs EHA.1, EHA.19)

88. Coastal Flooding hazards (with the exception of tsunami) are non-discrete hazards. It is anticipated that Coastal Flooding Hazards will always be identified as potentially significant, and screened in to the fault analysis for coastal UK sites. Coastal Flooding hazard analysis for screened-in hazards is expected to develop suitable inputs for faults initiated by these hazards covering Design Basis Analysis (DBA), Probabilistic Safety Analysis (PSA), Beyond Design Basis Analysis (BDBA) and Severe Accident Analysis (SAA). For consequential hazards it may be possible for these to be screened out of the fault analysis because they have no significant effect on nuclear safety at a particular site. Inspectors should confirm that Licensees have applied a systematic process for identifying and characterising the hazards significant to their site.

3.2 Design Basis Analysis for Screened in Coastal Flooding Hazards – (SAPs FA.4 – FA.9)

3.2.1 Design basis events – (SAPs EHA.3, EHA.4, EHA.12)

89. In order to meet the intent of EHA.3, EHA.4 and FA.5, the design basis hazard at an initiating event frequency of 10^{-4}/yr is expected to be conservatively derived in line with the advice presented in [1] Section 5.5.1.

90. *Uncertainty analysis*: At the low exceedance frequencies considered for the definition of Design Basis Events (DBEs) and even more so for BDBA, the analysis of coastal flooding hazards based on available data is subject to large uncertainties. These uncertainties are routinely handled by sophisticated statistical methods known as extreme value statistics (see [6] Section 3.2.1 and [1] Section 5.8.10). Inspectors should bear in mind that there are significant differences in Relevant Good Practice (RGP) applied to uncertainty analysis of coastal flood hazards and seismic vibratory hazards, especially in relation to how knowledge uncertainty is handled, (see advice in [1] Section 5.5.2). The inspector should seek assurance that in the derivation of coastal flood design bases, they are not overly sensitive to particular analysis assumptions, and that they are able to achieve a balanced overall plant design, see [1] Section 5.5.3. However in some cases the definition of a coastal flood design basis will be sensitive to particular analysis assumptions and this is unavoidable. In these cases a sensitivity analysis should be performed, and the outcomes should be justified and should be demonstrated to be adequately conservative.

91. *Climate change*: The Licensee is expected to account for the fact that climate change renders any statistical hazard analysis non-stationary, and take account of the inherently large uncertainties explicitly within the hazard analysis. The methodology used and the additional safety margin applied to account for climate change is expected to be proportionate to the hazard's contribution to nuclear risk. Periodic re-evaluation of design parameters is expected to be performed as the uncertainties affecting the estimates of future extremes of climate are reduced, or as observed trends show evidence of more extremes of climate. This is in line with the guidance on the managed adaptive approach that can be found in the ONR and EA document "Principles for Flood and Coastal Erosion Risk Management" [5].

92. For new build, ONR expects the designs to incorporate due consideration of the effects of climate change over the lifetime of the facility. To this end, ONR expects the designs to be capable of accommodating an adequately conservative emissions scenario but not necessarily the most conservative. The emissions scenario selected should be the

one that is considered on the basis of RGP to be most consistent to demonstrating that the risk arising from coastal flooding hazards, including the contribution from climate change effects, is as low as reasonably practicable (ALARP). An important consideration is that flood protection measures are made adaptable to cover possible changes to future estimates of climate change effects, as a way of managing the large uncertainties inherent in flood hazard predictions over the life-time of new nuclear reactor sites. This approach is referred to as "managed adaptive" by the flood and coastal risk community. A range of scenarios should also be considered to assess the implications of any disproportionate increase in consequences (cliff-edge effects, see [1] Section 5.5.3) where a small increase in flood magnitude will result in a significant increase in the radiological risk from flood and to assess the potential need for adaptation options. The design of new facilities would also be expected to be able to accommodate a wider range of emissions scenarios including conservative scenarios, although not necessarily the most conservative. ONR has generally accepted the UKCP09 [11] medium emissions scenario at the 84th percentile as adequately conservative for defining a design basis[9].

93. In addition, it is prudent to ensure that there are no features of the design which are completely undermined by more radical changes to the climate, and that managed adaptive approaches are credible. In this context the maximum credible scenario may be used, see [5] for more details. A current example of the maximum credible scenario for sea level rise and storm surge for the period to 2100 is provided by UKCP09, and is termed the H++ scenario, [9] Section 6.

