CRITICALITY SAFETY ACROSS THE FUEL CYCLE: A REVIEW OF KEY ISSUES AND SERCO EXPERIENCE,

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ABSTRACT

The UK SAPs requirements, specific to criticality are summarized in this paper together with a review of and references to the main criticality issues that need to be considered within the main stages of the fuel cycle.

Serco has carried out methods development and broad ranging technical and safety case assessments of criticality safety for activities at all these stages for various UK and international clients. This paper provides an overview of Serco's work together with illustrations of some particular activities.

Key Words: Fuel cycle, criticality safety, regulation, methods development, assessments

1 INTRODUCTION

The demonstration of criticality safety across fuel cycle operations over the lifetimes of a wide range of facilities is a key safety requirement. These operations cover many diverse technologies and processes and depending on the process, the fissile materials can be in solid, liquid or vapour phases. Operations also include the transport of fuel and waste to and from the facilities. Over many years, Serco has carried out methods development, and broad ranging technical and safety case assessments in support of criticality safety assurance. Serco and its pre-cursor organizations have also been the licensee for a number of critical facilities, including research and prototype reactors, at Winfrith, Harwell and other former UKAEA sites.

In the UK, criticality safety is assured by UK regulatory requirements, as embodied in the Safety Assessment Principles (SAPs). The SAPs are not prescriptive but the principles are consistent with international practice e.g. IAEA standards. There are separate requirements for the transport of fissile materials, which conform to IAEA RAM Transport Regulations. Serco staff are very experienced in regulatory compliance against these requirements and standards. Serco contributes to UK working parties on standards and in defining core competencies for criticality assessors. Internationally, we also contribute to OECD fronted activities, including participating in international criticality benchmarks.

There are many parts of the nuclear fuel cycle where it is necessary to consider criticality safety in plant operations throughout the lifetime of the plant. Criticality safety must be ensured in all processes and stages involving fissile fuel, namely: enrichment, fabrication of fuel, fuel handing transport and storage, spent fuel reprocessing (if required), processing of waste and its final disposal. Sub-criticality is assured by engineering design, and also by controlled operation within the operating licence. Serco provides safety consultancy on all these issues over all stages of the fuel cycle to various clients within the UK industry.

In particular some recent activities carried out by Serco have included:

- Support to fuel fabrication activities at the Sellafield MOX plant;
- Transport assessments for spent fuel, in particular from former UKAEA sites to storage locations in the UK;
- Support to reprocessing operations at the Thermal Oxide Reprocessing Plant (THORP); and
- Criticality assessments in relation to storage in a Geological Disposal Facility.

Many of these assessments have been carried out with the ANSWERS' criticality codes and several detailed papers on ANSWERS criticality code methodologies and assessments are also being presented at this conference.

2 REGULATORY REQUIREMENTS

Regulatory requirements for criticality safety in the UK have evolved from the Health and Safety at Work Act (HASW) 1974 and the Nuclear Installations Act 1965. The nuclear decision making and permissions process are governed by the UK Safety Assessment Principles (SAPs) [1] together with supporting Technical Assessment Guides (TAGs). The SAPs were first published in 1979, revised in 1992 and further revised in 2006 incorporating**:**

- lessons learned from operating experience;
- greater consistency with IAEA safety standards, codes and guides; and
- harmonisation with WENRA levels.

Although principles requirements documents for a licensee, the SAPs and the TAGs have set generally accepted standards and practices for criticality safety management. Internationally, IAEA safety standards for criticality safety are covered in numerous documents e.g. see references in [2], [3] and indeed UK requirements for the safety of fissile transport operations are provided for by IAEA RAM Transport Regulations [4]. Similarly the American Nuclear Society has produced a range of standards that are adopted in the US.

