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Meteorological Hazards			
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LIST OF ABBREVIATIONS

ALARP	As Low As Reasonably Practicable
BDBA	Beyond Design Basis Analysis
CMIP3	Coupled Model Intercomparison Project 3
CMIP5	Coupled Model Intercomparison Project 5
CMIP6	Coupled Model Intercomparison Project 6
DBA	Design Basis Analysis
DBE	Design Basis Event
EA	Environment Agency
EH	External Hazard
EIMT	Examination, Inspection, Maintenance and Testing
FRA	Flood Risk Assessment
HVAC	Heating, Ventilation and Air Conditioning (system)
IAEA	International Atomic Energy Agency
IPCC	Inter-Governmental Panel on Climate Change
LC	Licence Condition
LOOP	Loss of Off-site Power
NA	National Annexes (to Eurocodes, applicable to the UK)
NRW	Natural Resources Wales
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	Structure, System and Component
TAG	Technical Assessment Guide(s) (ONR)
UKCP09	UK Climate Projections 2009
UKCP18	UK Climate Projections 2018
UKMO	UK Meteorological Office
WENRA	Western European Nuclear Regulators Association
WMO	World Meteorological Organization

GLOSSARY

Term	Description
Atomisation	Separating something into fine particles
CMIP	Under the World Climate Research Programme the Working Group on Coupled Modelling established the Coupled Model Intercomparison Project (CMIP) as a standard experimental protocol for studying the output of coupled atmosphere-ocean general circulation models. CMIP provides a community-based infrastructure in support of climate model diagnosis, validation, intercomparison, documentation and data access. This framework enables a diverse community of scientists to analyse general circulation models in a systematic fashion, a process which serves to facilitate model improvement
Convection cell	Atmospheric fluid is warmed by the heat source, normally the Earth's surface, its density reduces and it rises under buoyancy. The fluid then begins to lose heat, and inevitably cools. This cooler, denser fluid descends back toward the surface by the to replace the rising newly heated fluid A system of motion forms, called a convection cell.
Convective storm	Commonly known as thunderstorms, convective storms are the atmospheric phenomenon responsible for weather hazards such as lightning, heavy rain, hail, and tornadoes
Cumulonimbus cloud	Cumulonimbus clouds, more commonly known as thunderclouds, exist through the entire height of the troposphere, usually characterised by their icy, anvil-shaped top. Cumulonimbus clouds are associated with extreme weather such as heavy torrential downpours, hail storms, lightning and even tornadoes
Cyclones	The term 'hurricane' is usually restricted to the Atlantic and north-east Pacific region. In the north-west Pacific they are known as 'typhoons' and elsewhere simply as 'cyclones'.
Cyclonic air masses/circulation	Atmospheric motion in the same sense as that of the earth, that is, counter clockwise in the Northern Hemisphere, clockwise in the Southern Hemisphere.
Dendrochronology	The science dealing with the study of the annual rings of trees in determining the dates and chronological order of past events.
Dew point temperature	The Dew Point is the temperature at which water vapour starts to condense out of the air and is the temperature at which air becomes completely saturated. Above this temperature the moisture will stay in the air as a gas.
Dry bulb temperature	The Dry Bulb Temperature refers to the ambient air temperature. It is called "Dry Bulb" because the air temperature is indicated by a thermometer not affected by the moisture of the air.
Electromagnetic pulse	An electromagnetic pulse (EMP) is an intense burst of electromagnetic (EM) energy caused by an abrupt, rapid acceleration of charged particles. Solar flares can generate EMPs.
Enthalpy	Enthalpy is a measure of the thermodynamic energy content of the air disregarding its kinetic and gravitational potential energy.
Fluvial	Fluvial flooding is when a river exceeds its capacity, often due to excessive rainfall over an extended period of time.
Föhn winds	A föhn is a generic term for warm strong and often very dry downslope winds that descend in the lee of a mountain barrier
Frazil ice	Tiny, round or pointed ice crystals formed in supercooled water and prevented from coagulating by turbulence.
Freezing level	The freezing level is the altitude at which the air temperature is 0°C. Temperature (and pressure and density) reduces with altitude in the atmosphere. This is called the lapse rate and near the surface is approximately 2°C/330m (2°C/1000 ft), but varies with moisture content. In the UK, altitude (above mean sea level) and height (above ground surface level) is conventionally measured in the imperial unit of feet; and conventionally in units of 1000 ft.
Freezing precipitation	This is precipitation that is liquid water for part of its descent, falling onto the ground in liquid form when the surface air temperature is below 0°C. The drops

	become super-cooled and freeze upon impact with soil or with any surface, resulting in the formation of a layer of ice.
Front	In meteorology, generally, the interface or transition zone between two air masses of different density.
H++	Plausible ‘high-end’ climate change scenarios, referred to as H++ scenarios, which are typically extreme climate change scenarios on the margins or outside of the 10th to 90th percentile range of possible climate change scenarios presented in the 2009 UK climate change projections (also known as ‘UKCP09’).
Hurricane	A hurricane is an area of low pressure over warm tropical or sub-tropical waters, with organised convection (i.e. thunderstorm activity) and sustained winds near the surface of at least 74mph (and stronger gusts) circulating either anti-clockwise (in the northern hemisphere) or clockwise (in the southern hemisphere). The whole storm system may be five to six miles high and 300 to 400 miles wide, although sometimes can be even bigger. It typically moves forward at speeds of 10-15mph, but can travel as fast as 40mph. The term 'hurricane' is usually restricted to the Atlantic and north-east Pacific region. In the north-west Pacific they are known as 'typhoons' and elsewhere simply as 'cyclones'. If sustained wind speeds are between 39mph and 73mph they are known as a 'tropical storms'. Collectively, they are often referred to as 'tropical cyclones'.
Hyetograph	A hyetograph is a graphical representation of rainfall intensity over time, often used to define a design basis storm event. They are used in rainfall-runoff modelling usually as part of designing drainage systems or assessing the pluvial flooding risk for a site.
Hydraulic head	The height above a datum plane (such as sea level) of the column of water that can be supported by the hydraulic pressure at a given point in a ground water system.
Jet stream	Relatively strong winds concentrated within a narrow stream in the upper atmosphere. Jet streams can have a strong influence on the track of storms in the lower atmosphere.
Katabatic wind	Katabatic wind (from the Greek: katabaino - to go down) is the generic term for downslope winds flowing from high elevations of mountains, plateaus, and hills down their slopes to the valleys or planes below. Katabatic winds exist in many parts of the world and there are many different names for katabatic winds depending where they are located and how they are formed.
Luminescence dating	Luminescence dating (including thermoluminescence and optically stimulated luminescence) is a type of dating methodology that measures the amount of light emitted from energy stored in certain rock types and derived soils to obtain an absolute date for a specific event that occurred in the past.
Orographic	Orographic means relating to mountains, especially as regards their position and form.
Palaeoclimate	A climate prevalent at a particular time in the geological past.
Pluvial	Pluvial flooding is defined as flooding that results from rainfall-generated overland flow before the water enters a river.
Pyroclastic	(Of rocks) Formed from the solid fragments ejected during a volcanic eruption.
Radiometric dating	Any method of determining the age of earth materials or objects of organic origin based on measurement of either short-lived radioactive elements or the amount of a long-lived radioactive element plus its decay product.
Squall line	A narrow band of high winds and storms associated with a cold front.
Stochastic	Having a random probability distribution or pattern that may be analysed statistically but may not be predicted precisely.
Supercell	A large slow-moving area of updraught and downdraught which causes violent thunderstorms, heavy hail, and tornadoes.
Terminal velocity	The constant maximum velocity reached by a body falling under gravity through a fluid (ie the atmosphere). In meteorology, applied to hail to define the velocity at which it hits the ground and (with its mass) defines its energy as a missile.

Tornado	A tornado is a rapidly rotating column of air that reaches between the base of a storm cloud and the Earth's surface. Tornados form in very unsettled weather conditions as part of severe thunderstorms. Tornado size and intensity vary greatly. Typically, a tornado is 20 to 100 metres wide at the surface, lasts for a few minutes and has a track of around a mile (1.6km). Wind speeds typically range from 75 to 100 mph (120 to 180 km/h).
UKCP09	UK Climate Change Projections (UKCP09) was published in 2009. It is based on sophisticated scientific methods provided by the UK Met Office, with input from over 30 contributing organisations. UKCP09 can be used to help organisations assess potential impacts of the projected future climate and to explore adaptation options to address those impacts.
UKCP18	UK Climate Change Projections (UKCP18), the 2018 update of UKCP09. The UKCP18 project will update the UKCP09 projections over UK land areas and update UKCP09 projections of sea-level rise, giving greater regional detail, further analysis of the risks we face, both nationally and globally, and provide more information on potential extremes and impacts of climate change.
Waterspout	A rotating column of water and spray formed by a whirlwind occurring over the sea or other body of water.
Wet bulb temperature	The Wet Bulb temperature is the temperature of adiabatic saturation. This is the temperature indicated by a moistened thermometer bulb exposed to the air flow and allowed to cool without heat transfer to the surroundings.

1 INTRODUCTION

1. This annex provides guidance on the main features of meteorological 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 meteorological hazards. Meteorological hazards are manifested through weather systems that produce varying combinations of: wind, precipitation, air temperature and associated humidity and lightning etc. These primary meteorological hazards directly influence secondary external hazards such as pluvial and or fluvial flooding, sea temperature and ground water levels and these are also included within the scope of this annex. Storm surge and wind driven waves are also caused by meteorological effects but these are discussed in the assessment of coastal flooding in Annex 3 [3]. This annex is supported by one Expert Panel Paper [4].

2. The Environment Agency (EA), the Scottish Environmental Protection Agency (SEPA) and Natural Resources Wales (NRW) have major roles in regulating river defence protection in England, Scotland and Wales respectively[2]. Each agency provides advice on climate change to the construction industry and for infrastructure planning purposes, eg [5]. An explanation of the respective roles and vires of the EA and the Office for Nuclear Regulation (ONR) is provided by [6].