<u>Extreme Sea Level</u>

94. Probabilistic methods are usually used to estimate the extreme sea level elevation for the hazard analysis for a storm surge and are taken to represent RGP. Since extreme sea levels at coastal locations depend upon tidal processes and the co-occurrence of storm surges, the accepted method for combining the deterministic tidal distributions with stochastic storm surge distributions is the JPM. This is an improvement on previous techniques that fitted extreme value distributions to either annual maximum sea levels, or a fixed number of extreme levels in each year. JPMs make the most efficient use of all recorded sea level data, and yield probabilities that have less dependence on extrapolation, [4] Section 5. However, as with any statistical method, the accuracy and timing of observations must be of high quality. The best dataset of extreme levels is obtained by calculating the probabilities of (deterministic) tide and skew surge, [4] Section 4. The skew surge is simply the difference between the height of the predicted astronomical high tide and the observed high water within a given tidal cycle. As such it is an integrated effect of the weather and all other interactions over a full tidal cycle and it measures properly the additional elevation of the sea surface due to a storm. This approach depends on reliable tide gauge data (for the difference between the tide level and the final water level) being available covering a sufficiently long period of time and for an adequate number of gauge stations in the region. Time series from several neighbouring locations may be correlated, providing a basis for developing a synthetic time series that is valid over a longer interval than the time span of any single-site local observations. The use of time series from other representative gauge stations, if available, may broaden the basis of the analysis and make it more reliable, although care must be taken to avoid "double counting".

95. If extreme sea levels are driven by storm surge, then it may be necessary for the Licensee to consider coastal flood hazards arising cumulatively over several tide cycles. The worst-case scenario may not be the tide cycle leading to the absolute highest water level for a number of reasons, such as the following:

[9] Inspectors should note that at the time of writing RGP in respect of climate change is expected to be influenced by the imminent publication of UKCP18, see Section 5.3.

- The first tide cycle may inundate and saturate land on- and off-site that may fail to drain completely before the next cycle, reducing its ability to absorb additional flood water before surface pooling is evident. This may be particularly relevant where partial flood defence for the site is offered by flood barriers maintained by the EA and other third party organisations; these barriers will not have been designed to withstand 10^{-4}/yr flood levels. Similarly a breach in a natural or artificial sea defence may occur towards the end of a high tide event, but leave the site exposed to the next high tide.

Waves

96. Offshore wave characteristics are typically computed using probabilistic methods using reliable offshore wave data that covers a sufficiently long period of time. Available data from observations (data from tide buoys, satellite measurements, etc) on the wave spectrum for the region near the site are expected to be incorporated into the hazard analysis. A sufficiently long record of wave data will include all physical processes leading to extreme waves (eg the wind over tide phenomenon). Wave hindcast data from numerical models can also be used for this purpose. Wave hazards are usually described by spectra of height against period, with heights generally characterised by the significant wave height and the 1% wave height. The maximum of both the wave height and the period will vary depending on the characteristics of the driving wind hazard (such as wind speed, duration and fetch length).

97. It should be noted that wind generated waves should be addressed coincidently with tide and surge hazards since the process is non-linear and it is not appropriate to superimpose the partial effects linearly. In computing the wind wave hazard, a reference water level such as the storm tide level should be assumed to occur coincidently with the wind wave event.

98. To determine the wind wave effects near the site, the offshore wave spectrum is usually first determined on the basis of the generating wind hazard or a probabilistic study of observed offshore waves. Following this, near-shore wave spectra, resulting from the transformation of offshore waves, are computed using established methods. These spectra can then be used in shoreline interaction studies. For further details on wave transformation models please refer to [4] Section 7.

99. Statistical analysis is then performed to compute the significant wave height for the design basis annual frequency of occurrence. Since wave heights and wave periods are correlated, an empirical relationship can be used to determine the wave period on the basis of the wave height for the chosen annual frequency of occurrence.

100. As the offshore waves travel to the near shore area of the site, they will undergo dissipation and transformation effects owing to changes in water depth, interference from islands and structures and other factors. The transformation and propagation of these offshore waves to the nearshore area is expected to be evaluated using (usually) a numerical wave transformation model or (less commonly) a physical model[10]. For further details on wave transformation models please refer to [4] Section 7.

