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CRITICALITY SAFETY			
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TABLE OF CONTENTS

1. INTRODUCTION 2

2. PURPOSE AND SCOPE 2

3. RELATIONSHIP TO LICENCE AND OTHER RELEVANT LEGISLATION 2

4. RELATIONSHIP TO SAPS, WENRA REFERENCE LEVELS AND IAEA SAFETY STANDARDS ADDRESSED 4

5. ADVICE TO INSPECTORS 10

6. REFERENCES 18

7. GLOSSARY AND ABBREVIATIONS 20

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NOT PROTECTIVELY MARKED**1. INTRODUCTION**

- 1.1 ONR has Safety Assessment Principles (SAPs) which apply to the assessment, by ONR specialist inspectors, of safety cases for nuclear facilities that may be operated by potential licensees, existing licensees, or other duty-holders. The principles presented in the SAPs are supported by a suite of guides to further assist ONR's inspectors in their technical assessment work in support of making regulatory judgements and decisions. This technical assessment guide is one of these guides.

2. PURPOSE AND SCOPE

- 2.1 This TAG contains guidance to advise and inform ONR staff in the exercise of their regulatory judgement, in respect of the assessment of criticality safety, as described in outline in ONR Safety Assessment Principles [1]. As with all guidance, inspectors should use their judgement and discretion in the depth and scope to which they employ this guidance.
- 2.2 This guidance is aimed at all applications, i.e. new and existing facilities, including modifications and decommissioning activities. For facilities that were designed and constructed to standards that are different from current standards, the issue of whether sufficient measures are available to satisfy the ALARP¹ principle should be judged on a case-by-case basis. Further generic guidance on assessment of ALARP is given in Ref. [2]. The related principle of As Low As Reasonably Achievable (ALARA) is discussed in Ref. [3].
- 2.3 Note that a separate TAG exists covering guidance to ONR inspectors assessing the criticality safety of transport package designs [4].
- 2.4 This guidance applies to all forms of surface facility that deal with fissile materials, including the operational phase of a future Geological Disposal Facility (GDF). The issue of post-closure criticality in a future GDF is covered in joint 'Guidance on Requirements for Authorisation' provided by the Environment Agency (EA) and other agencies [5].

3. RELATIONSHIP TO LICENCE AND OTHER RELEVANT LEGISLATION

- 3.1 **Licence conditions:** There are no nuclear site licence conditions (LCs) which directly refer to criticality safety, but a number are of relevance. The following licence conditions are highlighted here as particularly relevant to this guide, but the list is not exhaustive. Licence conditions are listed in full in Ref. [6].
- 3.2 **LC 4: Restrictions on Nuclear Matter on the Site:** This licence condition ensures that the licensee implements arrangements to control the introduction and storage of nuclear matter, including fissile material.
- 3.3 **LC14: Safety Documentation:** The licensee shall make and implement adequate arrangements for the production and assessment of safety cases to justify safety through the lifecycle of the facility. The licensee's arrangements should set out the methodology for criticality safety analysis, including the identification and categorisation of SSCs and controls underpinning the assessment in the safety case.
- 3.4 **LC 15: Periodic Review:** The adequacy of the safety case, including criticality aspects and the control of nuclear matter, should be reviewed at regular intervals against the current operating conditions, emergent operational experience, current good practice

¹ ALARP – As Low As Reasonably Practicable.

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and statutory requirements to ensure that adequate safety provisions are in place for current and future operations.

- 3.5 **LC 19: Construction or Installation of New Plant:** The design of new facilities should be considered at an early stage in order to minimise the likelihood of criticality and installation must be carefully controlled, e.g., to ensure that materials and construction meet the design specification.
- 3.6 **LC 20: Modification to Design of Plant Under Construction:** Modifications should be assessed to ensure that the impact of the change is considered in respect of the control of nuclear matter and criticality safety of the facility (e.g., by changing the size or shape of vessels or specification of materials, introduction of new faults or initiators).
- 3.7 **LC 21: Commissioning:** Inactive and, where appropriate, active commissioning tests should be carried out to ensure, for example, that design criteria have been met and that engineered protection is in place and operating effectively.
- 3.8 **LC 22: Modification or Experiment on Existing Plant:** Modifications should be assessed to ensure that the impact of the change is considered in respect of the control of nuclear matter and criticality safety of the facility (e.g., by changing the size or shape of vessels or specification of materials, introduction of new faults or initiators).
- 3.9 **LC 23: Operating Rules:** The limits and conditions necessary in the interests of criticality safety should be clearly specified in the safety case. Control within and compliance with these limits and conditions, which are known as operating rules, should be demonstrable at all times. Further guidance on limits and conditions can be found in Refs. [7, 8].
- 3.10 **LC 24: Operating Instructions:** Operations with fissile material which may affect safety must be carried out in accordance with written operating instructions. These operating instructions also ensure that operating rules are implemented.
- 3.11 **LC 25: Operational Records:** These may include, for example, records of fissile inventories and moderators in specific locations in the facility, sampling and analysis results, and dimensional checks.
- 3.12 **LC 27: Safety Mechanisms, Devices and Circuits:** The licensee should identify safety mechanisms, devices and circuits that are important to criticality safety and ensure that they are adequately maintained in accordance with LC 28.
- 3.13 **LC 28: Examination, Inspection, Maintenance and Testing:** It is expected that any structure, system or component associated with ensuring criticality safety, such as neutron counters, enrichment monitors and weighing scales, would form part of the licensee's site-wide arrangements under this licence condition. Note that Ionising Radiations Regulations 2017 (IRR17) [9] regulation 11 on 'maintenance and examination of engineering controls etc. and personal protective equipment' also defines similar expectations to LC 28.
- 3.14 **IRR17 Regulation 8: Radiation Risk Assessments:** The licensee should carry out a risk assessment in order to identify the measures required to restrict the exposures of workers and the public to ionising radiation. In cases where fissile material will be present, such measures should include the provision of safety systems, in order to take all reasonably practicable steps to prevent criticality accidents and, if they occur, to limit their consequences.