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[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. Meteorological hazards are described in terms of the overarching climate system, the weather systems relevant to the UK landmass and the individual hazards that result. Due to climate change (see Section 2.2) the statistics characterising and describing these hazards are often considered to be non-stationary adding to the complexity of hazard derivation. Where additional information is necessary this sub-section is supported by [4].

4. The weather in the UK is driven by local, regional and hemispheric scale physical processes that result from the complex movement of thermal energy within the earth's atmosphere, oceans and landmass. The aggregated outputs from these are known as the climate.

5. Weather can be defined in various ways but for the purposes of this annex is taken to be the time varying state of the atmosphere above a given point on the earth's surfaces, where the state is defined in terms of pressure, temperature, density, humidity and wind, precipitation speed and direction. Synoptic weather – the regional weather that forms the basis of forecasts by the UK Met. Office (UKMO) – is best considered in terms of air masses, where each mass is a section of the atmosphere with approximately similar characteristics in terms of pressure, temperature, moisture content etc. These air masses – that may cover an area of many hundreds of thousands of square kilometres – are usually classified according to latitude and the continental or maritime source region, eg "maritime" if they originate over an ocean, "polar" or "arctic" if they originate from higher latitudes.

6. Low pressure atmospheric systems are characterised by rapidly moving cyclonic air masses (rotating anti-clockwise in the northern hemisphere), often bringing stormy weather to the UK with high winds and precipitation. High pressure systems are characterised by slowly moving anticyclonic (clockwise) rotating air masses, and these often bring relatively calm weather with low wind speeds and little precipitation.

7. The overall motion of air masses is driven by the physics of the global atmosphere surrounding a rotating Earth which is warmed by the sun substantially more in equatorial regions than near the poles. At hemispheric and regional scales, the behaviour of air masses is controlled by atmospheric phenomena such as jet streams. These have a strong controlling influence on the tracks of air masses and their attendant weather systems. Although jet streams usually vary in position over several days, they can often repeat a preferred path for several weeks or even months at a time. This means that the movements of successive weather systems can sometimes be highly correlated.

8. Adjacent air masses affecting a given geographical region are separated by fronts. A cold front is where relatively cold air replaces warmer air at the surface; warm fronts are the opposite of this and occluded fronts are a local mixture of both. The various fronts can create significant weather events because it is here, where air masses interact, that rapid changes in temperature and pressure occur. The mixing of warm and cold air masses can lead to convective storms because warm air at the surface is displaced by colder air causing a rapid rising and cooling of the warm air. If sufficient moisture is present in the rising warm air significant convective cloud formation will occur due to the condensation of water vapour as the air cools, which usually results in precipitation: the stronger the front, ie the greater the temperature difference between the air masses, the higher the precipitation that can result. Warm fronts, in contrast, do not usually promote strong convection between air masses, but with sufficient atmospheric moisture lead to stratified clouds and relatively light rain.

9. At smaller scales local convective storms (often referred to as thunderstorms) can be generated by strong heating of the earth's surface in combination with a relatively high moisture content in the air. These storms are difficult to forecast due to their small spatial

scale. However, they can produce short duration extremes of precipitation (in the form of hail and rain), wind (and in some cases tornados) and lightning.

10. For a more specific description of the UK climate refer to [4] Section 2.

2.1 Hazard Description – (SAPs EHA.1, EHA.11): Hazards Arising from Weather Systems

11. It is evident that large scale weather systems, or small-scale systems, eg convective storms, bring with them a collection or combination of hazards, some of which are correlated (eg precipitation and lightning). These hazards can give rise to other secondary hazards (eg pluvial flooding from extreme precipitation), and consequential site hazards (eg site inundation and / or overloaded or blocked surface water drains). The head document, see [1] Section 5.2, identifies the following categorisation of hazards, which are adapted below to apply to weather hazards:

- *Primary hazard*: An external hazard generated directly by a weather system.
- *Correlated hazard*: An external hazard that can occur simultaneously with the primary hazard because both depend on a common weather event.
- *Secondary hazards*: An external hazard that is caused by and dependent on the occurrence of a primary hazard.
- *Coincidental hazards*: Realistic combinations of randomly occurring independent external hazards affecting the site simultaneously.
- *Consequential hazards / effects*: Hazards (internal and external) and / or the derived effects of primary, correlated and secondary hazards, leading to a direct challenge to site safety and / or site operations.

12. Where a primary hazard definition is represented by a design basis, different aspects of the design basis may originate from different weather systems or phenomena. For example, short duration extreme precipitation rates are likely to be dominated by small scale convection storms, ie thunderstorms, whereas longer duration precipitation rates will likely originate from large scale weather systems, eg low pressure storm systems. Table 1 provides an example list – not comprehensive – of primary and secondary hazards and consequential hazards / effects as they may arise for the different weather systems.

13. A selection of the hazards from Table 1 are briefly described below, they include primary hazards themselves along with some examples of the significant secondary, and consequential hazards / effects.

2.1.1 Precipitation – *(primary hazard)*

14. As portions of the atmosphere become saturated (relative humidity → 100%), water vapour first condenses on atmospheric condensation nuclei eg dust that are always present and then due to collision and coalescence, gravitational force leads to precipitation as rain, snow, or ice depending on temperature and a range of other factors. This section is supported by [4] Section 6.1.

15. Rain: This is precipitation that arrives at the surface in liquid form (of varying droplet sizes), although it may originally have formed as ice crystals, hail or snow in the atmosphere. Rainfall is usually presented quantitatively in the form of a rate, eg mm/hour, while the distribution of rainfall with time is commonly represented graphically as a rainfall hyetograph. If rainfall rates exceed the ability of local drains and ground to absorb and remove, then localised flooding will eventually occur.

16. Snow: This is a granular material composed of small particles of ice in an open structure of varying density. However, melting and refreezing may result in more compact structures known as snow grains, ice pellets or hail (discussed below). Snow forms in clouds if the temperature is below $0^{o}C$ as a result of the uplift of moisture-laden air. This causes condensation of water vapour to ice crystals and their subsequent aggregation into snow particles. Commonly, snow forms on weather fronts moving across the UK during winter; the upward movement of air may also be caused by flow over mountainous areas, leading to often heavy orographic (or relief) precipitation and the heavy snowfall associated with upland areas. When the atmosphere at ground-level is cold (less than around 1°C), snow reaches the ground without melting into rainfall and, if temperatures remain cold, accumulates into snowpack.

17. Hail: This is a form of precipitation consisting of irregular lumps of ice (hailstones) and is usually associated with severe convective storms, so is as likely (if not more so) in summer as winter. Hailstones consist mostly of water ice and can vary in size between 5 and 150mm in diameter. The terminal velocity of hail (the speed at which hail is falling when it strikes the ground) varies with the diameter of the hail stones, the friction with the air, and wind speed.

18. Freezing precipitation: This is precipitation that is liquid water for part of its descent, falling onto the ground in liquid form when the surface air temperature is below $0^{o}C$. The drops become super-cooled and freeze upon impact with soil or with any surface, resulting in the formation of a layer of ice.

19. Example secondary hazards:

- Pluvial flooding: The capacity of surface water drainage systems may be exceeded leading to pluvial flooding hazards and flooding of roofs and elevated areas which can reduce the effectiveness of lightning protection systems.

- Fluvial flooding: Extreme precipitation in the surrounding region and catchment areas can lead to fluvial flooding and high groundwater levels. For more details on this hazard, see [4] Section 6.2.

- High groundwater level: Extreme precipitation, river levels and even sea levels can raise the level of groundwater. The speed at which groundwater responds and then returns to a normal level is dependent on antecedent conditions and the hydraulic characteristic of the local geology, and the rate of water accumulation and depletion in the source region feeding the groundwater. High groundwater levels also reduce rain infiltration and can produce flooding and overland flow even with low rainfall amounts and intensities.

- Drought: Conversely a lack of precipitation can lead to a reduction in groundwater level and reduction in moisture content in near surface geology.

- Thaw flooding: Where a snow-pack has accumulated through a sustained period of below freezing temperatures, a rapid thaw may occur with a rise in air temperature. This is a particular hazard when precipitation falls as rain onto a snowpack, leading to rapid melting and high runoff, increasing flood risk. The effects could be further amplified by the blockage of surface water drainage systems due to icing and snowpack.

20. Example consequential hazards / effects:

- Ponding on-site: Pluvial and fluvial flood hazards can lead to ponding on low lying areas of the site, or in extremis, inundation of the site, ingress to buildings through pipe trenches, airbricks or other low level penetrations, and subsequent damage to structures, systems and components (SSCs).

- Snow loading on structures: Extreme snow and ice loading can lead to damage to SSCs, particularly the roofs of civil structures, due to overloading and potential disruption of power delivery systems (eg due to the build-up of ice on power lines). These loads can be further increased by the additional weight of rain on an antecedent snowpack.

- Snow drift: Extended periods of freezing weather can lead to a substantial accumulation and drifting of snow and ice - due to wind effects, creating hazards such as elevated loadings on civil structures and power lines, clogging of heating, ventilation and air conditioning (HVAC) systems, restrictions to site access and movement around site, etc.

- Missile hazard from hail: Extreme hail events have been known to cause widespread damage to infrastructure resulting in the loss of off-site power to some nuclear sites.

- Loss of foundation bearing capacity: Extremes in groundwater levels, both high and low (due to drought) can reduce the bearing capacity of the soil potentially leading to foundation instability. Shrinking or swelling of foundations may result in damage to infrastructure, cooling pipes, flood defences and other structures.

- Blocked drains: The accumulation of frozen material or debris may block drains and gullies, reducing the capacity of surface water drainage systems. This could be further exacerbated by a potentially reduced hydraulic head resulting from, for example, a high tide or storm surge at coastal sites causing backing-up at the seaward outfall end of drainage systems. Blocked drains may also cause water to overflow the drainage system and find alternative routes to low points on-site, such as cable trenches and then into building basements, or may collect at or flow through topographical features such as slopes, causing instability.

- Breach of roofing membrane / building fabric: Precipitation may collect on roofs, especially flat roofs or those with too shallow a fall, leading to overloading or finding leak paths allowing water to directly enter the building structure. This can lead directly to adverse effects on electrical switchgear and the potential for radiological consequences, such as increased potential for criticality with stored fissile material and breach of containment if the building contains mobile radioactive material. Excessive precipitation can lead to backing up of drains, failure of flood defences such as waterproof seals around cables in trenches, all of which can lead to floodwater ingress in to buildings.

