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| ONR Technical Inspection Guide (TIG)  Criticality Safety |



ONR Technical Inspection Guide (TIG)

Criticality Safety

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Table - Revision commentary

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| Issue No. | Description of Update(s) |
| 6 | Review period updated. |
| 7 | Significant amendments to tables to provide guidance on ONR expectations against individual questions within the tabulated question sets for key LCs.  Supporting guidance tables moved to a separate Annex to this TIG to ensure this TIG is compatible with other ONR TIGs. |

# Introduction

1. Criticality is an important nuclear safety hazard in plants where fissile material is processed (this includes nuclear fuel manufacturing plants), handled or stored. Criticality is also an important consideration during defuel/refuel operations on nuclear reactor plant. The potential consequences of a criticality accident can be considerable, for example, high/potentially lethal radiation doses to workers and potentially high radiation doses off-site, there is also a potential for the accident to damage plant and equipment, which can in turn provide further challenges to the safety of the workforce and the public. Hence it is of importance that Office for Nuclear Regulation (ONR) inspectors periodically satisfy themselves that the licensee has adequate arrangements in place, to protect the workforce and the public against the potential occurrence of accidental criticality events. Inspectors should use risk informed judgment in deciding upon the required periodicity of inspections in this area.

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# Purpose and Scope

1. The purpose of this inspection guide is to aid ONR inspectors who are not criticality safety professionals, when conducting their duties in this area. It is stressed, however, that ONR’s expectation is that non-specialist inspectors will **as a minimum** seek the advice of ONR criticality safety specialists and ideally will ensure inspections, whose focus is on the management of criticality safety by the licensee, are led by ONR criticality safety specialists.
2. For non-criticality specialist inspectors, Appendix 1 provides some basic guidance on the key physical factors affecting criticality safety whilst the References section in this document lists several useful documents and reports which will allow non-specialist inspectors to gain a greater understanding of the subject.
3. The guidance contained in this Technical Inspection Guide (TIG) should not be regarded as being mandatory. Inspectors are expected to use their discretion in choosing topics from this guide and the associated tables in the Annex to this document [1] to direct their inspection activities and/or in choosing specific questions for discussion with the licensee in a topic area, when seeking to obtain the necessary confidence that the licensee has robust arrangements in place to control all its operations with fissile material.
4. This TIG refers out to detailed guidance [1] in which multiple tables are provided, containing sample inspection question sets for criticality safety focused inspections, together with examples of the evidence that licensees may wish to present to demonstrate satisfactory compliance against the question sets. The question sets have purposely been set out under those Licence Conditions (LC) which from ONR experience are judged to have a key bearing upon the maintenance by the licensee of adequate criticality safety standards. A more general safety culture question set is also included within the tables.
5. The information provided in the total set of tables reflects ONR experience collated during criticality focused interventions on UK licensee sites over many years and takes account of feedback provided by the community of criticality professionals within ONR, as well as the UK nuclear industry as represented on the UK Industry Forum i.e., the Working Party on Criticality (WPC). Several valuable improvements to the contents of the tables have also been made at the suggestion of the Defence Nuclear Safety Regulator (DNSR) and the Environment Agency (EA). The tables presented have also sought, where relevant, to incorporate key learning, useful information etc. from papers presented at the 4 yearly global gathering of criticality safety professionals i.e., the International Conference on Nuclear Criticality, ICNC.
6. Whilst the guidance contained in [1] is intended to be comprehensive, it is envisaged that individual tables, or questions from the tables, can be used as required by inspectors when conducting their compliance inspections in facilities where there is a significant criticality hazard. The guidance can also be used to inform System Based Inspections (SBI) in fissile material facilities.
7. The requirement to ensure criticality safety at nuclear sites is not addressed specifically in any of the Nuclear Site LCs, nor is it addressed explicitly in current legislation (although the requirement is implicit in the Health and Safety at Work Act 1974, the Ionising Radiations Regulations 2017, and the Nuclear Installations Act of 1965 – as amended). However, various Nuclear Site LCs do have legal requirements which directly impinge upon criticality safety, and it is these LCs which are reflected in [1].
8. Whilst the questions in the tables of [1] are generally aimed at plant applications, they can be adapted to inspections related to the transport of fissile material. However, it should be noted that specific question sets for criticality safety inspections, focused on transport, are already available and can be found in [2].

# References

The references provided below link this TIG to other ONR guidance in criticality safety (e.g., Technical Assessment Guides (TAGs) and ONR’s Safety Assessment Principles (SAPs)). However, in addition, for those inspectors wishing to enhance their knowledge of the subject, references have been provided to other reading material which will provide the Inspector with a simple but more detailed description of the subject.