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NOT PROTECTIVELY MARKED**4. RELATIONSHIP TO SAPS, WENRA REFERENCE LEVELS AND IAEA SAFETY STANDARDS ADDRESSED****SAPs Addressed**

- 4.1 This section reproduces the SAPs, and the associated supporting text, that refer explicitly to criticality safety. The SAPs form a complete document and should be taken as a whole. This is particularly true for matters relating to the assessment of criticality safety. It is not appropriate to base an assessment on a few selected principles, possibly taken out of context, without considering all other relevant principles. Indeed, many of the principles are relevant to criticality safety and the ONR assessor should constantly bear this in mind. Hence, in order to carry out a comprehensive assessment, it will generally be necessary to refer to several other Technical Assessment Guides (TAGs) in addition to this one.
- 4.2 It should be noted that the SAPs call for fault studies to use a Design Basis Analysis (DBA) approach in the identification of all safety measures. This is a potential source of confusion alongside the application of the principle ECR.2 "Double Contingency Approach (DCA)", which is widely used both internationally and nationally in criticality safety assessment. Advice to inspectors on this issue is given below. The paragraph numbers in the extract below relate to numbering in the 2014 SAPs [1].

570 Criticality safety principles apply to the processing, handling or storage of fissile materials in significant quantities with respect to the minimum critical mass, and in locations where criticality is not intended. The principles in this sub-section, which should be read in conjunction with the Fault Analysis section, are specific to criticality safety.

ECR.1 Wherever a significant amount of fissile material may be present, there should be safety measures to protect against unplanned criticality.

571 The hierarchy of controls set out in the Key engineering principles sub-section (paragraph 145ff.) is appropriate for criticality safety, and gives preference to minimising the amount of fissile material present, consistent with the process requirements. The principal means of passive engineering control of criticality should be geometrical constraint. Where sub-criticality cannot be maintained through geometrical constraint alone, additional engineered safety measures should be provided, such as fixed neutron absorbers. Reliance on neutron absorbers requires assurance of their continued presence and effectiveness.

572 Further safety measures may need to be provided, for example to:

- a) control the mass and isotopic composition of the fissile material present;*
- b) control the concentration of fissile material in solutions; and*
- c) control the amount of neutron moderating and reflecting material associated with the fissile material.*

573 The design and operation of facilities and equipment dealing with fissile material should facilitate the termination of a criticality incident.

ECR.2 A criticality safety case should employ the double contingency approach.

574 The double contingency approach requires a demonstration that unintended criticality cannot occur unless at least two unlikely, independent, concurrent changes in the conditions originally specified as essential to criticality safety have occurred.

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575 For long-term storage of radioactive waste containing fissile materials, traditional deterministic criticality assessments can lead to very conservative limits on fissile materials. Consideration should be given to a risk-informed approach that balances the risks from an unplanned criticality against other factors, such as the dose accrued as a result of the preparation of waste packages.

Discussion of SAPs**Paragraph 570**

- 4.3 This paragraph points out that the scope of criticality safety is limited to processes intended to be sub-critical. This covers essentially all facilities apart from reactors, which constitute a special case in that they are designed to achieve criticality in a controlled manner. Here, protection of the workforce is achieved by the provision of massive bulk shielding and multiple high-integrity containment systems. In general, in all other situations, including reactor fuel handling (e.g., on-site transport, storage, loading and unloading of fuel from reactors) the possibility of criticality requires consideration.
- 4.4 Formal criticality safety analysis may not be required for processes containing only a small fraction of the minimum critical mass of the relevant fissile isotope, where there is no reasonably foreseeable mechanism of significantly increasing the mass of fissile material present. An explicit demonstration of the lack of need for criticality safety measures should be provided.
- 4.5 It should be pointed out that the Fault Analysis principles in the SAPs apply to all types of fault, including criticality, and hence the ONR assessor should also refer to these principles when carrying out an assessment.

Principle ECR.1

- 4.6 ONR would expect the licensee's safety case to identify a system of criticality safety measures, which should follow the accepted hierarchy of protection:
- i) Passive engineered safety measures, i.e. measures that are continuously available and require no action by a safety system or an operator to achieve and maintain a safe state;
 - ii) Active engineered safety measures, i.e. measures requiring action by a safety system to achieve and maintain a safe state; and
 - iii) Administrative safety measures, i.e. measures requiring action by an operator to achieve and maintain a safe state.

ONR would expect to see a robust justification where criticality safety is maintained by administrative safety measures alone.

Paragraph 571

- 4.7 The preferred means of ensuring criticality safety is the introduction of geometrical constraints, e.g., limited volume vessels and limited diameter pipes. The geometrical constraints mean that the neutron leakage is sufficiently great to prevent a critical chain reaction. The safety case should show that the dimensions of components are such that criticality safety will be maintained for any reasonably foreseeable mass and concentration of fissile material, and any reasonably foreseeable change in geometry.
- 4.8 Generally, in order to be effective, neutron absorbers rely on moderating materials to reduce the energy of the neutron spectrum. Hence, in cases where reliance is placed on neutron absorbers to maintain criticality safety, the licensee must provide assurance

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that sufficient neutron absorber and sufficient neutron moderating material will be present, and that their distribution within the system will ensure the effectiveness of the absorber under all reasonably foreseeable conditions. Strong preference should be given to the use of fixed absorbers rather than soluble absorbers, since the latter require continuous demonstration of their presence and appropriate concentration during operations. The continuing presence and effectiveness of fixed neutron absorbers also requires demonstration; however, such requirements are normally much less onerous than for soluble absorbers (e.g., through periodic testing or sampling). Reassurance of the effectiveness of neutron absorbers (and any associated moderator, where appropriate) is important both during operations, and also during and following any related maintenance operations.