- Icing on exposed components: Precipitation combined with a low air temperature can lead to icing hazards to exposed surfaces; this is known to cause an increase in dead loads and affect the dynamic response of structures, especially open structures subjected to wind action such as conductors in transmission lines, potentially leading to Loss of Off-site Power (LOOP). Similar but usually less pronounced effects should be expected frequently in steel trusses under winter conditions. It may also impair the proper functioning of exposed devices with moving parts such as valves and pressure relief devices.

- Reduced site accessibility: This can result from extreme rainfall or snow events that cause disruptions in transportation in the area around sites. Wind-blown snow in particular can cause dangerous blizzard conditions and snow-drift accumulation, particularly with the light powder-snow which results from snow falling through dry, cold air. This needs to be taken into account within site emergency management plans, for example through the provision of nearby or on-site staff accommodation for periods of extreme weather.

- Induced geotechnical hazards: Extreme precipitation can induce slope instability, mudslides, embankment failures etc.

2.1.2 Lightning – *(primary hazard)*

21. Lightning is a visible electrical discharge most commonly produced in thunderstorms – a particularly extreme weather system caused by rapid convection of warm moist air at a cold front. It is generally generated in cumulo-nimbus cloud or squall lines extending to altitudes over 3000m or in mid-level clouds at 2000m or over where the freezing level is within the clouds. Lightning transients exhibit extremely high voltages, currents and current rise rates. The extreme electric field created around lightning discharges can, under certain circumstances, produce point discharges in nearby equipment including breakdown (a conductive path) in all but the most robust of insulators. Once a path has been established for the return stroke, currents of tens to hundreds of kilo-amperes flow.

22. While it is not currently possible to predict when and where lightning will strike, statistical information can provide some indication of the areas prone to lightning activity as well as the seasons when such activity is most likely to occur. It should be noted that lightning is an unpredictable transient phenomenon with characteristics that vary widely from event to event and where measurement of current flow is difficult. This section is supported by [4] Section 8.

23. A relevant standard for application to conventional buildings is [7].

24. Example secondary hazards:

- Electrical fires

25. Example consequential hazards / effects:

- Breaches of building containment and structural damage, eg damage to off-site electricity transmission lines leading to LOOP.
- Damaging electrical surges.
- Electromagnetic pulses generated from close strikes.
- Damage to telephones, computers and other electronic devices leading to loss of safety function.
- Structural damage.
- Conventional health & safety hazards to personnel on-site.
- Missiles, eg due to spalling of concrete.

2.1.3 Wind – *(primary hazard)*

26. Wind can be considered as a steadily moving stream of air, upon which is superimposed a fluctuating component that changes both speed and direction over timescales of seconds to minutes to hours. Large, short-term fluctuations in speed and direction are known as gusts. Another dynamic effect is turbulence, which is caused when wind flows over and around objects. Turbulent flows can generate intense very local vortex structures with rapidly varying speed, direction and pressure. Extreme wind is typically generated by weather systems such as: extratropical cyclones, strong convection cells (thunderstorms) and the passage of fronts, and may be associated with blizzards, ‘föhn’ winds, air flows induced by gravity (eg katabatic winds) and other local phenomena. For more details, see [4] Section 7.

27. *Hurricanes* or tropical cyclones are especially violent rapidly rotating storm systems with sustained wind speeds in excess of 70mph or higher that form over bodies of warm water. Whilst the UK has not historically been affected directly by hurricanes, it can be affected by the remnants of such storms (eg ex Hurricane Bertha, 2014). The Great Storm of 1987 is classically an example of a sting jet, where a rapidly or “explosively” deepening depression leads to a descending jet of air on the southern flank of a depression. Winter storms in the UK have quite often been recorded with wind speeds in excess of 100mph in exposed coastal locations or on mountain tops.

28. *Tornados* are spatially highly localised, very intense, rapidly rotating low pressure vortex structures that are off-springs of thunderstorms and quite common in the UK. Supercells (large intense storm systems) are responsible for producing the largest and most violent tornadoes; however these large events are rare for the UK. If a tornado forms over water, it may be referred to as a waterspout and these have often been recorded in the UK. Tornadoes result when the thermal energy stored within a parent thunderstorm is converted into kinetic energy close to the surface via a tornado vortex, causing intense low-pressure cores and localised very high wind speeds. A feature of tornados is the large sudden pressure drop as its core tracks across a point on the surface.

29. An early study of tornado risk was undertaken for ONR in 1985 [8], but more recent work is summarised in the supporting Expert Panel paper [4], Section 7.5.

30. Example secondary hazards:

- Large wave generation on open water and storm surge, and associated wind driven spray – (See TAG 13 Annex 3 [3])

31. Example consequential hazards / effects:

- Large aerodynamic forces can be created on exposed surfaces of structures as wind flows around and over them.
- Changes in air pressure locally to inlet / outlet of HVAC and filtration systems which may affect their operation / effectiveness, and the effectiveness of equipment attached to HVAC systems relying, for example, on pressure differentials for containment, eg gloveboxes.
- Loose objects and objects resulting from structural damage can become missiles that can cause impact damage, eg displaced cladding panels or miscellaneous debris on roofs etc. Tornadoes can lift potential missiles into the air more effectively than direct winds.
- Breaches of building containment and structural damage, eg LOOP.
- Tornados can create sudden pressure drops that may have similar consequences to structures as other strong aerodynamic forces.
- All of the above hazards can cause restrictions to movement both on and off the site.

2.1.4 Air temperature extremes (low) – *(primary hazard)*

32. High pressure systems in winter often bring clear skies and still conditions. This, combined with the sinking of cool air from the upper atmosphere, can result in air with a low enthalpy, usually low dry bulb temperatures and low moisture content. Clear skies, especially at night, can promote the radiation cooling of exposed surfaces, further reducing surface temperatures significantly below the local air temperature[3].

33. Example secondary hazards:

- Low sea water temperatures and risk of frazil ice particularly in shallow estuaries or basins.

34. Example consequential hazards / effects:

- Thermally induced loads can be created particularly on exposed SSCs.

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[3] Black ice on tarmac roads is a common consequence of such cooling.

- Low temperature can lead to a higher risk of brittle fracture of safety critical components eg cranes, fuelling machine gantries and support structures.

- Increased thermal loads on HVAC equipment.

- Freezing of contained water and diesel stocks, especially if pipes / tanks are uninsulated or sited in exposed locations on-site. Flowing liquids resist freezing better than stationary volumes. The potential to freeze liquids at a given external air temperature is strongly dependent on the ratio of liquid volume to the surface area exposed to cold air; small diameter pipes or open shallow ponds are especially prone to freezing.

- Human Factor effects from low temperatures may impair the ability of personnel to carry out safety related tasks.

- Frazil ice (secondary hazard) can accumulate on cooling water intakes in shallow coastal water, leading to reduced flow and / or blockage (consequential hazard).

- Long term corrosive effects of salt based de-icers eg effects of road grit on metalwork located close to or over roadways.

2.1.5 Air temperature extremes (high) – *(primary hazard)*

35. Air with a high energy content, or high enthalpy, is usually associated with high pressure weather systems in summer (heatwaves), see [4] Section 8. Typically, high dry-bulb temperature[4] air has an increased capacity to carry moisture hence total moisture content is usually higher, but cloud formation is less likely. Heatwaves are generally associated with periods of unbroken insolation (sunshine) and little wind.

36. Long spells of unbroken sunshine can lead to enhanced radiation heating of exposed surfaces (solar gain) and the presence of warm thermal layers close to these surfaces. The air temperature at these points can be significantly above ambient and this is effectively the temperature to be considered as a hazard to SSCs. Combined with low wind speeds, this very warm air will only be replaced by cooler air slowly, allowing greater heat transfer to exposed surfaces.

37. Long periods of high temperature (heatwaves) tend to gradually raise the surface temperature. However, continued warming of the earth’s surface is limited by the vertical stability of the atmosphere. Eventually the vertical temperature profile becomes so unstable that strong convection is set up; this can result in thunderstorms in temperate regions such as the UK. Such thunderstorms can be very intense, localised in extent, and their locations can be difficult to predict.

38. High air temperatures are also characteristic of drought conditions, although in this case high temperature is combined with low atmospheric moisture content. This case is covered in Section 2.1.10.

39. Example secondary hazards:

    - High sea water temperatures particularly in shallow estuaries or basins.

    - Intense thunderstorms producing localised high rainfall, high windspeed and lightning.

40. Example consequential hazards / effects:

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[4] An indirect indication of the humidity is measured by the difference between a dry bulb and a wet bulb temperature. When the relative humidity reaches 100%, these two temperatures coincide with the dew point temperature, so that any moisture in gaseous form condenses into liquid water.

- Thermally induced loads can be created particularly on exposed SSCs.
- Increased thermal loads on HVAC equipment, leading to high thermal loads on eg electrical equipment and potential for overheating from reduced ability to cool.
- Human Factor effects from high temperatures may impair the ability of personnel to carry out safety related tasks.
- Refer to consequential hazards applicable to high rainfall (Section 2.1.1), high windspeed (Section 2.1.3) and lightning (Section 2.1.2).

2.1.6 Low air pressure effects on open water – *(primary hazard)*

41. Low pressure weather systems over the sea have the effect of locally raising the sea level above what would otherwise occur. This happens because the sea surface responds to the rise and fall in regional atmospheric pressure, by a decrease / increase in its surface height with reference to mean sea level. This is discussed further in Annex 3 [3].

42. Example secondary hazards:

- *Surge*: Short-term rise in sea level caused by a reduction in local air pressure (air pressure reduction of 1mb produces a sea level rise of around 1cm). If this is coincident with a high tide then maximum sea level height in the tide cycle is enhanced.

2.1.7 High air pressure effects on open water – *(primary hazard)*

43. High pressure weather systems have the opposite effect to low pressure systems, ie they locally depress sea level.

44. Example secondary hazards:

- Contributes to low sea level.