101. In certain settings, bimodal sea states may be a particular concern. These are characterised by the simultaneous arrival at the shore of steep irregular waves generated by local wind waves and more regular swell waves (see paragraph 19) caused by more distant conditions. Coarse-grained or mixed beaches may be drawn down strongly by such bimodal seas, and this may be a particular concern if that beach happens to play an important flood protection role. The susceptibility of the site to bimodal seas should be established as part of the hazard analysis.

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[10] The wave phenomena that are expected to be considered include friction, shoaling, refraction, diffraction, reflection, breaking and regeneration. Wave calculations should also cover: local water current structure, local winds, and possible changes in bathymetry due to wave actions.

102. Available historical data on observed extreme waves for the region, if available, should be reviewed to help provide long term context.

Combination of Extreme Sea Level & Waves

103. It should be noted that methods have been developed to combine both extreme sea levels and wave spectra so as to probabilistically derive scenarios consistent with the design basis annual frequency of exceedance. These methods are outlined further in [4] Section 7 and currently represent RGP in terms of assessing this hazard.

104. Evaluation of the characteristics of design basis scenarios for Coastal Flood hazard are expected to include:

- The selection of an appropriate spectrum of incident waves, the upper wave limit (wave height, period), the duration of the waves interacting with the shoreline, and a sensitivity study of the numerical model parameters;
- The selection of an appropriate spectrum of incident waves to challenge the foreshore and sea defences to the reasonably foreseeable effects of erosion and storm damage;
- The evaluation of any additional increase in the computed still water level due to storm surge, including such effects as wave setup. The extra wave setup will further increase the wave heights.
- Due to the complexity of wave-structure interactions the consequences of a range of combinations of conditions (for a given joint probability) should be explored / modelled to identify the most severe conditions for particular defences.

105. The inspector should note that some design basis scenarios may be more relevant to a particular site than others, due to details of the site, local offshore region, or the SSC under consideration.

Shoreline Interaction & Flood Defences

106. In assessing the interaction with the shoreline, wave effects that are expected to be considered include wave run-up across the structures, overtopping (including overflow and breaching) of embankments, wave spray, and undermining of the toe. These effects can be estimated by modelling the shoreline interaction and various methods are available to do this; however, the applicability of the methods should be verified for the specific details of the site including, where appropriate, the use of physical models. Further information on this is provided in [4] Section 7.

107. The hydrostatic and hydrodynamic loading on structures important to safety should be evaluated. The action of water on structures may be static or dynamic, or there may be a combination of effects. In many cases the effects of ice and debris (combination hazards) transported by any water entering site are important variables in the evaluation of pressure. For a given set of site conditions, the entire range of water elevations that are expected to occur should be evaluated, since it is possible that the maximum loading conditions may occur at a time other than that of the maximum extreme sea level. The duration of wave loading should also be computed for design considerations.

108. When considering siting aspects for nuclear new build sites, the stability of the shoreline is an important factor in determining site acceptability, in particular for sites with soft substrates where significant morphological changes may occur. Such changes may occur gradually over the life of the nuclear site; they may also occur suddenly over the duration of a single storm event. Inspectors should confirm that both aspects have been considered.

109. The stability of the shoreline near the site is expected to be investigated together with the effects of the prospective site on the stability of the shoreline. Any changes that may affect the drainage of rivers, such as morphological change, or the construction of barrages or bridges, should also be considered in the flow patterns of water from both the river and the sea.

110. Two aspects require particular attention: the long term stability of the shoreline[11] and its shorter term stability against severe storms. It should be noted that it is usually not sufficient to consider only the storm that causes the probable maximum extreme sea level because this may not produce the conditions critical to erosion. Storms of rather longer duration or wind fields with directions such that they cause higher waves for longer periods of times at the site are usually adopted for consideration in the analysis of the effects of erosion on the shoreline and on the coastal defences.

111. Numerous tools are available to model the effects of short-term shore response to storm conditions. These tools are normally augmented by others to cover medium and long term shore response. These latter methods especially are subject to large uncertainties and require expert interpretation. For more details refer to [4] Section 7.