Paragraph 572

4.9 In addition to the use of geometrical constraints and neutron absorbers, there are several other parameters, control of which can be used to achieve criticality safety:

i) Fissile mass: Criticality safety can be achieved by restricting the mass of fissile material to below the minimum critical mass appropriate to the process conditions. If this approach is adopted, consideration must be given to fault sequences which could increase the neutron multiplication of a system, e.g., the introduction of excess fissile material. Robust safety measures must be put in place to prevent the accumulation of an unsafe mass. Inspectors should note that the accurate measurement of fissile mass can be difficult and it should be demonstrated that appropriately conservative methods have been used (further guidance is given in Paragraphs 5.41 to 5.45 below);

ii) Isotopic composition: The most common fissile isotopes in current nuclear industry applications are U-235 and Pu-239. Uranium normally comprises mostly U-235 and U-238, and sometimes U-233. Plutonium normally comprises mostly Pu-239 and Pu-240 (with increasing proportions of other Pu isotopes for material produced at higher fuel burn-up, e.g., Pu-241). These isotopes have varying relative importance to criticality safety (e.g., Pu-240 is a neutron poison, and U-233/Pu-241 are usually more reactive than their respective other fissile counterparts U-235/Pu-239). ONR would expect the licensee's safety case to identify safe limits and conditions with regard to isotopic composition, with any isotopic assumptions made demonstrated to be valid across the expected moderation range. The safety case should identify appropriate measures to ensure that these limits and conditions are satisfied;

iii) Moderation: The critical mass of fissile material can be significantly reduced by the presence of moderating material. Ideally, the safety case should demonstrate that criticality safety would be maintained even with optimum moderation for the system type being considered. In choosing the moderating material in the safety assessment, all materials that may reasonably be present should be considered (including materials used in fire-fighting operations) and the most reactive configuration should be identified. This will often be optimum moderation by a hydrogenous material such as water, oil or plastics (including PVC, which may contain polythene as a plasticizer). It should be noted that licensees sometimes attempt to make criticality safety cases based on limited or zero moderation arguments. Here, it is argued that while some moderator may be present, there will be an insufficient quantity to form a critical system. Such arguments may be acceptable if adequately substantiated (e.g., by demonstration of adequate control of moderating materials in combination with adequate margin to safety for excess moderator);

iv) Reflection: Similarly, the critical mass of fissile material can be significantly reduced by the presence of reflecting material. In general, a close-fitting thick reflector should be assumed. In choosing the reflecting material to consider in the safety assessment, all

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materials that may reasonably be present should be considered. In addition to materials within the process, the reflecting effects of other nearby materials and structures, including personnel, should also be addressed. It should be noted that licensees sometimes attempt to make criticality safety cases based on limited reflection arguments; licensees may justify that limited reflection conditions are bounding on conditions which could arise taking into account the potential form, quantity and location of reflecting materials. Such arguments based on limited reflection should be adequately substantiated for all foreseeable conditions;

v) Density: For fissile material in solid form, there will generally be a range of possible densities up to the maximum theoretical density. It is well established that, for fissile material in solid form, the critical mass decreases with increasing density [10]. Hence, safety cases should generally consider the maximum theoretical density unless it can be demonstrated deterministically that the process cannot give rise to this density, or should provide assurance that this density cannot be achieved. Despite this, inspectors should be aware that in some systems a lower density may present the bounding case. For example, where multiple units are present (arrays), assuming a lower density for fixed masses of material may lead to increased interaction between units by virtue of an increased solid angle of interaction. For fissile powders, a lower density fissile material may present a bigger hazard because a greater moderator-to-fissile ratio can be obtained if moderators mingle with the fissile material. The neutron multiplication factor of low density powders can be very sensitive to the addition of moderator;

vi) Concentration: The neutron multiplication of fissile material in solution or suspension will vary as a function of the concentration of the fissile material. This is largely due to the competing effects of dilution of the fissile material, i.e. reducing the density, and neutron moderation and absorption by the liquid. There will be a concentration at which the neutron multiplication is highest. This is known as the optimum concentration. The optimum concentration of a particular system can vary according to the geometry of a system, and so care should be used when applying an optimum concentration from one system to another of different geometry, even if the solution/suspension parameters are identical. Ideally, the safety case should demonstrate that criticality safety would be maintained even at optimum concentration. If this is not possible then assurance should be provided that the concentration can never achieve an unsafe value;

vii) Interaction: This concerns multiple fissile units, each of which is sub-critical in isolation. The combined system may be critical due to the interaction between the units, i.e. the transfer of neutrons between the units. In cases where interaction effects may be important, safety measures should be put in place to ensure criticality safety. Such measures may take the form of spacers to constrain the separation of the units, or absorbing material placed between the units;

viii) Homogeneity/heterogeneity: Care must be taken when making assumptions regarding homogeneity or heterogeneity of systems. Factors such as isotopic composition, concentration, particle size and geometry will affect whether critical parameters are greater for homogeneous or heterogeneous systems. For example, the dominance of heterogeneity effects are commonly pronounced when considering minimum critical masses for moderated systems containing a small proportion of fissile material (e.g., U-235 or Pu-239) embedded in fissionable material (e.g., U-238), such as low enriched uranium and MOX fuel rods, pellets and powders. However, the dominance of heterogeneity effects is also observed in minimum critical dimensions of systems with a higher fissile content [11, 12]. Heterogeneity effects may also be a concern for neutron absorbers because neutron self-shielding in lumps of absorber can reduce the overall effectiveness. The size of the effect may not be immediately obvious, even to