45. Example consequential hazards / effects:

- Loss of ultimate heat sink for cooling systems. This could be exacerbated when the weather system combines high pressure with high air temperature as correlated hazards. Could result in reduced effectiveness of cooling water pumps if these are sited incorrectly.

2.1.8 Dust storms and sandstorms – *(primary hazard)*

46. Large scale weather systems may have sufficient energy to enable transportation of dust and fine sands between continents. The UK can be subject to the deposition of Saharan dust. However, there is currently no evidence that such weather presents a significant hazard to nuclear plant in the UK.

2.1.9 Volcanic hazards – *(primary hazard)*

47. There are no active volcanoes in the UK, so the hazards arising from direct volcanic action, relating to, for example, lava flows or pyroclastic explosions, are not considered to be credible. However, the plume dust from distant volcanic explosions does have the potential to be hazardous to nuclear sites if weather conditions are such that the dust plume is transported over the UK landmass. A recent example of this is the Eyjafjallajoekull volcanic eruption on 14 April 2010 that caused UK airspace to be closed from 15-20 April because of the hazard to aircraft engines.

48. The hazard to nuclear SSCs is that the dust contains particles that can be ingested by air intake structures, block filters and adversely affect associated plant.

49. Example consequential hazards / effects:

- Blockage of air intake systems and reduced efficiency of HVAC, gas turbine and diesel generators.

2.1.10 Extremes in humidity or moisture content – *(primary hazard)*

High humidity conditions

50. *Winter*: High moisture conditions during winter are commonly associated with fog or visible water droplets that are suspended in the air near the surface, often considered as low-lying cloud. The prevalence of this hazard is influenced by nearby bodies of water, the site topography and wind conditions and is particularly prevalent along the east coast of the UK.

51. *Summer*: High moisture conditions during summer tend not to lead to visible water droplets in the air because of the higher temperature and associated ability of the air to carry more moisture. However, the effects of high moisture content can be manifested by an increased latent heat load on HVAC equipment and enhanced rates of condensation on relatively cool surfaces.

52. Example secondary hazards:

- Reduced visibility (fog) and site accessibility, see [4] Section 8.
- Condensation.
- Salinity of condensation at coastal sites.

53. Example consequential hazards / effects:

- Exposed SSCs may be subject to enhanced corrosion and degradation rates. This can cause blocking of air filters, or loss of functionality to exposed or unprotected metalwork and related components.

Low humidity conditions

54. *Winter*: Low moisture conditions during winter are commonly associated with high pressure weather systems, very clear weather, low temperatures and low wind speeds (anticyclone conditions). This is covered in Sections 2.1.4 & 2.1.7. There are no other secondary or consequential hazards identified.

55. *Summer*: Low moisture conditions during summer are characteristic of high pressure weather systems and drought conditions. These conditions are usually combined with high temperature and low wind speeds. This is covered in Sections 2.1.5 & 2.1.7. The following secondary and consequential hazards are associated with drought conditions:

56. Example secondary hazards:

- Low river and reservoir levels.
- Low groundwater levels.
- Electrical discharge (enhanced potential for).

57. Example consequential hazards / effects:

- Loss of foundation support to buildings.
- Potential to lose access to off-site towns water supplies.
- Reduced conductivity to earth for lightning protection systems.

2.1.11 Marine environment (high salt content humidity) – *(primary hazard)*

58. The atmosphere over the open sea and in coastal areas contains sodium chloride in the form of solid particles or as minute drops of saline solution. Concentration levels of saline atmospheres are influenced by the degree of atmospheric evaporation of sea-water and upon dispersion factors such as wind. Salt particles resulting from atomisation in surfs and breakers generally settle at distances governed by particle size and direction and velocity of wind, causing atmospheric salinity values to fall rapidly with the distance inland from the coast.

59. Salt can cause or accelerate corrosion of metals via an electrochemical process and the effect can be increased as temperature and humidity rise. Corrosion of this type will occur on most exposed metal structures and components (such as electrical insulators) unless protected and maintained. Due to the electrochemical process this form of corrosion can cause significant damage to metalwork and to reinforcement within concrete structures.

60. Example consequential hazards / effects:

- Corrosion by electrochemical reaction. Rates of corrosion can be enhanced significantly in salt laden atmospheres, potentially increasing the vulnerability of affected SSCs.
- Shorting out of electrical insulators on grid connections leading to LOOP.

2.2 Issues Affecting Extreme Weather in the UK and Surrounding Region – (SAP EHA.11, EHA.12)

61. It is generally accepted by the informed technical community that climate change is now being largely driven by human activities, reinforced by natural climate variability and this will affect both current and future climate and associated weather.

62. At local scales, some of the meteorological hazards discussed above may be affected by changes in land cover, land-use and urbanisation. At regional scales, trends are likely to relate to changes in atmospheric behaviour at regional and larger scales. For example, more intense storms will result from increased availability of thermal energy due to climate-change driven warming of the atmosphere and sea.

63. Due to the typical lifetime of a nuclear site (of the order >100 years); changes to meteorological hazards as a result of climate change could be significant. The inspector should be aware that the statistical extrapolation of past datasets for the development of projections of future meteorological conditions may not adequately capture changes in the future trend in these hazards, nor the degree of variability around this.

64. A summary of the current research and UK Climate Change Projections as they apply for various emission scenarios is provided in [4] Section 5.

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

65. This section is supported by [4] Section 3.

66. The long-term data used to evaluate extreme values of meteorological hazards should ideally cover a period commensurate with the annual frequency of exceedance used for assessing the corresponding design basis. Ref. [9] advises that typically the hazard cannot be estimated with sufficient accuracy for return periods (inverse of frequencies) more than three to four times the length of the sample period. This presents a challenge for nuclear facilities that require a 10^{-4}/yr design basis and beyond design basis hazard estimates, where good quality instrumental data only exists for 50 – 100 years.

67. Hence, site-specific meteorological hazard analyses need to draw upon all available data sources, including palaeoclimate proxy data, historical, and instrumental data

sources, where such data are likely to enhance nuclear safety significant arguments. For example, historical events such as the UK great storm of 1703 should be assessed as potential hazards for nuclear sites. This is an event for which credible historical records exist in the UK, see [4] Section 3.2.

68. Where some of these data are not readily available (eg as might be the case for sediment cores which could provide proxy palaeoclimate data) then these could be sought. In addition, the use of synthetic data generated from stochastic weather generators based on the statistical characteristics of observed data can provide the basis to support projections of climate change. All the information collected should be compiled in specific site catalogues or databases for each of the hazards under consideration. For all the data types discussed below inspectors should seek assurance that data uncertainties have been properly characterised and accounted for in the hazard analysis.

2.3.1 Palaeoclimate Data

69. Natural sources can offer insights into weather patterns from similar climatic periods over long timescales. Examples include assessment of the accumulation of windblown sediments, the erosional imprint of past wind directions, and assessment of palaeoflood level frequencies and magnitudes from analysis of floodplain and river bed sediment deposition. The timing of flood events can be assessed using radiometric and luminescence dating and by the use of lichen growth curves and dendrochronology (tree ring dating). Such data sources can have significant uncertainties and historically have not routinely been investigated for use in hazard analyses. However, inspectors should be aware that increasingly these data sources are now being used to provide context for hazard analysis – refer to [4] Section 3.1.

2.3.2 Historical Accounts / Records

70. The record of historical and anecdotal accounts of meteorological events can 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. From data of this type, and by using an empirical classification system for each phenomenon, a catalogue of events and their associated intensities may be collected for the region. The size of the region in geographical terms, from which such data should be obtained, should be such as to enclose weather phenomena and their effects relevant to the site in question.

71. Assessments based only on these data alone are likely to be biased spatially and temporally and inherently uncertain. This is because they tend only to reflect very local phenomena (ie the flooding of a street or town centre, rather than the entire catchment). Also, personal narratives often are highly uncertain and local, as are newspaper reports.

72. However historical documentary data may be useful for augmenting instrumental data to extend the instrumental climate record over hundreds of years and may reveal more extreme weather events than those recorded by instruments. This may somewhat alleviate the degree of statistical extrapolation required from short instrumental records. Existing hazard studies have generally not exploited this data source as effectively as say, for example, seismic hazard. For more information see [4] Section 3.2.

2.3.3 Instrumental Data

73. Meteorological data is gathered from weather monitoring stations. The UKMO operates a network of weather stations and these record wind speeds, precipitation rates, temperatures and many other weather variables on a sub-daily basis; it uses these as

input to numerical weather prediction models and the development of weather forecasts for the UK. Other organisations install and operate weather stations at sites of use to their business interests; data from these may also be available. Typically, datasets vary in timescale and quality from place to place, but good quality data is generally available for much of the UK and mid-latitude land areas bounding the North Atlantic back to the 1950s and, in some cases, back before the beginning of the 20th century, [4] Section 3.2.

74. Care should be taken when supplementing UKMO data with other local sources of data. Whilst the UKMO follow recognised standards for data collection, field measurements made by different organisations may not necessarily follow the same standards and may require statistical processing to allow integration. Some examples could be:

- The standard 10m height and instrument exposure for measuring wind speed and direction may not be observed owing to the logistics of instrument installation.
- Measurement techniques for recording maximum wind speed may vary. The general tendency is to record average values for a given constant duration, such as 3 second gusts, 60 second averages or 10 minute averages (the averaging time is a characteristic of the database).
- Air temperatures (such as dry bulb and dew point temperatures) are recorded continuously at some recording stations and at frequent intervals at other stations. At some secondary locations, only the daily maximum and minimum air temperatures are recorded.
- Data that are routinely collected and used for analyses of extreme maximum precipitation generally include the maximum 24-hour precipitation depth. Records based on shorter averaging times contain more information. This variation necessitates careful evaluation and, if possible, adjustment of the data before processing.
- Meteorological stations may be moved at times during their operation and land use changes or construction near stations may affect raw data time series.

75. Meteorological data that have already been processed and statistically manipulated to provide hazard values at a specific annual frequency of exceedance (typically 0.02/yr) are also available through publicly available standards, the most relevant and up-to-date of which are the suite of UK National Annexes (NA) to Eurocode 1 (Actions on Buildings), Refs. [10], [11], [12], [13], [14], [15], [16])[5]. These hazard data are presented as hazard maps and tables, and the source data is updated periodically and is freely available. However, the uncertainty around these values is not defined.