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| [1] | ONR, "NS-INSP-GD-053 - Annex 1 - Guidance on Conducting Criticality Safety-focused Inspections". |
| [2] | ONR, "NS-TAST-GD-097 - Criticality Safety Assessment of Transport Packages". |
| [3] | Wood and ONR, "Research into the Effect of Temperature on the Criticality Safety of Fissile Systems (ONR352, 203171-AA-0022, Issue 2.0)," 2019. [Online]. Available: https://www.onr.org.uk/documents/2019/onr-rrr-077.pdf. |
| [4] | IAEA, "IAEA Safety Standards – Specific Safety Guide No. SSG-27 – Criticality Safety in the Handling of Fissile Material," 2014. |
| [5] | ONR, "Safety Assessment Principles (SAPs) for Nuclear Facilities - 2014 Edition (Revision 1)," January 2020. [Online]. Available: https://www.onr.org.uk/saps/saps2014.pdf. |
| [6] | ONR, "NS-TAST-GD-041 - Criticality Safety". |
| [7] | ONR, "NS-TAST-GD-018 - Criticality Warning Systems". |
| [8] | J. Lilley, Nuclear Physics: Principles and Applications, J Wiley and Sons Ltd. |
| [9] | INL, "Criticality Safety Basics for INL FMHs and CSOs (INL/EXT-06-01183, Revision 1)," April 2012. [Online]. Available: http://inldigitallibrary.inl.gov/sti/5427214.pdf. |
| [10] | Los Alamos National Laboratory, "Nuclear Criticality Safety Guide (LA-12808, UC-714)," September 1996. [Online]. Available: https://digital.library.unt.edu/ark:/67531/metadc680802/m2/1/high\_res\_d/399709.pdf. |
| [11] | Los Alamos National Laboratory, "A Review of Criticality Accidents (LA-13638, 2000 Revision)," August 1999. [Online]. Available: https://www.nrc.gov/docs/ML0037/ML003731912.pdf. |
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# Appendix A – Key Physical Factors Affecting Criticality Safety

The factors which are important for criticality safety include type of nuclide, mass of nuclide, enrichment, density/concentration, shape, moderation, reflection, neutron absorbers and interaction. These factors are briefly discussed in the following.

**Type of nuclide**

The most important fissile nuclides are those of uranium and plutonium, in particular U-235 and Pu-239. Some other uranium and plutonium nuclides are non-fissile, for example U-238 and Pu-240.

**Mass**

The mass of fissile material is an important factor. For each nuclide there is a mass below which a criticality is not possible in any system. Where facilities process or store inventories of fissile material in excess of the critical mass, criticality must be prevented by controlling other factors, as discussed below.

**Enrichment**

Reducing the relative proportion of fissile nuclides in a fissile material will reduce its reactivity and increase its critical mass.

Enrichments vary considerably, for example, natural uranium contains circa 0.7 % of the fissile isotope Uranium-235 (U-235), whereas the level of U-235 in civil reactor fuels can be up to about 5% and the U-235 level can be > 90 % for specialised systems.

**Moderation**

This is the slowing down of the high energy neutrons produced in fission by collisions with atoms of the moderator. This process is important because the probability of a neutron causing fission is appreciably greater for thermal neutrons (< 0.1 eV) than for fast neutrons (>100 keV). Optimising the amount of a moderator will therefore maximize both neutron production and reactivity.

The most effective moderators are those with a low atomic weight, for example, water, heavy water, polythene, plastic containers, graphite and people. Hydrogen has the same mass as a neutron hence ensuring maximum energy exchange when a neutron collides with a hydrogen atom. Hydrogen moderation can hence lead to compact fissile systems. However, it should be noted that hydrogen also absorbs some thermal neutrons i.e. it also acts to slightly reduce the reactivity of the fissile system.

In contrast, graphite is much less efficient than hydrogen at slowing neutrons down and hence large masses and volumes of graphite are required to act as an efficient neutron moderator. However, graphite does not absorb thermal neutrons and hence if large enough quantities of graphite are present, then it can still pose a potential threat to criticality safety.

**Density/concentration**

The density or concentration of fissile material in a moderated system is an important factor which determines whether or not criticality is possible. Because moderators can also absorb neutrons, very dilute arrangements of fissile material in moderator will not be able to achieve criticality.

**Shape**

The reactivity of any given mass of fissile material is very dependent on its shape.   
In general, compact shapes with low surface areas reduce neutron leakage and increase reactivity. The most reactive shape is a sphere because this has the lowest surface area for any given volume. Increasing the surface area/volume ratio decreases reactivity and can be used to prevent criticality via the creation of inherently safe vessel shapes, such as slab tanks.

**Reflection**

This is the process in which neutrons escaping from fissile material are reflected back into it. This reduces net leakage and increases reactivity. Commonly encountered reflectors are concrete, water, steel, graphite, aluminium and beryllium, although virtually any material will act as a reflector to some extent.

**Neutron absorbers**

Neutron absorbers are substances which have a high neutron absorption cross section, i.e. a high probability of absorbing/capturing neutrons, thus making these neutrons unavailable to cause fission. Neutron poisons are generally considered to be neutron absorbing materials intentionally added to a fissile system (i.e. they are present solely and intentionally to absorb neutrons and hence to reduce the reactivity of the fissile system to which they have been added). Neutron absorbing material, in contrast, refers to everything else that may cause an effect upon the fissile material system, but which has not been added intentionally.

Examples of materials with a high neutron absorption cross section (i.e. a high probability of absorbing neutrons) include boron (rich in the B-10 isotope), cadmium, gadolinium and hafnium.

**Interaction**

If two systems are placed close together (for example, waste drums containing fissile material, each of which is subcritical in isolation), neutrons from one system can reach the other system and will increase the likelihood of the overall system to go critical. Hence the spacing between adjacent systems containing fissile material is important. Also, when a person steps between such systems they could unwittingly introduce additional moderation.

**Heterogeneity**

This is not a straightforward nor necessarily intuitive topic, for example, for uranium enrichments of less than 10%, an optimised heterogeneous arrangement of fuel and moderator is more reactive than a homogeneous arrangement. This effect can also apply to Mixed Oxide (MOX) fuel. For higher uranium enrichments, an optimised homogeneous arrangement of fuel and moderator can be more reactive than any practical heterogeneous arrangement.

**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 [3]; 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.