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experienced specialists. Careful consideration must be given to ensure that heterogeneity has been properly considered;

ix) Volume: Criticality safety can be achieved by restricting the volume of fissile material to below the minimum critical volume appropriate to the process conditions. Volume of moderator within a process may also be controlled, commonly in conjunction with restrictions on fissile mass. For a fixed volume, the most reactive state may at a different concentration from the optimum used to derive the unconstrained minimum safe mass. Consideration must be given to fault sequences which could increase the neutron multiplication of a system, e.g., the introduction of additional liquid (fissile or non-fissile), dilution, concentration (through evaporation or precipitation and colloid formation). In some cases volume may be restricted by geometry and accountancy for number of containers. Robust safety measures must be put in place to prevent the accumulation of an unsafe volume; and

x) Temperature: Standard reactor physics theory shows that temperature variations could affect criticality safety margins. The neutron multiplication factor of a system may increase or decrease significantly with temperature depending on competing parameters [13]; therefore, inferences drawn from one fissile system may not apply to another. Consideration must be given to the effect of temperature changes on the reactivity of the particular system in question.

The interaction between these different factors can be complex in some systems. Inspectors should also have an awareness of the common ‘anomalies’ of criticality which can affect the parameters above [14].

Paragraph 573

- 4.10 The consequences of some criticality incidents, e.g., Tokai Mura in Japan in 1999, could have been reduced if there had been an effective means of terminating the incident rapidly. Hence, the licensee should give prior consideration to the provision of systems that can reduce the neutron multiplication of a critical system to a sub-critical level whilst ensuring dose to workers is ALARP. An example of this might be a system that injects a neutron absorber such as boron into a critical solution, or can safely modify conditions in the facility from a safe location such as a shielded control room. Where a criticality accident cannot be fully engineered out, it may be appropriate to consider the provision of additional engineered hardware to facilitate termination at the design stage. Such equipment might be linked to the criticality warning system. Further guidance on Criticality Warning Systems is given in Ref. [15].

Principle ECR.2

- 4.11 The Double Contingency Approach (DCA) is well established in both UK and international standards [1, 16] (where the approach is also referred to as the Double Contingency Principle (DCP)). It represents a very important element in the demonstration of defence in depth and reinforces Key Engineering Principles EKP.1 to EKP.5 [1]. ONR expects licensees to provide a clear demonstration of compliance where practicable. See Paragraph 4.15 for further explanation.

Paragraph 574

- 4.12 As mentioned above, DCA is well established in both UK and international standards and has been used successfully for many years. The Fault Analysis SAPs call for Design Basis Analysis (DBA), and suitable and sufficient Probabilistic Safety Analysis (PSA), to be carried out for all credible initiating events, which includes those faults which could

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potentially result in a criticality accident. The purpose of this section is to explain how the DCA and DBA should be applied for criticality faults where reasonably practicable.

- 4.13 In general, there may be several initiating events that can lead to each contingency. For example, flooding may result from several initiators, e.g. operator error, pipe or vessel failure, firefighting, or extreme weather.
- 4.14 Based on the initiating event frequency and unmitigated consequences, DBA should be used to ensure suitable and sufficient safety measures are in place to provide robust protection against the contingency.
- 4.15 In addition, there may be several contingencies that could result in a criticality incident, e.g., flooding, over batching, increased reflection, or loss of absorber. It should be shown that for a criticality to occur at least two contingencies must occur concurrently where each contingency is unlikely and independent, i.e., is such that one contingency cannot cause another or both initiate from a common event. This does not necessarily imply that the changes are simultaneous; the first condition change may need to persist until the second change occurs, e.g., flooding following an unrevealed over batching, in order to present a criticality hazard. Care is required when defining contingencies that could be unrevealed for a long time period (e.g., double batching a container within a long-term store). It should then be shown that at least two unlikely, independent and concurrent contingencies are required to result in a criticality incident. Additionally, frequent operations (e.g., fissile material movement) may require several safety measures to ensure that a contingency limit is regarded as unlikely. Though risk targets may be considered separately from the double contingency approach, it is generally considered that contingencies are not unlikely if they could be foreseen to occur more than once in a plant lifetime (50 years [17]).
- 4.16 In assessing a licensee's arrangements, ONR inspectors should look for DCA, DBA and PSA to be used in a complementary manner in order to demonstrate robust defence in depth in the protective measures identified, that the relevant risk targets have been met, and to support a justification that overall health and safety risks are being managed to ALARP.
- 4.17 It is recognised that it may not be reasonably practicable to apply a particular approach in all situations. Such situations will be considered on a case-by-case basis by ONR inspectors, without prejudice for a particular approach, in order to come to a judgement on whether the licensee has included all safety measures that are reasonably practicable, and that overall health and safety risks have been demonstrated to be reduced to ALARP [18, 19].

Paragraph 575

- 4.18 The balancing of risks is appropriate to all assessments. For example, traditional deterministic criticality assessments can lead to very conservative limits for fissile materials in waste packages, which may in turn lead to generation of a larger number of packages for onward storage/disposal, and/or operational dose uptake associated with handling. In these cases, a risk-based approach should be considered. This should balance the risks from unplanned criticality against other factors.