112. An analysis should also be performed to determine the potential for instability of the shoreline at the site and for any possible consequences for items important to safety. Severe storms can cause significant modifications of the littoral zone, particularly to the profile of a beach. Although the long term profile of a beach in equilibrium is generally determined by its exposure to moderately strong winds, waves and tidal currents rather than by infrequent events of great magnitude, events of both types should be considered. The longshore transport of sand in the littoral zone should also be evaluated by studying the tidal currents and the wave climate as they occur in the given segment of beach, with knowledge of how the waves interact with the shore to move sand.

<u>Tsunamis</u>

113. The potential for both local and distant tsunamis is expected to be investigated. As noted in paragraph 44, existing UK-wide work has characterised the tsunami hazard in the UK. Licensees are expected to have considered this information and any research relevant to their site location. The occurrence of underwater and near shore seismic or volcanic activity in the site region (recommended in Ref. 4 as about 1000km) is an indication of the possible occurrence of local tsunamis at the site. Further information on the characterisation of seismic sources is given in Refs. [3], [12], although inspectors should confirm that Licensees have considered the characteristics of all potential sources, not all of which may have been captured by these references. For more details see [4] Section 8.

114. For existing UK nuclear sites and those sites identified as potential development sites, current research suggests there is not a potential for the occurrence of significant tsunamis at the site. However if such an occurrence were to be suggested and demonstrated, a site-specific tsunami hazard analysis is expected to be performed that includes a detailed numerical simulation to derive the design basis tsunami. For assessing the tsunami hazard for all types of tsunami source, the numerical simulation should cover the generation, propagation and coastal processes, with appropriate initial conditions and boundary conditions.

115. When considering the propagation of the tsunami it should be noted that the resolution and accuracy of the near shore bathymetric and topographic data can have a significant effect on the computed results. The spatial grid size should be small enough to represent properly the coastal and underwater morphology near the site. The effect of tsunami arrival at high tide and low tide levels should also be considered in the

[11] Long term in this context should be consistent with the whole lifecycle of the site or facility.

numerical simulations. Considering the possibility of extremely rare phenomena such as tsunamis together with significant storm surge is considered overly conservative, and is enveloped by beyond design basis considerations.

Design Basis Considerations

116. As highlighted by Refs. [10], [13] a nuclear site should be protected against the design basis flood by one of the following approaches:

(a) The 'dry site' concept: In this case, all items important to safety should be constructed above the level of the design basis flood together with an appropriate margin, with account taken of wave effects and effects of the potential accumulation of ice and debris. This can be accomplished, if necessary, by locating the plant at a sufficiently high elevation and away from long term erosion risk, or by means of construction arrangements that raise the ground level at the site. The site boundary should be monitored and maintained. In particular, if any filling is necessary to raise the site above the level of the flood conditions for the design basis flood, then erosion protection is likely to be required. The erosion protection is an engineered plant item and should be considered as an item important to safety. It should therefore be adequately designed and maintained as part of the site's EIMT arrangements.

(b) Permanent external barriers such as levees, sea walls and bulkheads: In this case, care should be taken that appropriate design bases (eg for seismic qualification where relevant) are selected for the design of the barriers. The values of the parameters of the flood design bases for the barrier's structures may be different, and even more severe, than those defined for design of the plant structures, systems and components. Inspectors should assure themselves that periodic inspections, monitoring and maintenance of the external barriers are conducted, even if such barriers are not under the responsibility of the Licensee[12]. Levees, sea walls and bulkheads should be checked to ensure that water can leave the site, and to ensure that these external barriers do not act as a dam to prevent the release of water from the site to rivers or other water bodies. The permanent external barriers should be considered as SSCs and classified appropriately.

117. Where permanent or removable external barriers are installed for flood protection and are claimed in the safety case, Applying ONR SAP EHA.7, the design parameters for these barriers may need to be more onerous than those derived from the design basis flooding event.in accordance with SAP paragraph 262. The barriers should be subject to appropriate safety management arrangements (including periodic inspections, monitoring and maintenance). Inspectors should further assure themselves that their design and ability to deliver such safety functions is consistent with the expectations of the single failure criterion, see [1] Section 5.8.7.