76. Care must be exercised in using such design code hazard data, since the revision cycle with which this is updated may not at the time of use include recent extremes, or be representative of recent changes local to the site, thus not meeting the intent of EHA.2. Also, such data is necessarily only an approximation to the actual hazard at a particular site, so augmenting code based data with a site-specific hazard study is likely to be proportionate.

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[5] The National Annexes to the Eurocodes (Refs. [11], [14], [16]) provide hazard maps that define UK hazard values for snow, wind, and temperature that have a 0.02 annual frequency of exceedance. These also provide methods to adjust the hazard values (obtained from the maps) to account for site-specific aspects eg topography, roughness, altitude etc. These hazard maps are similar to the previous hazard maps in the now withdrawn British Standards, except that the source data record has been increased (eg for wind from 11 years to 30 years). Of note specifically for wind while the 10-minute averaging period is the meteorological standard for much of continental Europe, the UK uses a 1 hour averaging period, therefore a factor of 1.06 is adopted by the Eurocode to adjust the measured 1-hour average source data to the 10-min period, based on empirical calibrations [12].

2.3.4 Synthetic Data

77. Although not obtained from direct measurement, numerical Global Climate Models and Weather Generators can be used to create synthetic-datasets, and to assess future climate change effects. Models can be downscaled to create Regional Climate Models and these were used in conjunction with various emission scenarios to develop the UK Climate Projections 2009 [17] (UKCP09). An update to these based on the 5th Inter-Governmental Panel on Climate Change (IPCC) assessment report – UK Climate Projections 2018 (UKCP18) – is currently ongoing and is expected to build upon the current set of projections (UKCP09), using the latest science and supercomputing capabilities[6]. These projections represent RGP for the UK.

78. The inspector should note that this is a fast developing and complicated field and expert advice will likely be needed to support assessment of this area, in particular the management of epistemic uncertainty. – Refer to [4] Section 3.4.

2.3.5 Previous Meteorological Hazard Studies

79. As part of the documentation of a site-specific hazard assessment it would be 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 pedigree of the study, these can provide useful information on hazard levels at the site. Although of interest, the usefulness of regional and national hazard studies (notably the Eurocodes) may be limited for site-specific applications, since the hazard maps they produce may be considered too coarse and approximate for site-specific use.

2.3.6 Statistical data processing

80. Before a site-specific dataset can be used to derive the hazard via extreme value analysis 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). As an example, for structural design purposes wind speed data may need standardising in terms of, for example, uniform averaging time periods, altitude, surface roughness, exposure, local topographical effects and duration of the mean wind speed.

81. In particular locations for some hazards such as snow, the data available may contain individual exceptional values that cannot be treated by the usual statistical methods. In these cases, the Licensee may choose to consider such events separately.

82. If the data are being used as input for a non-code based, or bespoke analysis, the data processing should take account of the characteristics of the facility to ensure its use is consistent with EHA.4 and leads to a conservative estimate of the design basis. As an example, for a bespoke Computational Fluid Dynamics analysis the data for mean wind speed should be processed so that the input duration is consistent with any dynamic characteristics of the site facility that may be susceptible to wind hazard and result in turbulent wind flow that could result in damage to nearby structures. For additional information see [4] Section 4.

2.4 Notable Aspects of Plant / SSC Response to Meteorological Hazards – (EQU.1, EAD.2, ELO.1, ELO.4, ECE.5, ECE.6, EMC.7, TAG 017 [3])

83. The impacts of meteorological 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 on weather effects is provided below based on applicable regulatory experience gained from UK sites over recent years.

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[6] Further information can be found at http://ukclimateprojections.metoffice.gov.uk/

2.4.1 Overview

84. Meteorological hazards often occur in various combinations (eg precipitation & lightning, wind and precipitation) and 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 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. For example, wind damage to the roof of a building containing electrical switchgear during a storm will almost certainly combine with heavy rainfall, potentially leading to short-circuit and loss of electrical supplies.

85. Precipitation can bring large quantities of water onto the site, which must be managed by drains and gullies etc. In major storm conditions, Licensees may take advantage of roads and natural topographical features to route excess water away from safety significant buildings and areas. Inspectors should be aware that drains can easily be blocked by snow and debris. Also, water may find its way into buildings through pipe / cable trenches, if these are inadequately sealed. Basements are especially prone to flooding and SSCs located in basements are therefore particularly vulnerable.

86. Storms often also exhibit lightning, which can damage electrical equipment and structures and is also a direct threat to life. Protection against lightning is routinely provided by various types of conductors that provide a preferential route to ground for any lighting strike in its vicinity. The quality of the ground connection is significant and this can be impaired by, for example, a period of dry weather that reduces the moisture content of the ground, thereby reducing its conductivity and its ability to act as a sink for the very large electrical currents that arise during a lightning strike.

87. These considerations are more important when a multi-unit or multi-installation site is being assessed, and in particular if SSCs are shared between units. Many multi-facility sites use delay tanks to allow monitoring of waste water before discharge, especially if arising from potentially contaminated areas. Storm conditions can cause excess water to enter such tanks, which may then overflow, discharging potentially contaminated liquid through an unmonitored route. Old structures, especially those on large sites, are likely to have drainage systems that do not meet modern RGP, or even modern conventional building standards. There have been examples where flood water has entered such structures through drains that have backed up to the point of overflowing into the building, or through flat roofs where the waterproof membrane has been breached. If such structures contain contaminated material, then there is potential for contaminated liquid to leave the building by an unmonitored route. If water entry occurs in a building containing fissile waste, then there is the potential for a criticality event, so inspectors should be aware of the potential radiological consequences of poor storm water management in these cases.

88. Meteorological 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. For example, windstorms, ice, lightning and precipitation could also impede emergency response by slowing down measures for evacuation or relocation and / or by interfering with communications and operator shift turnover.

89. Some SSCs can be susceptible to the amount of heat transfer from or to the atmosphere, rather than the short duration value of high or low air temperature; this usually depends on their heat capacity. Such systems will therefore be sensitive to a combination of temperature and duration over which the temperature persists. For

example, water containing systems with low heat capacity, such as narrow bore pipes, may be susceptible to short duration freezing conditions. Conversely, other SSCs, such as large water tanks, may have inherent resistance to freezing conditions if they have high heat capacity. HVAC systems can be sensitive to both the value of external air temperature and the duration over which it exists.

90. *Modifications to the site and adjacent areas*: Nuclear sites usually exist for ~100 years when allowance is made for the various lifecycle stages including decommissioning, and may undergo significant changes over that period as the safety, security, commercial etc. needs of the site evolve through time. Changes may also occur to land use around the site, such as the construction of new structures that changes the natural drainage characteristics assumed wen the nuclear site was originally planned and designed. These changes may affect the sites' response to meteorological hazards in complex ways and inspectors should be mindful of the potential adverse impact of such changes to say, drainage capacity and routes, increased capacity for surface water to collect or be re-directed to places not initially intended when the site was first constructed.

91. *Corrosion*: Moisture laden air is well known to promote corrosion of many structural materials especially metals such as (non-stainless) steel, through electro-chemical reaction with the atmosphere. Corrosion rates are enhanced at coastal sites by the presence of salt (saline) in the moisture or as salt particles, see Section 2.1.11 for more details. At sites on the west coast of the UK, subject to prevailing west / south-westerly on-shore winds and substantial precipitation, rates of corrosion are elevated for all susceptible materials, especially so for exposed steelwork.

92. *Provision of weather information*: Weather warnings and forecasts in the UK can be provided by the UKMO. Such warnings can be used by the Licensee to inform operational decisions such as limiting activities on-site. Inspectors should assure themselves that the safety management arrangements employed by Licensees facilitate the consideration of uncertainties in such forecasts / warnings when they are used to aid operational decisions.

2.4.2 Monitoring

93. It is possible to provide monitoring of local weather conditions at the site location, particularly air temperature and wind speed / direction. These can provide data to control rooms and can be used, normally in conjunction with weather forecasts, to initiate precautionary measures, such as restricting external work at height (high wind speed), or restricting the use of overhead travelling cranes (where steel embrittlement may be susceptible to low air temperature). The ability to respond to such weather related monitoring information should be captured in a site's arrangements such as operating instructions under Licence Condition (LC) 24, and inspectors should seek evidence that Licensees' have adequate arrangements in this regard.

2.4.3 Ageing and Maintenance

94. The response of SSCs and their ability to withstand meteorological hazards can be significantly affected by physical changes (corrosion) induced by ageing and poor maintenance; therefore, the impact of ageing and the adequate definition of Examination, Inspection, Maintenance and Testing (EIMT) should be included in any assessment and captured under the Licensee's LC28 arrangements if appropriate. This is especially important on older facilities, but it should also be taken into account during the design or modification of plant. Typical examples of susceptible areas are fixings, flashings, support steelwork and insulated tanks where the insulation has allowed water to penetrate and contact the metalwork beneath. The latter example is often made worse by the difficulty in performing visual inspections.

95. Protection is often provided by equipment design to intrusion of foreign material, especially dust and water, by an "IP rating", according to the international protection

marking standard IEC 60529. For example, electrical equipment that is suitable only for indoor use attracts a lower IP rating than similar equipment that is water resistant and suitable for outdoor use; equipment that can be used in submerged applications has a higher IP rating. Tables of IP ratings and what they mean are widely available.

96. A significant exacerbating factor at coastal locations is the presence of salt laden moisture, see paragraph 91.

2.4.4 Housekeeping

97. Finally, the potential for meteorological hazard induced SSC faults can be reduced by good housekeeping. Generally, this involves the removal of temporary equipment that might become a missile or secondary hazard to safety related SSCs, or block access routes that are needed for safety significant operator actions. Equipment can be stored in purpose built, hazard resistant, locations and include restraint systems and marked zones where specified equipment is prohibited or restricted.

98. There are a number of minor housekeeping issues that can significantly improve a site's resilience to weather hazards and constitute a regular inspection / maintenance regime. The following are typical examples where regular and / or post extreme weather event inspections are beneficial: gutters and drains to ensure they are free of debris especially after a storm, non-return flaps on drains through sea walls to ensure the working mechanism remains operational, lightweight building cladding panels to ensure their fixings remain in good order.