WENRA Reference Levels and IAEA Standards**NOT PROTECTIVELY MARKED**

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- 4.19 Part of the specification for the update of the Safety Assessment Principles was to consider the Reactor, Decommissioning and Storage Safety Reference Levels published by the Western European Nuclear Regulators' Association (WENRA); and IAEA Standards, Guidance and Documents. The update of this Technical Assessment Guide also considers the WENRA and IAEA publications for specific applicability.
- 4.20 There are no WENRA reference levels referring explicitly to criticality safety [3].
- 4.21 The need for safety measures to minimise the probability of unintended criticality is mentioned in many IAEA publications. Ref. [20] deals specifically with criticality safety in handling of fissile material, but other IAEA publications contain further application-specific guidance which includes criticality safety guidance (e.g., Ref. [21]).

5. ADVICE TO INSPECTORS**Introduction**

- 5.1 The purpose of this guidance is to ensure that those in ONR who are assessing criticality safety cases, and who have a good working knowledge of the subject, are better placed to examine safety cases and to identify, in the context of our regulatory function, any possible weaknesses or safety issues of concern.
- 5.2 In carrying out a criticality assessment, ONR inspectors may wish to consult industry standard handbook data, such as Refs. [11, 22, 23, 24, 25, 26] and current national and international standards, such as Refs [16, 27] and [28, 29, 30, 31, 32, 33, 34, 35, 36]. A further useful source of guidance for ONR inspectors is in published papers presented at international conferences and practitioner meetings; see Refs. [8, 18, 37, 38, 39]. For complicated systems, ONR inspectors may wish to commission a suitably qualified and experienced consultant to carry out independent and confirmatory criticality calculations or a complete review of the criticality safety case.
- 5.3 ONR assessors should also take into consideration the lessons that can be learned from past criticality incidents and near misses (e.g., Ref. [40]).
- 5.4 Criticality safety is of particular importance on account of the very high levels of neutron and gamma radiation associated with criticality accidents. Individuals in the immediate vicinity of such an event may receive radiation doses that could result in severe deterministic effects, which will often be fatal. For this reason, an unplanned criticality can be a major hazard to the operator, particularly in nuclear chemical facilities where work on fissile material is often carried out in lightly shielded areas. Nuclear facilities that contain significant quantities of fissile material with respect to the minimum critical values should thus be designed and operated to provide adequate protection against the hazard from an unplanned criticality.
- 5.5 For processes entirely contained within suitably shielded cells or cooling ponds, the risk of an unplanned criticality event occurring should be reduced such that it is as low as reasonably practicable. The immediate consequences of such an event may be small in radiological terms, but would indicate a significant loss of process or management control, would be contrary to the objective of minimising the generation of radioactive waste, and have significant consequential impact on the nuclear industry worldwide as has been seen from previous criticality accidents.
- 5.6 The primary means of reducing risk should be reducing the frequency of criticality and the inspector should seek demonstration that all reasonably practicable measures have been considered.

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- 5.7 If additional dose reduction factors have been claimed in the risk analysis (e.g., presence of shielding), their safety function should be recognised in line with defence-in-depth principles. It should be demonstrated that claimed shielding remains effective under the relevant fault conditions, i.e., the shielding safety function is substantiated against the initiating event, fault sequence or the criticality excursion itself if this is sufficiently energetic. Consideration should also be given to weaknesses in shielding (e.g., instrument penetrations) or arrangements for temporary access to the area. Shielding considerations should account for neutron and gamma dose components in areas where gamma dose may normally dominate. Secondary effects of an uncontrolled criticality event should also be considered (e.g., fuel clad failure, containment breach, steam generation) and the associated radiological impact adequately considered in evaluating the overall risk. Appropriate emergency arrangements should be in place to ensure that such an event can be adequately managed, including any required provision for termination.

Operating Rules

- 5.8 Under the requirements of LC 23, the licensee shall produce an adequate safety case to demonstrate safety and to identify the limits and conditions necessary in the interests of safety. Such limits and conditions are referred to as operating rules. For a criticality safety case, these should be limits and conditions defined in terms meaningful to the facility with straightforward demonstration of compliance. ORs should avoid requiring the operators to undertake involved calculations to determine compliance. Instead, methods such as pre-calculated compliance tables, diagrams, or on-line monitors programmed to perform the necessary calculations should be provided to assist the operators. ONR considers that masses or volumes of fissile material or moderators are appropriate parameters to define operating rule limits. Where appropriate, criticality safety specialists should consider liaising with operators in their working environment (e.g., through facility walk-downs) to gain assurance that ORs are straightforward and practical to implement.
- 5.9 Detailed guidance on operating rules is given in Ref. [7]. It is ONR's general expectation that several sets of ORs will be defined. The first are to describe the upper limits of normal operation. The dutyholder should also make clear in the safety documentation safety limits and any actions needed to restore the plant/operations to a safe state. A set of ORs should define the boundaries of safe operation for a plant or operation.