118. Whatever approach is adopted the Licensee is expected to demonstrate that:

- All items important to safety (SSCs), including monitoring systems, are designed to withstand the flood producing conditions constituting the design bases defined for the site. Where appropriate, the inspector should take account of the Ingress Protection rating of the SSC when considering its resilience against water ingress.
- Arrangements are in place to give forewarning of developing weather conditions that could lead to flooding.
- Monitoring is available that is able to detect flood conditions on or near the site. Inspectors should assure themselves that the data provided by such monitoring is able to alert the site operators to take any safety related mitigating actions

[12] If flood defences are not under the direct control of the Licensee (see paragraph 77 et seq), inspectors should assure themselves that alternative arrangements (eg contracts) are in place to recognise and maintain their ability to deliver nuclear safety functions.

required to comply with safety case claims, or initiate emergency procedures if required.

3.2.2 DBA Inputs from the coastal flooding hazard analysis

119. The inspector should seek to ensure that sufficient input data of appropriate quality is provided to facilitate the DBA process. Design Basis parameter values should be underpinned by hazard curves for the various hazards including extreme sea level, significant wave height, and joint probability curves for various annual frequencies of exceedance (as appropriate).

120. It is not yet considered RGP to develop hazard curves for tsunami in the UK, and this is an area of ongoing research. However, it is expected that the various source scenarios are assessed conservatively to demonstrate that the tsunami hazard is suitably bounded by the extreme sea level and wave design basis scenarios.

3.2.3 Beyond design basis events & cliff-edge effects – (SAPs EHA.18, EHA.7, EHA.9, EHA.11, EHA.12)

121. In order for the Licensee to carry out BDBA as intended by EHA.18 and EHA.7, the hazards arising from coastal flooding hazards should be derived for return frequencies less than 10^{-4}/yr, and the results are usually presented as hazard curves. The BDBA is normally carried out on a best estimate basis; the purposes of BDBA are explicitly outlined by EHA.18 paragraph 246 and are covered in detail in TAG 13 Section 5.5.3 [1].

122. The Licensee should demonstrate that the possibility of faults and failures resulting from beyond design basis hazard floods is remote. The term “just beyond the design basis” should be interpreted as a higher (lower frequency) hazard level that provides a margin over the DBE level. This margin should, in a qualitative sense, account for the level of uncertainty in both the DBE definition and the plant response analysis, such that if the plant can still be shown to be robust at this level, there is high confidence that the design is sound and the risk arising from it has been reduced ALARP (ERL.4).

123. The Licensee should select a suitable beyond design basis level and provide justification that it meets the intent of the SAPs and the advice provided in this section.

3.3 Probabilistic Safety Analysis – (SAPs FA.10 – FA.14)

124. Coastal Flooding hazards are non-discrete hazards and therefore occur at a range of frequencies of exceedance significant to nuclear safety. It is anticipated that coastal flooding initiated faults will be included in the PSA plant model unless it can be shown that the consequential effect of such faults is not significant. The inspector should ensure that all credible fault sequences are accounted for, and that these have been modelled in the PSA by an appropriate process, see [1] Section 5.6. The hazard analyses should deliver appropriate mean hazard curves and associated uncertainty fractiles (confidence levels) so that the risk contribution from coastal flooding hazards can be calculated as part of the site PSA. NS-TAST-GD-030 [14] provides general guidance on PSA and the need to address external hazards, but no specific guidance is offered on coastal flooding hazards.

125. The use of PSA for coastal flooding hazards is not well developed in the UK nuclear industry. While there is a long history of sea defences around UK coastlines, the availability of reliability data arising from the failure of such defences may need to be adapted to make it suitable as input to a PSA calculation. Where fragility data is needed and unavailable, then Licensees would be expected to fully justify this and to make pragmatic judgements with regard to fragility information that is available to facilitate the PSA process. It may be possible to develop fragility curves for some

equipment but for other equipment it may be difficult to justify such a curve and a binary choice should be considered (ie working / not working).

3.3.1 PSA inputs from the coastal flooding hazard analyses

126. The inspector should seek to ensure that sufficient input data is provided to facilitate the PSA process. For a major nuclear plant this should include at least:

- Site-specific hazard curves covering a range of exceedance frequencies from at least 10^{-2}/yr down to as low as 10^{-7}/yr or beyond.

127. Ideally the hazard curve should be provided at a range of epistemic uncertainty fractiles including the mean, 15%, median, 84% and others as necessary, to give an indication of the epistemic uncertainty distribution associated with the site-specific hazard analysis. If no analysis of epistemic uncertainty has been undertaken inspectors should assure themselves that the hazard data entering the PSA constitutes best estimate.