3 SAFETY ANALYSIS – (FA.1)

99. 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 meteorological hazard specifically.

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

100. Meteorological hazards are non-discrete hazards. It is anticipated that the major meteorological hazards, wind, precipitation, temperature and lightning and combinations thereof will always be identified as potentially significant, and screened in to the fault analysis for UK sites. Meteorological hazard analysis for screened-in hazards should develop suitable inputs for faults initiated by these hazards covering Design Basis Analysis (DBA), Probabilistic Safety Analysis (PSA) 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.

101. Inspectors should confirm that Licensees have applied a systematic process for identifying and characterising the hazards significant to their site. Table 1 provides a non-comprehensive list of those meteorological hazards generally considered to be significant to nuclear safety.

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

3.2.1 Design Basis Events – (SAPs EHA.3, EHA.4, EHA.11, EHA.12)

102. 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.

103. *Uncertainty analysis*: At the low exceedance frequencies considered for the definition of Design Basis Events (DBEs) and even more so for beyond design basis analysis (BDBA), the analysis of meteorological 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 paragraph 107). Inspectors should bear in mind that there are significant differences in RGP applied to uncertainty analysis of meteorological hazards and seismic vibratory hazards, especially in relation to how knowledge uncertainty is handled, see TAG 13 Section 5.8.10 [1]. The inspector should seek assurance that in the derivation of meteorological DBEs, they are not overly sensitive to particular analysis assumptions, and that they are able to achieve a balanced overall plant design, see [1] Section 5.8.10.

104. *Climate change*: The Licensee is expected to account for climate change and the inherently large uncertainties explicitly within the hazard analysis. The assessment methodology and the additional safety margin applied to account for climate change is expected to be proportionate to the hazard’s contribution to nuclear risk (see advice in [1] Section 5.5.2). Periodic re-evaluation of design parameters should 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.

105. For new build, ONR expects the designs to incorporate due consideration of the effects of climate change over the life-time of the facility, including the effects of emissions scenarios selected on the basis of RGP. 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 sites. 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 eg, a small increase in flood level could result in a significant increase in the flood risk 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 [17] medium emissions scenario at the 84th percentile as adequately conservative for a design basis[7].

106. 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. In this context the maximum credible scenario may be used, see [6] for more details. A current example of the credible maximum scenario for sea level rise and storm surge for the period to 2100 is provided by UKCP09, and is termed the H++ scenario, [4] Section 6.

Probabilistic Meteorological Hazard Analysis

107. Statistical analysis techniques are commonly used to assess meteorological hazards and these techniques are able to take into account gaps, missing data and outliers to the available dataset. However, the inspector should be aware that the application of these methods is somewhat sensitive to expert judgement and therefore gives rise to epistemic uncertainty that should also be considered in the design basis definition. The statistical methods and probability distributions[8] most commonly used, eg the generalised extreme value approach, and the peak over threshold method, along with the use of expert judgement needed to apply these methods are discussed further in [4] Section 4.

108. The inspector should note that caution is needed when attempts are made to fit an extreme value distribution to a dataset representing only a few years of records. If extrapolations are carried out over very long periods of time by means of a statistical technique, due regard should be given to the physical limits of the variable of interest. Care should also be taken in extrapolating to time intervals well beyond the duration of the available records (Ref. 4 suggests a limit for ‘return’ periods greater than three to four times the duration of the sample and some statisticians suggest just twice).

109. Although each meteorological hazard has aspects that need to be analysed in slightly different ways, the general framework for a site-specific hazard study is largely the same. This is outlined below and illustrated in Figure 1 of this annex.

110. The general procedure for assessing a meteorological hazard is broadly outlined in the steps below.

   i) A study of the representative data available for the region under analysis, including as appropriate geological, historical, synthetic data from weather generators and climate model projections. This should also consider exceptional events that may need to be analysed separately.

   ii) The data should be evaluated to determine its quality ie, representativeness, completeness, effectiveness of the quality assurance programme and homogeneity, along with uncertainties;

   iii) Where necessary, data from different sources will need to be standardised prior to use in statistical analysis;

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[7] 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.

[8] Extreme annual values of meteorological parameters constitute samples of random variables, which are themselves characterised by specific probability distributions. In principle, the dataset should be analysed with probability distribution functions appropriate to the datasets under study. Among these, the generalised extreme value distributions are widely used: Fisher–Tippett Type I (Gumbel), Type II (Fréchet) and Type III (Weibull).

iv) Selection of the most appropriate statistical distribution and methodology for the dataset;

v) Statistical Analysis of the data to evaluate moments (statistical measures) of the probability distribution function of the parameter under consideration (expected value, standard deviation and others if necessary), from which the mean annual frequency of exceedance and associated confidence limits may be estimated;

vi) Application of deterministic analysis to derive physical limits to the hazard severity that can be used to constrain the upper limits from the statistical analysis.

vii) Use of Climate Model Projections to derive an appropriate climate change safety margin / factor.

111. For plant with limited nuclear inventory or limited unmitigated dose potential, the design basis requirements can be less onerous, [1] Section 5.5.2. The inspector should ensure that the final design basis value is at least as onerous as that derived from the relevant design code for conventional structures.

112. For assessing combination events or weather systems, eg the combined event of wind and precipitation, a heat wave, or successive storm systems bringing a range of meteorological hazards, more complex approaches than that described above are being developed through scientific research. The individual hazard values for such combinations are likely to be less than if the hazards were assessed individually. The inspector should be aware that such methodologies exist and should seek expert advice to ensure the results are demonstrably conservative. A summary of the current science for assessing combination events is provided in [1] Section 5.8.1.

113. *Use of Design Codes*: The Eurocodes (eg Refs. [10], [11], [12], [13], [14], [15], [16]) are examples of publicly available design codes applicable to the UK commonly used for the design of conventional structures, see Section 5 for more details. Design codes can be used to support design basis hazard values in certain circumstances, see paragraph 111. However, as highlighted in Section 2.3 and Section 5, the inspector should be aware of the limitations of the source data for such design codes. It is unlikely that the application of such codes without additional supporting site-specific analysis would be considered appropriate for a nuclear site, see paragraph 111 above.

114. Some of the significant design bases and their attributes are outlined below.

Design Basis Precipitation (Rain)

115. The design basis extreme precipitation event identifies amount of precipitation accumulated over various durations of time for a certain return period, generally corresponding to the 1 x 10^{-4}/yr event. Therefore, the design basis is defined by a range of events with durations ranging from 5 min to 24 hr or more. Sometimes a deterministic approach based on the physics of the atmosphere is applied to identify the maximum credible precipitation event physically possible. This can be used to provide context to the uncertainty arising from the statistical analysis. For the analysis of pluvial and fluvial flood risk the duration of the precipitation event to be analysed should be that determined to be critical for the facility. Therefore, sensitivity analysis of the surface water drainage systems and wider catchment areas utilising various design basis precipitation events (or event series) may be required[9]. The inspector should ensure that the analysis is not sensitive to changes in assumptions, eg if the DBE follows a period of wet weather that has saturated the catchment area.

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[9] 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.

116. In the UK, guidance on the assessment of pluvial and fluvial flooding is provided by the Environment Agency (England) [5], Natural Resources Wales (Wales) [18] and the Scottish Environmental Protection Agency (Scotland) [19]. Additional information on hydrological estimation in England and Wales is provided by the Centre for Ecology and Hydrology (eg Refs [20], [21]) and further information on flood modelling and the impact of climate change is provided in [4] Section 6.1.

Design Basis Precipitation (Snow)

117. The design basis snow event is commonly expressed in terms of a characteristic load (or pressure) that will depend on both snow depth and packing density. However, due to the combination effects of wind and the local site geometry, blown snow can give rise to snow drifting and non-uniform snow deposits, and hence non-uniform structural loads. Design codes, [13], [14], provide simplified methods for analysing these effects developed from significant research that has gone into this field. However, if the geometry of the facility is such that the snow loads cannot be derived via design codes then bespoke analyses methods are available. Where practicable the Licensee should demonstrate that the resulting design loads are at least as onerous as those derived from the relevant design codes (using a code compatible representation of the facility). The principles ECE.14 and ECE.15, along with further information in TAG 17 [22] for assessing such analyses should be referred to. Another factor to be considered in the hazard assessment for extreme snow is the additional weight of rain on an existing snowpack; the loads from the snowpack should therefore be supplemented by a rainfall level corresponding to a low frequency of exceedance.

Design Basis Precipitation (Hail)

118. The design basis hail event should comprise the maximum likely hail size (diameter and weight) and an estimate of the concurrent terminal velocity. Hail can add to loads on structures in a similar way to snow, and the design basis should have considered this aspect. It is also possible, for fragile safety related structures and exposed SSCs, that hail is a missile hazard; such cases, if they exist, should be identified by Licensees and a proportionate safety analysis undertaken.

Design Basis Lightning

119. Historically, lightning has commonly been addressed in a deterministic manner using design codes, eg [7], sometimes without an explicit design basis definition consistent with SAP EHA.4. However RGP is changing towards using UK lightning detection networks and available data to derive probabilistically a design basis peak current for this hazard, see paragraph 152. Inspectors should seek assurance from Licensee safety cases that the protection provided by application of the design code is adequate against the derived lightning design basis definition and that the risk is As Low As Reasonably Practicable (ALARP). For more details see [4] Section 8.

Design Basis Wind

120. This hazard is typically expressed in terms of speed and direction for a uniform averaged time period (ie 1 hour for the UK, or typically 10min for Europe) for a uniform height and ground surface roughness, and incorporating adjustments to account for local topographical effects, proximity to coast etc. It is also necessary for a gust pressure or velocity, along with its duration, to be defined. The inspector should note that the design basis chosen should be associated with the time durations determined to be critical for the facility. Further information on the impact of climate change on wind, including wind storms and tornadoes is provided in [4] Section 7.