ALARP

- 5.10 The ALARP principle applies to criticality, as it does to all risks. In general, we would expect the licensee to implement all criticality safety measures that are reasonably practicable and to follow relevant good practice. We would also expect the licensee to demonstrate that the minimum quantity of fissile material will be used consistent with the process requirements, and that the minimum number of fissile material movements will be carried out consistent with the process requirements. ONR has similar expectations with regard to any other materials (e.g., moderators) which can affect criticality safety.
- 5.11 Optioneering is a very important part of an ALARP justification. Licensees should demonstrate that an appropriate optioneering study has been undertaken to identify all the options available for carrying out a particular process and that the safest reasonably practicable option has been implemented, in accordance with ONR guidance [2].
- 5.12 We would expect that the accepted hierarchy of protection has been applied. The hierarchy of protection states that the preferred order of protective measures is as follows:
- i) Passive engineered safety measures;

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- ii) Active engineered safety measures; and
 - iii) Administrative safety measures.
- 5.13 Further guidance on the hierarchy of protection is given in Ref. [1].
- 5.14 A licensee may attempt to justify not implementing criticality safety measures on the basis of a Cost Benefit Analysis (CBA). Specifically, it may be argued that the cost of criticality safety measures would be grossly disproportionate to the risk that would be averted by their introduction.
- 5.15 However, it should be noted that CBA is only one possible input into the overall ALARP decision-making process in assessing the adequacy of criticality safety measures. In particular, the results of a CBA are always subject to uncertainty and so the conclusions should be viewed with caution. Primary consideration should be given to relevant good practice, e.g., the hierarchy of protection, which may override the conclusions of a CBA.
- 5.16 Detailed guidance on the ALARP principle is given in Ref. [2].
- 5.17 An holistic approach should be taken to ensure that the total risk is reduced to a level that is ALARP. In other words, it is no use reducing the risk from criticality to a very low level if this is more than offset by a large increase in another component of the risk.

Hazard Identification

- 5.18 ONR assessors should seek assurance that all credible faults that could give rise to a criticality incident have been identified. Evidence of this may be provided through detailed Hazard and Operability (HAZOP) studies, facility walkdowns and reviews of past incidents and near misses. The list of credible faults should consider normal operations and maintenance activities and should include process faults, internal and external hazards, and human errors. The importance of considering human errors cannot be overemphasised since most of the criticality incidents that have occurred have been due to human error. Advice from fault studies and human factors specialists should be obtained where appropriate.
- 5.19 In identifying all the credible faults that could lead to a criticality incident, consideration should not be restricted to the major process vessels and pipework where fissile material normally resides, but should also include adventitious accumulation in unexpected locations, e.g., ducts and drains. In addition, the licensee should also consider the possibilities of precipitation of fissile material from solutions and of fissile solutions drying out due to evaporation, leading to the unexpected accumulation of solid fissile material.
- 5.20 ONR assessors may seek further evidence from licensees where criticality faults are claimed to be incredible.

Assessment Philosophy

- 5.21 Operating configurations should be analysed using demonstrably conservative conditions, taking into account all reasonably foreseeable circumstances and considering the context of the assessment. This is necessary to identify the most reactive condition. Analysis may be based on configurations of materials, or on circumstances other than the most reactive, but these should be fully justified. The analysis should fully take account of the variability of factors such as geometry, material composition, temperature, neutron moderation, reflection and absorption (including neutron absorbers), fissile material quantity (e.g., adventitious accumulation) and

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interaction effects, and of deficiencies in accounting procedures and enrichment identification. The effects of burn-up credit may be considered where appropriate, given suitable justification. Further guidance on burn-up credit is given in Ref. [41] (see also Refs. [20, 21, 42]).

- 5.22 As noted in Section 4.12 above, the Fault Analysis SAPs call for DBA to be carried out for all faults. In addition to incorporating DBA, wherever reasonably practicable, it is expected that a criticality safety case also demonstrates compliance with the Double Contingency Approach. This requires that at least two unlikely, independent and concurrent changes in the process conditions specified as essential to criticality safety must occur before a criticality incident is possible.
- 5.23 The safety justification may be supplemented by a Probabilistic Safety Analysis (PSA) where appropriate. The scope and depth of PSA may vary depending on factors such as the magnitude of the risk, the novelty of the design, the complexity of the facility and the conclusion that the safety case is supporting. For some facilities, qualitative arguments demonstrating large safety margins, clear and robust application of DBA/DCP (and associated good practice) may be sufficient to demonstrate that the overall risk is ALARP. A more thorough PSA may be expected for more complex systems to confirm that a balanced design of the facility has been achieved such that no particular feature of the facility makes a disproportionate contribution to the overall risk of criticality. A PSA should be performed where appropriate to enable a numerical assessment of the risk arising from the facility to be made, and a judgement made as to its acceptability against the accident frequency principles.
- 5.24 As with all risks, the criticality safety case should demonstrate that the risk from unintended criticality is ALARP. In some cases, this may mean that a greater level of protection should be provided than is suggested solely by application of DBA and/or the DCA.

Safely Sub-critical Margins

- 5.25 It is expected that the criticality safety case identifies and justifies an appropriate value for the minimum safely sub-critical margin. This may be defined in terms of limiting values of the effective neutron multiplication factor, or limiting fractions of critical parameters, such as critical masses or critical dimensions. In setting these parameters, the sensitivity of reactivity to changes in the chosen parameters should be accounted for. Advice on computational criteria for criticality safety is available in Ref. [43]; this is a useful reference as it advises on all of the issues to be considered, such as nuclear data error and limits on code accuracy.

Calculation Methods

- 5.26 Licensees use a variety of hand calculation methods and computer codes in criticality safety assessments. ONR specialist assessors may use hand calculation methods to perform independent checks and scoping calculations on a sampling basis. ONR assessors will use their discretion in the level and depth of sampling and may be influenced by the safety significance of the submission. Commonly used criticality hand calculation methods are discussed in Refs. [10, 44].
- 5.27 However, where more detailed calculations (e.g., using computer codes) are required, consultants working under contract to ONR may be asked to perform these calculations. A framework for assessing contractor competence can be found in Ref. [45].
- 5.28 In cases where Monte Carlo computer codes have been used, ONR assessors may seek evidence from the licensee that the calculations are adequately sampled and converged.