3.4 Severe Accident Analysis – (SAPs FA.15, FA.16, FA.25)

128. As noted in [1] Section 5.7, a severe accident is a fault sequence that has the potential to leave the plant in a degraded state leading to the release of nuclear material. SAA is concerned with plant states or scenarios that constitute a severe accident and how further mitigation can be provided; generally such plant states are assumed to arise from internal plant failures. However, it may be credible that coastal flooding hazards could lead to severe accident site conditions or plant scenarios that differ from those assumed for other reasons (eg severe internal plant faults); therefore the effects of such hazards should be considered during the development of an appropriate severe accident analysis for the site and the consideration of further measures to reduce risks ALARP.

129. Coastal Flooding hazards can (and are likely to) affect both on-site and off-site areas more or less simultaneously.

3.4.1 SAA inputs from the coastal flooding hazard analyses

130. The inspector should ensure that sufficient input data is provided to facilitate the SAA process. For a major nuclear plant this may include the identification of likely plant states from a severe, very low frequency coastal flooding event (eg tsunami).

4 EMERGENCY PLANNING & ARRANGEMENTS (AM.1)

131. The potential effects of coastal flood hazards should have been considered as part of the hazard identification and analysis process, as discussed in Section 3.1, and used to inform the site's emergency plan and arrangements under LC11. If the response to such hazards is fully accounted for by the arrangements in place to cover other fault conditions, then this should be stated. If not, the arrangements should be revised as appropriate to take account of additional consequences that could arise from a coastal flood event. Inspectors should consider the following issues:

a) Common cause effects: A consideration with coastal flooding hazards (and major consequential hazards) is that they provide a common cause effect across the site, ie several independent fault conditions may be created on the site simultaneously. The site's emergency arrangements should recognise this and be able to respond in a pragmatic way to this possibility.

b) Provision of Coastal Flooding Warnings: Flood warning services can be made available (paragraph 69), also on-site monitoring can be used to assist Licensees is decision-making under their emergency arrangements (paragraph 81).

c) Off-site infrastructure: The emergency arrangements are expected to recognise that the provision of supplies and staff from off-site may be hindered for the duration of, and following, a severe coastal flood event and often associated meteorological event, and identify ways of mitigating the adverse effects on nuclear safety if this occurs.

d) Post-Fukushima Resilience Equipment: After the Fukushima accident following the Great Japan Earthquake in 2011, ONR recommended the establishment of off-site stores of emergency backup and recovery equipment, capable of recovering basic safety functions following a severe external hazards event [15]. The site's emergency arrangements should refer to such equipment where appropriate, and the type of equipment should be justified by the types of severe accidents that external hazards could generate.

e) Local Authority Off-site Plan: ONR regulates Local Authorities in respect of the adequacy of their Off-Site Emergency Plans. Such plans are based on what is considered to be a reasonably foreseeable radiation emergency as identified by the site operator and, if they consider coastal flooding at all, will likely concentrate on managing the infrastructure away from any nuclear licensed sites within their geographical area of responsibility. Inspectors (or relevant site inspectors) should consider the significance of natural external hazards and their potential for widespread common cause effects both on and off nuclear licensed sites in respect of the adequacy of off-site plans. Inspectors should be aware that for natural hazards especially, emergency response services, transport links and off-site power supplies may not be available for some considerable time following an event.

4.1 Emergency Arrangements Inputs from the Coastal Flood Hazard Analysis

132. The inspector should seek to ensure that sufficient input data is provided to facilitate the development of adequate emergency plans both on-site and off-site where this is necessary and appropriate, see [1] Section 5.9. This may include representative Coastal Flooding scenarios to be assumed for emergency planning purposes.

5 RELEVANT STANDARDS AND GOOD PRACTICE

133. Understanding the natural variabilities and the climate induced changes to the phenomena that bring about coastal flooding hazard (with the exception of tsunami) is a complex and fast developing scientific field. The primary relevant standard for nuclear plant is International Atomic Energy Agency (IAEA) safety standard SSG-18 [13], this covers at high level the safety principles to be applied; the guidance in this annex is consistent with these. The EA also publish guidance on flooding and climate change, eg [8].