121. For many types of facility, the Licensee may consider design codes (eg Refs. 5, 6) to be appropriate for assessing local effects and for deriving the design basis wind loads from the site-specific hazard analyses. Prior to application care should be taken to note

important exclusions or limitations within the code that may require more specialist assessment. Some examples that may be relevant are lattice towers, guyed masts and guyed chimneys, torsional vibrations of buildings, modes of vibration higher than the fundamental mode, and the very local effects for congested sites with large structures placed close together.

122. In the case that a bespoke analysis of structural responses to wind effects is required it is expected that both static and, where they could be significant, dynamic effects are assessed. Site-specific effects can for example result from local amplification of wind speed due to details of site layout. Dynamic effects may result from vortex shedding from tall buildings, and from gusts or the innate time varying nature of the hazard itself. Where practicable the Licensee should demonstrate that the resulting loads are at least as onerous as those derived from the relevant design codes (using a code compatible representation of the facility). The principles of ECE.14 and ECE.15, along with further information in TAG 17 for assessing such analyses should be referred to.

Design Basis High & Low Air Temperature

123. The air temperature duration required for the design basis depends on the application. For example, for analysis of thermal loads on structures the instantaneous dry bulb extreme temperatures may be used. Whereas for the design of HVAC and dehumidification equipment, hourly ambient dry bulb and wet bulb temperatures may be more appropriate. Estimates of the duration for which the ambient dry bulb and wet bulb temperatures remains above or below given values (ie the persistence) may also be necessary for plant design purposes, particularly where there is significant thermal inertia, and this should be accounted for in the hazard analysis. For sites that utilise evaporation based designs for the ultimate heat sink (eg mechanical draught cooling towers), the analyses should identify as a minimum dry bulb and wet bulb temperature values representing (a) maximum evaporation potential and (b) minimum water cooling (eg cooling capacity of the cooling tower). The inspector should be aware that the Licensee may choose to develop a time varying design basis to define extreme high and low air temperature that aims to be more realistic. However, this is likely to be a less onerous approach than using a short-term extreme value. The inspector should consider such examples on their merits.

Design Basis High & Low Cooling Water Temperature

124. The design basis cooling water temperature is usually specified as a constant local sea temperature with no variation in duration. However, particularly for shallow estuarine locations, that there is a correlation between atmospheric temperatures and its variation and sea water temperatures. This is of particular importance for hazards that require specific conditions to arise such as frazil ice, where the duration of cold weather and associated cold sea temperature can influence whether frazil ice may form.

Design Basis Combination Events

125. As highlighted by Table 1 the occurrence of meteorological conditions such as storms involve the combination of several correlated hazards eg precipitation, wind, lightning as well as secondary hazards such as storm surge and wave, see [1] Section 5.8.1. As highlighted in TAG 13 Section 5.5.3 [1] this is an area of active research and the Licensee is expected to review the state of RGP that applies to a particular hazard combination, or take an obviously conservative approach to defining such combinations if RGP is difficult to determine. The effect of combination effects on climate predictions is outlined in [4] Section 5.7.

Design Loads

126. From assessment of the hazards above, design basis loads and scenarios will be derived. However, these should not be viewed as immediately suitable for use by the

Licensee for design purposes. Consideration should be given to the intent of ECE.6 and EHA.7 to preclude cliff edge effects, this may require inclusion of additional margin increasing the design basis scenario to ensure they are adequate for design purposes (refer to TAG 17 et al for further information on this).

3.2.2 DBA inputs from the meteorological hazard analysis

127. 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. Table 1 summarises those meteorological hazards generally accepted to be most significant to nuclear safety and provides a list of associated hazard parameters that are normally considered appropriate to defining design bases for each one.

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

128. In order for the Licensee to carry out BDBA as intended by EHA.18 and EHA.7, the hazard arising from meteorological hazards should be derived for frequencies less than 10^{-4}/yr, and the results are usually presented as a hazard curve. 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 the Head Document Section 5.5.3 [1].

129. The Licensee should demonstrate that the possibility of such faults and failures occurring at this elevated beyond design basis hazard level 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 / SSC 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 adequate and the risk arising from it has been reduced ALARP (ERL.4).

130. 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 [1] Section 5.5.3.

131. For some external hazards, normally those of less significance to nuclear safety, or those for which SSCs are very resilient, it may be possible to demonstrate resilience to a hazard level well beyond the DBE, such that an ALARP position can be justified without detailed BDBA.

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

132. Meteorological hazards are non-discrete hazards and therefore occur at a range of exceedance frequencies significant to nuclear safety. It is anticipated that meteorologically 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 meteorological hazards can be calculated as part of the site / station PSA. Where only mean or best estimate hazard information is available, inspectors should ensure that Licensees have recognised this and made a proportionate attempt to characterise the hazard uncertainty. NS-TAST-GD-030 [23] provides general guidance on PSA and the need to address external hazards, but no specific guidance is offered on meteorological hazards specifically.

133. The use of PSA for meteorological hazards is not well developed in the UK nuclear industry and it is likely that there is little fragility data to be obtained from within the UK.

Nevertheless, inspectors should ensure that such fragility data as is used by Licensees is fit-for-purpose and appropriate. Where fragility data are needed and unavailable, then Licensees would be expected to put in place a research programme to furnish it, and in the meantime to make pragmatic judgements with regard to fragility information that is available to facilitate the PSA process.

134. Given the immaturity of the PSA method in this area, inspectors should not rely on the absolute quantitative results, but use them in conjunction with other safety analyses, to form an overall judgment of adequacy of the meteorological safety case.

3.3.1 PSA inputs from the meteorological hazard analyses

135. The inspector should seek to ensure that sufficient input data is provided to facilitate the PSA process. For a major nuclear plant 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^{-6}/yr.

136. 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 uncertainty distribution associated with the site-specific hazard analysis. However, external hazards PSAs are not well developed in the UK. Such experience as there is suggests that simple risk estimates formed by combining mean hazard and fragility definitions is appropriate. The effects of uncertainty could be analysed through sensitivity studies.

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

137. 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 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 meteorological 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 SAA for the site.

138. Meteorological 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 meteorological hazard analyses

139. The inspector should seek to 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 meteorological event (eg severe tornado or storm event).

4 EMERGENCY PLANNING & ARRANGEMENTS (AM.1)

140. The potential effects of meteorological hazards should have been considered as part of the hazard identification and analysis process, as discussed in Section 3, and used to inform the site's emergency plan and arrangements under LC11. If the response to meteorological hazards is fully accounted for by the arrangements in place to cover other fault conditions, then this should be stated. If not, arrangements should be revised as appropriate to take account of additional consequences that could arise from meteorological events. Inspectors should consider the following issues:

a) Common cause effects: A consideration with meteorological 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 meteorological information: Meteorological information in the UK is provided by the UK Met Office and the available weather forecasts provide effective early warning for many meteorological hazards in the UK. A further source of advice is The Flood Forecasting Centre, a joint collaboration between the UKMO and the EA, where the advice is informed by both meteorological and hydrological expertise. On-site monitoring should also be available for these hazards, with indications (wind speed, tide height etc) provided to operators (normally in the control room) so they can assess the impact of the various hazards and determine through their LC arrangements an appropriate response.

c) Off-site infrastructure: Weather warning services can be made available (paragraph 92) and on-site monitoring can be used to assist Licensees is decision-making under their emergency arrangements (paragraph 93).

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 [24]. 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 meteorological events 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 Meteorological Hazard Analyses

141. The inspector should seek to ensure that sufficient meteorological data is made available to relevant site staff and local authorities 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 meteorological hazard levels to be assumed for emergency planning purposes.

5 RELEVANT STANDARDS AND GOOD PRACTICE

142. The scientific field of climate change and weather forecasting is complex and fast developing. The primary relevant standard for nuclear plant is International Atomic Energy Agency (IAEA) safety standard SSG-18 [9], this covers at high level the safety principles to be applied. Also relevant are the Western European Nuclear Regulators Association (WENRA) guides [25], [26]. The guidance in this annex is consistent with these principles set out in these references. The EA also publish guidance on flooding and climate change, eg [5]. More detailed published standards are available as Eurocodes, see below.

143. 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 the UKMO. These organisations can undertake a bespoke site-specific analysis, based on local data and a detailed understanding of local conditions relevant to the challenges posed by meteorological 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.

144. *Climate change*: There are two main sources for climate change projections for the UK. The first is the Coupled Model Intercomparison Project (CMIP) 5 projections developed for the IPCC Fifth Assessment Report of 2013 [27]. These replace the CMIP3 projections developed for IPCC AR4 in 2007 and will, in turn, be replaced by new CMIP6 projections in due course. Second, there are the projections developed by the UKMO and at the time of publication (2018) the UKCP09 projections are used by end-users to assess future climate change in the UK [17]. UKCP takes the IPCC projections and makes a UK interpretation.

5.1 Current Practice in the UK Expert Community

145. Current practice in extreme weather hazard analysis is not currently codified into published standards, but resides in the practice of the expert community. Inspectors should assure themselves that Licensees have engaged with the expert community as appropriate. The panel paper [4] provides a summary of the approaches used by this community. As noted therein, the subject of extreme weather analysis and climate change prediction is the subject of intense research at the present time.

146. *Uncertainty*: This practice does not at this time have in place approaches to deal explicitly with epistemic uncertainty in the derivation of design bases (as is the case with seismic hazard). So, the use of expert judgement is included implicitly, and not recognised as a specific source of uncertainty in itself.

5.2 Use of Design Codes

147. The use of design codes, for example Eurocodes [10], [11], [12], [13], [14], [15] & [16], primarily intended for conventional structures has value but inspectors should be aware of the limitations implied by their use. Eurocodes in particular specifically exclude direct application to nuclear structures. Licensees should therefore use them with caution. It is unlikely that ONR would view the use of Eurocodes alone to define design basis values as adequate for major hazards plant.

148. A feature of Eurocodes is that the extrapolation methods used to generate low frequency hazard estimates only allow the mean hazard value to be derived; they do not provide any measure of the associated uncertainty. Therefore, an appropriate approach to defining the hazard at a level equivalent to a conservative 10^{-4}/yr level may be to use the mean hazard at a lower frequency, say 10^{-5}/yr. Inspectors should refer to [1] Section 5.5.1 for further guidance.