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- 5.29 The calculation methods and data used in criticality safety assessments should be verified and validated for the expected range of conditions.
- 5.30 The licensee may also consider the use of more than one assessment method as part of the criticality safety analysis.
- 5.31 Validation should be against experiment whenever this is reasonably practicable. In some cases, small differences in specification (e.g., geometry or materials) may render an experiment unsuitable as a validation benchmark and licensees should provide a justification that any experiments used as evidence of validation are appropriate. Note that there is a large quantity of validation data available in the ICSBEP database. Where suitable experimental data are not available, validation by comparison with an independent method may be acceptable. Further guidance on validation is given in Ref. [46].
- 5.32 Verification should demonstrate that the calculation method or computer code has been used correctly, in accordance with its specification, and for situations for which it has been validated.

Fissile Inventory Information

- 5.33 Licensees should determine the fissile inventory of the relevant system conservatively, taking into account all fissile isotopes present. These will usually be uranium and plutonium isotopes but could, in some circumstances, include other exotic species, e.g., curium isotopes. The system should also account for, and trend, process errors with the potential to increase inventories (e.g., accumulation in a glovebox).
- 5.34 In uranium systems, the dominant isotopes are usually U-235, which is fissile, and U-238, which is fissionable. Cases may occasionally be submitted that consider U-233, which is fissile. In plutonium systems, the dominant isotopes are usually Pu-239, which is fissile, and Pu-240, which is fissionable, though the significance of other Pu isotopes can increase for Pu derived from high burn-up fuel, especially in some systems where the neutron spectrum is not predominantly thermal. Care should be taken when considering systems where enhanced credit is taken for more complex Pu isotopics.
- 5.35 In uranium systems, it is necessary to determine the maximum U-235 (or U-233) content. Similarly, in plutonium systems, it is necessary to determine the maximum Pu-239 content. It should be noted that some exotic species have relatively low minimum critical masses [31]. Hence, in cases where exotic species are modelled as U-235 or Pu-239, evidence should be provided that the representation is suitably conservative. Licensees should conservatively account for fissile inventory accountancy errors, as well as process errors (see Paragraph 5.33), which have the potential to increase fissile accumulation.
- 5.36 Inspectors may encounter cases for mixed Pu/U systems (e.g., MOX). These can be isotopically complicated, the case relying on assumptions about the ratios of both plutonium and uranium isotopes. Note that the most reactive ratio will vary depending on the amount of moderator in the system and that validation evidence is much more limited than for other systems [32]. Historically, computer codes have also proved to be less accurate for MOX systems than simpler fissile systems. Licensees should demonstrate that they have considered these issues.

Movement Control

- 5.37 A reliable and robust movement control and prior authorisation system should be provided in facilities handling fissile material in order to minimise the probability of forming a critical assembly. Ideally, the movement control system and supporting

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operational records should track the locations and movements of fissile material and moderators (where these are important for criticality safety). Reflectors and neutron absorbers should also be tracked where appropriate.

- 5.38 The licensee should demonstrate that there is an adequate movement control and prior authorisation system in place. For example, in cases where complex fissile material movements are carried out, the movement control system may consist of a computer-based system supplemented by checks of paper-based records by facility personnel who are independent of the process operators. This system may be periodically validated by physical inventory verification.
- 5.39 However, where fissile material movements are simple, it may not be reasonably practicable to provide a computer-based safety system. In such cases, a paper-based records system may be adequate.

Substitution Arrangements

- 5.40 Sufficient protection based on engineering and operational safety measures should be retained at all times. In cases where designated safety measures are unavailable, adequate substitution arrangements should be provided. The extent of protection should be commensurate with the level of risk at the time that it is present. The purpose of substitution arrangements is to demonstrate that the risk remains acceptably low during planned or unplanned safety measure outages. For example, in the event of failure of a fissile concentration monitor, manual sampling could potentially substitute with a frequency demonstrated to be adequate in a safety assessment. The justification for such substitutions should be included in the safety case.

Fissile Material Assay

- 5.41 Fissile material assay is commonly formally credited within Safety Measures in criticality safety cases for both operational and decommissioning facilities. This may be undertaken using destructive techniques (e.g., chemical sampling), or Non-Destructive Assay (NDA) techniques (e.g., weighing or interrogation of the radiation emitted by a sample).
- 5.42 Fissile material assay may range from real-time process monitoring (e.g., to allow a response to detected process deviations), to quantitative assay to allow sentencing of material within set limits (e.g., prior to onward processing or waste disposal). Any fissile material assay technique which is formally claimed within a criticality safety case should be supported by appropriate substantiation of the approach and the underpinning assumptions, for both normal operating conditions and relevant fault conditions, to ensure it is suitably conservative and fit for purpose. This justification and underpinning of assumptions can be complex for certain Non-Destructive Assay techniques. For example, when using neutron and gamma interrogation, the assay result can vary significantly with the assumptions made for parameters such as (but not limited to) fissile material geometry and distribution, interstitial matrix material, container make-up and geometry, isotopic make-up, and presence of 'interference' materials (such as those contributing to alpha-n reactions, which lead to enhanced neutron emissions). Licensees are expected to give due consideration to Relevant Good Practice for the NDA technique being employed (e.g., the guidance given in Ref. [47]).
- 5.43 The level of conservatism used in an analysis should take into consideration the overall risk, not just criticality risk. Inspectors should be aware that in some situations over-conservatism may lead to a safety dis-benefits downstream, for example generation, handling, storage and disposal of additional waste packages containing quantities of material that do not present a significant criticality safety concern. The licensee should demonstrate that risks have been appropriately balanced to ALARP.