134. It is likely that for new nuclear build and for plant containing significant nuclear hazard, Licensees will seek expert analysis from recognised bodies such as specialist contractor organisations. These organisations will undertake a bespoke site-specific analysis, based on local data and a detailed understanding of local conditions relevant to the challenges posed by coastal flood hazards. The statistical techniques employed, computer models used, data collection methods employed and the manner in which uncertainty is handled are not generally controlled by published standards, but are based on custom and practice within the expert community of which these organisations are a part (see paragraph 135). Note that the return frequencies required for a nuclear safety case are lower than those required for other industries and infrastructure.

5.1 Current practice in the UK expert community

135. The analysis of coastal flooding hazards from tide, storm surge and waves is complex and generally the preserve of an expert community of specialists. Although many different numerical models are available for coastal flood hazard analysis, recent guidance from the EA [16] provides a good practice framework and lays down required standards of accuracy to ensure consistency in modelling approaches. The models and methods available are explained in greater detail in the Expert Panel paper [4] Section 7. A typical sequence of assessment, including the use of such models, is shown in Figure 1, and consists of:

- establishing the still water levels (including climate change allowance);
- establishing a representative wave field offshore, based on regional coastline configuration;
- transforming the wave the wave field inshore to the site location;
- predicting the potential for short-term and long-term shoreline change and eventually overtopping of sea defences.

136. Whilst Figure 1 depicts a generic approach, there are a number of recognised computer codes available to perform the tasks shown.

137. It is also possible to construct physical scale models of sea defence structures and subject them to representative wave action such as might occur during a design basis combination of extreme waves and sea levels. Indeed, a final evaluation of extreme waves and sea levels on proposed coastal defences is often performed using physical models. Physical models can be driven with scaled waves that match the 10^{-4} annual probability extreme value, and can be used to assess the efficacy of various rock defence structures (eg toe armour, step and ramp). Physical models are particularly useful in the assessment of tsunami impact (however unlikely that may be) since numerical tools fail to reproduce tsunami nearshore and onshore processes well as their wavelengths shorten. New wave generators can now produce a range of realistic tsunamis with long wave lengths led by both crests and troughs [17].

138. Given the level of expertise required to interpret safety case submissions, where coastal flood hazard is likely to be significant to nuclear safety, inspectors are advised to seek specialist advice from the Expert Panel and / or a relevant Technical Support Contractor.

139. *Uncertainty analysis*: Aleatory uncertainties are captured by the normal statistical methods employed in coastal flood hazard analysis, such as extreme value analysis or skew surge probability analysis. Epistemic uncertainties are not formally assessed using current methods (unlike for a seismic hazard), although expert judgement is used, for example in estimating the value for H++ climate change sea level rise.

140. For further details on the design of sea defences for nuclear sites, refer to TAG 17 [10].

5.2 Use of design codes

141. There are no formal design codes covering coastal flood and erosion hazard analysis for application to nuclear sites. However, there are a number of guidance documents that are generally applicable to the design and management of coastal defence structures. The CIRIA Rock Manual [16] and the Beach Management Manual [18] covers a wide range of topics relating to the design and management coastal structures and beaches. The Rock Manual [19] contains detailed discussion of the analysis of physical site conditions, physical structures and the design of defence structures. The Beach Management Manual [18] gives comprehensive advice on beach management, including coastal erosion and environmental protection. There is also a British Standard (BS6349) [20], which relates to maritime works and included guidance for assessing impact loadings. These and the other references below contain guidance on establishing the severity of flood hazards at a given site and guidance on the effects of shoreline change.

- The EA and ONR’s Principles for Flood and Coastal Erosion Risk Management (2017) document [5] provides advice on how flood and coastal erosion risk issues are taken into account when considering proposals for new build developments.

- The United States Nuclear Regulatory Commission (USNRC) uses a number of codes and guides in forming its regulatory decisions for US sites; however these are primarily relevant to the US context. The main document of interest is the USNRC Standard Review Plan Section 2.2.1 [21], but a number of other USNRC documents are also relevant:

- FEMA (the United States Federal Emergency Management Agency) provides a list of resources that are useful for assessing flood risk [22]. Some of these are relevant to the US context only but most provide general information and guidance.