149. Other relevant codes exist such as for lightning hazard [7], see paragraph 119.

150. Other design codes for conventional structures will likely have limitations when compared against the expectations of the SAPs, especially since the design hazard values for conventional structures tend to be less onerous than those needed for nuclear structures. The Licensee would need to provide evidence that design bases developed from such codes meet the intent of EH.4, or provide a hazard value by an alternative means that does, see also paragraph 75. It may be proportionate, based on the hazard's contribution to nuclear risk (for low consequence facilities for example), for the Licensee to use such codes, but as highlighted in Section 2.3 above, the inspector should be aware of the limitations of the source data used to provide hazard definitions with such design codes.

151. The 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 [28], but a number of other USNRC documents are also relevant:

- USNRC, Regulatory Guide 1.76, "Design-Basis Tornado and Tornado Missiles for Nuclear Power Plants", March 2007, https://www.nrc.gov/docs/ML0703/ML070360253.pdf
- USNRC Regulatory Guide 1.221, "Design-Basis Hurricane and Hurricane Missiles for Nuclear Power Plants", October 2011, https://www.nrc.gov/docs/ML1109/ML110940300.pdf
- USNRC Interim Staff Guidance DC/COL-ISG-7, "Assessment of Normal and Extreme Winter Precipitation Loads on the Roofs of Seismic Category I Structures", https://www.nrc.gov/docs/ML0914/ML091490565.pdf
- USNRC Interim Staff Guidance DC/COL-ISG-024, "Implementation of Regulatory Guide 1.221 on Design-Basis Hurricane and Hurricane Missiles", https://www.nrc.gov/docs/ML1213/ML12132A512.pdf

5.3 Near-term Development of Relevant Good Practice

152. Weather prediction and forecasting, its simulation by numerical models and the understanding of the physical and chemical processes that make up UK weather is the subject of active research at this time. Over the next decade there will likely be developments in computer codes and statistical data analysis techniques. Some research areas relevant to the analysis of low frequency extreme weather events relevant to nuclear safety are highlighted:

- Better understanding of what constitutes a severe storm. Is this just an extrapolation of weather parameters expected in more moderate storms or are other factors significant, such as unusual combinations of weather hazards and the relationship to wider climate features such as jet streams.
- The ability to simulate weather systems at small scale consistent with the size of a nuclear site. At present the granularity of computer models is too course generally to accurately model weather hazards at a site. This may be important because very severe storm events are often small-scale and current computer models effectively smooth out or average such hazard parameters (say rainfall intensity) over relatively large topographic areas, although improved high resolution modelling is expected with the publication of UKCP18, see paragraph 153.
- Work is currently underway by the Royal Meteorological Society and others to collate the latest approaches to hydrometeorology, see [29] for more details.

- Lightning: Work is under way by the UKMO and by others to gain a better understanding of the frequency and severity of lightning hazard, see [4] Section 8 for more details. In due course this may enable more confident predictions of peak currents for use as design bases at specific UK locations.

- A Hi-impact weather group under the auspices of the World Meteorological Organization (WMO) [30] with the idea of promoting best practice. Another group, the Engineering for Climate Extremes partnership [31] is currently collating tools (initially in the US) with a view to providing guidance in extreme weather prediction in the future.

153. *Climate change*: The UKMO UKCP09 projections are being developed in several ways 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 assessments 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 less than 5km to better simulate convection storms for adaptation planning. Some regional climate data at resolutions of 3km is already available for future decades for the UK (see [4] Section. 5.8), and these datasets are rapidly expanding.

6 REFERENCES

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[4] ONR Expert Panel on Natural Hazards, “Analysis of Meteorological Hazards for Nuclear Sites,” Expert Panel Paper No: GEN-MCFH-EP-2017-1, 2018.

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TABLE 1 – EXAMPLE PRIMARY METEOROLOGICAL HAZARDS, AND ASSOCIATED CORRELATED, SECONDARY AND CONSEQUENTIAL HAZARDS

Primary Hazard – (Design Basis Hazard Descriptor)	Example correlated hazards that may occur in combination	Secondary Hazards	Consequential Hazards/Effects
Precipitation (Rain, Snow, Hail): - Rainfall depths for various durations - Rainfall event intensity – (Hyetographs) - Extreme snow loading - Hail size, weight, & terminal velocity	- Wind - Lightning - Low / High Temperature	Pluvial Flooding	Overload of ground level drainage systems – (Increased debris or snow ice movement leading to drain blockage / ponding / inundation of site / loss of containment / restrictions to access and site operations / lightning conductor system bypassed)
		Fluvial Flooding	Overload of ground level drainage systems – (Ponding / inundation of site / loss of containment / increased debris movement leading to overloaded drains or blockage of system / restrictions to access and site operations)
		High Groundwater Level	– Ponding / inundation of site / reduction in foundation bearing capacity / slope instability)
		Drought - Low groundwater level - Low reservoir level	Loss of foundation support to buildings / Loss of off-site towns water
		Thaw flooding	Overload of ground level drainage systems – (Ponding / inundation of site / loss of containment / increased debris movement leading to overloaded drains or blockage of system / restrictions to access and site operations)
			Overload of above ground drainage systems – (Water ingress / containment breaches / restriction of operations / above ground drainage blockage roof overloads / lightning conductor system bypassed)
			Blown snow giving rise to snow drifts – (Altering site access routes / altering site drainage routes / increasing structural loadings / blocking HVAC vents and heat exchangers)
			Icing of exposed surfaces and cables – (Conventional H&S hazards / loss of power / freezing of supply lines)
			Impact damage from hail – (Containment and SSC damage / loss of off-site power)
			Extreme precipitation can impact on slope stability – (Mudslides, embankment failures, restrictions to access and

Primary Hazard – (Design Basis Hazard Descriptor)	Example correlated hazards that may occur in combination	Secondary Hazards	Consequential Hazards/Effects
			site operations, loss of life)
			Accelerated corrosion rates on exposed materials, especially metalwork, due to electro-chemical reaction with atmosphere.
Lightning: - Stroke Amperage, rate of rise, amount of charge transferred - Local ground flash density - Site or SSC lightning attractive area	- Precipitation - Wind	Electrical fires	Loss of SSC function, conventional health & safety risks to personnel on-site – (Loss of life)
			Breaches of building containment and structural damage - (Loss of SSC function), and potential for missiles, eg from spalling of concrete
			Damaging electrical surges, and electromagnetic pulses generated from close strikes – (Damage to telephones, computers and other electronic devices leading to loss of safety function)
			Conventional health & safety risks to personnel on-site – (restrictions to access and site operations, loss of life)
Wind: - Max. speed and azimuth direction for various durations - Vertical speed profiles - Gust speed and duration - Max. and rate of pressure drop (tornado)	- Precipitation - Lightning	Waves on open water & wind driven storm surges: See TAG 13 Annex 3	Contribution to coastal flooding risk – (Overtopping of site flood defences / inundation of site / loss of containment / biological hazards / restrictions to access and site operations)
		Wind driven sea water spray	Accelerated corrosion rates on exposed materials, especially metalwork, due to enhanced electro-chemical reaction.
			Aerodynamic forces on SSCs including static pressure differences from tornados – (Breaches of containment, damage to structures, restrictions to access and site operations, operation and effectiveness of HVAC and filtration systems)
			Wind driven missiles – (Impacts on SSCs leading to breaches of containment and loss of SSC function, restrictions to access and site operations)
Low Air Temperature: Minimum dry bulb temperature and coincident wet bulb or humidity for various durations Hazard may need to be considered in conjunction with duration of the causative weather system.	- Precipitation - Wind	Low cooling water temperatures Frazil ice	Blockage due to frazil ice or pack ice – (Intake structures restrictions, cooling water induced faults)
			Frost, radiation cooling and icing of exposed surfaces leading to loss of function and / or structural damage (higher brittle fracture risk), frozen liquid systems, frozen drainage systems
			Some SSCs may be susceptible to the amount of heat transfer to the atmosphere. This would involve combining temperature and duration – (Radiation heat loss under clear skies, increased

Primary Hazard – (Design Basis Hazard Descriptor)	Example correlated hazards that may occur in combination	Secondary Hazards	Consequential Hazards/Effects
			loads on HVAC equipment)
			Salt based de-icers leading to enhanced corrosion levels to metalwork.
			Conventional health & safety risks to personnel on-site, Human Factors effects – (Restrictions to access and site operations)
High Air Temperature: Maximum dry bulb temperature and coincident wet bulb or humidity for various durations. Hazard may need to be considered in conjunction with duration of the causative weather system (eg heat waves).		High cooling water temperatures	Reduction in ultimate heat sink capability – (Cooling water induced faults)
		Thunderstorms causing high rainfall, high windspeed and lightning	Refer to other parts of this table.
			Some SSCs may be susceptible to the amount of heat transfer from the atmosphere. This would involve combining temperature and duration – (Radiation heating of SSCs (solar gain), thermally induced loads, UV damage of components, loss of HVAC systems)
			Conventional health & safety risks to personnel on-site, Human Factors effects – (Restrictions to access and site operations)
Low Air Pressure	- Precipitation - Wind	Surge	Overtopping of sea defences
High Air Pressure	- High / Low Temperature - Drought	Low sea level	Loss of ultimate heat sink
			Refer to other parts of this table.
Volcanic hazards – Dust			Blockage of air intake systems and reduced efficiency of SSCs that they supply.
Low Humidity and Moisture Content	- High / Low Temperature	Low river / reservoir levels	Loss of access to off-site water supplies
		Low groundwater levels	Loss of foundation support to structures
			Reduced conductivity to earth for lightning protection systems
			Refer to other parts of this table.
High Humidity and Moisture Content	- High / Low Temperatures	Reduced visibility	Restrictions on-site access and movements around site.
		Condensation Salinity of condensation	Enhanced corrosion rates on exposed surfaces.
			Refer to other parts of this table.
Marine Environment (high salt content humidity)	- High humidity		Enhanced corrosion levels to exposed materials, especially metalwork potentially increasing the vulnerability of affected SSCs.

FIGURE 1 – FLOW CHART ILLUSTRATING A GENERIC FRAMEWORK FOR ASSESSING METEOROLOGICAL HAZARDS