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- 5.44 Special arrangements may need to be employed during commissioning and decommissioning of facilities, where the level of uncertainty may be higher than for normal operation of a facility. In particular, there may be uncertainty in the amount, form and location of fissile material present, and a need to derive bounding assumptions. In such circumstances, it would be expected that such uncertainties are taken into account when deriving demonstrably conservative sub-critical margins, which may result in an additional safety factor being applied. Increased levels of inspection and monitoring may be expected to underpin assumptions derived in the case and resolve uncertainties.
- 5.45 Characterisation of the fissile content should be undertaken as far as reasonably practicable. The addition of neutron absorbers may also be considered to reduce neutron interaction and to isolate from other fissile materials.

Mitigation of Criticality Consequences

- 5.46 Consideration should be given during facility design, operation and periodic review to the actions that may be necessary to make the facility safe following a criticality accident. Possible approaches could take the form of installation of isolation valves, remote control systems, local stocks of soluble neutron absorbers, portable shielding or other means of safely altering process conditions to achieve a safe state and restore management control.
- 5.47 The radiological effects from an unplanned criticality should be identified and reduced ALARP (see principle FP.6 in the SAPs [1]). This should include identification of those individuals at risk from injury and identification of the range of measures that have the potential to reduce exposures. Such measures should be commensurate with the level of risk and may include fixed warning systems, portable gamma monitors or the provision of suitable shielding.
- 5.48 Public Health England, PHE², has provided general guidance on the protection of on-site personnel in the event of a radiation accident [48]. This guidance applies to all types of sites, including nuclear sites. PHE points out that a radiation accident may give rise to both deterministic health effects and stochastic health effects. (Note that, in general, off-site personnel are unlikely to receive doses high enough to result in deterministic effects as a result of a criticality incident.)
- 5.49 The PHE guidance states that the purpose of prior measures for on-site personnel for radiation accidents should be to avoid deterministic effects and to reduce the probability of stochastic effects so far as is reasonably practicable (in line with the ALARP principle). Priority should be given to the avoidance of deterministic effects.
- 5.50 A criticality incident is one type of radiation accident that could give rise to very high doses, resulting in deterministic effects to on-site personnel. Hence, a system of safety measures should be provided to reduce the probability of a criticality incident so far as is reasonably practicable. This is fully consistent with principle ECR.1 in the SAPs.

Working Party on Criticality

- 5.51 In the UK, the Working Party on Criticality has existed under its current title since 1977 and includes practitioners from regulatory bodies and industry. The papers and minutes of this committee provide a guide to current industry good practice. The committee is non-executive in status, but nonetheless is recognised and authoritative and has a

² Formerly the *Health Protection Agency* (HPA) and before that the *National Radiological Protection Board* (NRPB).

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number of roles, including the provision for exchange of information between different UK organisations. It also has a role in co-ordinating the UK response to international initiatives.

Assessment Guidance

- 5.52 This section presents suggested guidance in the form of a list of points the ONR assessor may look for when considering a licensee's criticality safety assessment. This list is not exhaustive.
- i) Comprehensive and conservative fissile inventory identification;
 - ii) Adequate knowledge of the process and flowsheet conditions;
 - iii) Identification of possible faults that could lead to criticality;
 - iv) Production of a safety analysis, including limits and conditions necessary in the interests of safety (operating rules). This analysis should cover both normal and fault conditions;
 - v) Appropriate choice of calculation methods, e.g., use of computer calculations, hand calculations and/or handbook data;
 - vi) Adequate sampling and convergence of Monte Carlo computer codes;
 - vii) Adequate validation and verification of calculation methods;
 - viii) Demonstration of appropriate sensitivity analyses to variations in key parameters within the modelling approach used;
 - ix) Where appropriate, cross checks of calculations using independent methods (e.g., novel or complex scenarios, where limited validation is available, or when safety margins are small);
 - x) Independent peer review carried out where appropriate;
 - xi) Adequate ALARP assessment, including a demonstration that the minimum quantity of fissile material will be used and the minimum number of fissile moves will be carried out, consistent with the process requirements;
 - xii) Compliance with the hierarchy of protection, i.e., preference given to passive engineered safety measures such as geometrically favourable vessels and pipework; and
 - xiii) Confirmation that the licensee's criticality safety analyst and peer reviewer are SQEP.

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AHSB	(UKAEA) Authority Health and Safety Branch
ALARP	As Low As Reasonably Practicable
ANS	American Nuclear Society
ANSI	American National Standards Institute
CBA	Cost Benefit Analysis
DBA	Design Basis Analysis
DCA / DCP	Double Contingency Approach / Principle
ECR	Engineering Principle: Criticality Safety
FP	Fundamental Principle
HAZOP	HAZard and OPerability (study)
HPA	Health Protection Agency
ICNC	International Conference on Nuclear Criticality Safety
ICSBEP	International Criticality Safety Benchmark Evaluation Project
IRR17	Ionising Radiations Regulations (2017)
ISO	International Organisation for Standardisation
LC	Licence Condition
MOX	Mixed OXide
NDA	Non Destructive Assay
ONR	Office for Nuclear Regulation
OR	Operating Rule
PHE	Public Health England
PSA	Probabilistic Safety Analysis
SAP	Safety Assessment Principle(s)
SQEP	Suitably Qualified and Experienced Person
TAG	Technical Assessment Guide(s)
UKAEA	United Kingdom Atomic Energy Authority
WENRA	Western European Nuclear Regulators' Association

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