- The US Army Corps of Engineers publishes the Coastal Engineering Manual (CEM) [23]. The purpose of this manual is to provide guidance on the application of techniques and methods to the solution of coastal engineering problems.

- NUREG/CR-7046, “Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America”, Nov. 2011, https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr7046/

- JLD-ISG-2012-06, “Guidance for Performing a Tsunami, Surge, or Seiche Hazard Assessment”, January 2013, https://www.nrc.gov/docs/ML1231/ML12314A412.pdf

5.3 Climate change and near-term developments affecting relevant good practice

142. *Climate change*: There are two main sources for climate change projections for the UK, of which the most important are the UK Climate Projection reports (UKCP09). There are also the Coupled Model Intercomparison Project 5 (CMIP5) model projections developed for the IPCC Fifth Assessment Report of 2013 [24]. The UKCP09 projections are used by end-users to assess future climate change in the UK [11]. They take the IPCC projections and make a downscaled, UK interpretation. The UKCP09 projections are being updated and will shortly be published as UKCP18. This will use the wider CMIP5 models and will increase the small-scale modelling of physical

processes to allow for better resolution of convection in the atmosphere. It will have a better modelling capability over the land and will provide new analyses of projection uncertainties. Most projection data will be provided at a resolution of around 60km although there will also be downscaled experiments run at a resolution of around 5km to better simulate convection storms. UKCP18 will include improved assessments of future sea level rise. Another objective of UKCP18 will be an improved quantification of uncertainties.

143. *Other developments*: Coastal flood hazard simulation by numerical models is a mature technology that is routinely used to provide operational flood warnings in the UK. However, these predictions are limited by the ability to predict accurately storm tracks and intensities in future climates. Over the next decade there will be further developments in statistical data analysis techniques. Some research areas relevant to the analysis of low frequency extreme flooding events relevant to nuclear safety are highlighted:

- Best estimates of extreme sea levels, derived using JPMs are available for the entire UK coastline [25]. Current EA funded research is currently updating the estimates using improved statistical methods and capturing the seasonal dependency of storm surges and high tide.

- The Natural Environment Research Council (NERC) have funded a project to explore the consequences of plausible severe storms (Synthesising Unprecedented Coastal Conditions: Extreme Storm Surges - SUCCESS) [26].

- Post Fukushima learning relevant to PSA has prompted the development of external hazards PSA through a research programme known as ASAMPSA-E (Advanced Safety Assessment Methodologies: Extended PSA), see [1] Section 5.6. An example publication relevant to coastal flooding is at [27].

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TABLE 1 – EXAMPLE COASTAL FLOOD HAZARDS, AND ASSOCIATED PRIMARY, CORRELATED AND CONSEQUENTIAL HAZARDS

Primary Hazard – (Design Basis Hazard Descriptor)	Example correlated hazards that may occur in combination	Secondary Hazards	Consequential Hazards / Effects
Storm Systems (Low air pressure / Extreme wind)	- Pluvial hazards - Fluvial hazards if downstream of tidal reach	Waves on open water Storm surges	- Overtopping of site flood defences - Inundation of site - Loss of containment - Restrictions to access and site operations - Damage to flood defences - Changes to coastal morphology, erosion, and changes to tidal flow patterns - Exposure of offshore cooling water intakes - Blockage to intakes and outfalls
Tide	- Low air pressure[#] - High air pressure[#] - Pluvial hazards[#] - Fluvial hazards[#] - Tsunami[#]	All coastal flood secondary hazards	
Earthquake Submarine landslide Meteorite Impact	- Submarine landslide may be correlated with earthquake	Tsunami – high water levels Tsunami – low water levels	
High air pressure	Fluvial hazards due to drought conditions if downstream of tidal reach	Low water level	

[#] Note that tide is not statistically correlated with any of these hazards. Nevertheless, the state of tide, especially high tide, when combined with other hazards is an important consideration. Any correlated hazards could coincide with high water spring tide, albeit with a low probability. Inspectors should confirm that the combinations considered are appropriate.

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FIGURE 1 – FLOW DIAGRAM SHOWING STAGES OF A COMPREHENSIVE (BUT TYPICAL) ASSESSMENT OF COASTAL FLOOD RISK AND EROSION AS A GUIDE TO UNDERSTAND WHAT TO EXPECT FROM A COASTAL PROCESS ASSESSMENT.