A number of the safety assessment principles are relevant to and explicitly refer to criticality safety. The concept of defence-in-depth, which requires multiple levels of protection for all safety related activities, whether organisational, behavioural, or equipment related, is a particularly important general principle. There are criticality related principles in regard to engineering, radiation protection, fault analysis and waste management and there are various TAGs supporting these for the assessment of nuclear licensee's arrangements for criticality safety. For example, the TAG [5] published in 2009 gives additional guidance for the engineering principles below. The latest guidance is generally aimed at new facilities; for older facilities designed against earlier standards, the adequacy of measures is judged against the ALARP principle on a case by case basis. The adequacy of criticality aspects is covered in the site licence conditions and other legislation.

Engineering Principles:

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 scope therefore covers facilities apart from reactors, where clearly criticality is achieved in a controlled manner. There are two essential principles.

EC1: Wherever significant amounts of fissile materials may be present, there should be a system of safety measures to minimise the likelihood of unplanned criticality.

There is a hierarchy of controls for all stages of a facility's life-cycle. These are around minimising the amount of fissile material, consistent with the required process, geometrical constraint, and some additional engineered safety measures including fixed neutron absorbers.

EC2: A criticality safety case should incorporate the double contingency approach.

This approach requires that unintended criticality cannot occur unless at least two unlikely independent concurrent changes in the conditions originally specified as essential to criticality have occurred. It is also noted in the SAPs that for long-term storage of radioactive waste, consideration should be given to a risk-informed approach where traditional deterministic criticality assessments can lead to very conservative limits on fissile materials.

The principles EC1 and EC2 should also be considered in conjunction the overall fault analysis principles.

Radiation Protection

RP2: Adequate protection against exposure to radiation and radioactive contamination in accident conditions, should they occur, should be provided in those parts of the facility to which access needs to be gained. This should include prevention or mitigation of accident consequences.

It is a requirement that adequate warning systems (not necessarily a Criticality Incident Detection (CID) system) should be provided wherever fissile material is present, unless an assessment shows that no criticality excursion could give any individual a whole body dose exceeding the annual whole body dose limit, or that the predicted frequency is acceptably low.

Fault Analysis

The fault analysis principles apply to criticality safety because of the very high levels of neutron and gamma radiation fields associated with criticality accidents, which could be fatal. There is a general requirement that fault sequences should be analysed and one of these has a specific requirement in respect of criticality safety.

FA.3 Fault sequences should be developed from the initiating faults and their potential consequences analysed.

The calculated doses should include those arising from the potential release of radioactive material, direct radiation, and criticality incidents.

Waste Management

Several principles explicitly refer to criticality safety.

RW.5 Radioactive waste should be stored in accordance with good engineering practice and in a passively safe condition.

In regard to the management of radioactive waste, the overall safety case is required to identify any operational limits and conditions required for safe storage. These have to take account of a number of factors which may include: environmental conditions, heat and gas generation, and also radiological and criticality hazards (taking account of on-site storage and long term management, which may include disposal).

RW.7 Information that might be required now and in the future for the safe management of radioactive waste should be recorded and preserved.

Records are required for the radionuclide inventory, the amount, radioactive waste category, physical, biological and chemical form and associated uncertainties in the estimates of the radioactive wastes. For waste containing fissile material this should include criticality-relevant information.

3 STAGES OF THE FUEL CYCLE

The key stages of the fuel cycle, Figure 1, include [3]: mining/ milling operations, chemical conversion process, enrichment, fuel fabrication, in-reactor operation, interim storage of spent fuel, possible reprocessing to produce MOX fuel, transport to long-term storage and disposal. All stages, beyond the enrichment stage, require the potential for criticality hazards to be addressed. Sub-criticality is assured by engineering design, and also by controlled operation within the operating licence. It should be noted that operational criticality safety issues and current areas of interest are studied by The Working Party on Criticality (WPC) [6], a non-executive national committee of experts with links to many international bodies such as the ANS, IAEA and OECD/ NEA.

Fuel Conversion and Enrichment

At the conversion stage, where homogeneous processes are involved with uranium at an isotopic composition of ~0.7 atom % ^{235}U there is no criticality safety hazard. Enrichment facilities can present a hazard however and therefore have to comply with regulatory requirements for criticality safety as outlined in the previous section (for the UK). Criticality safety is achieved by careful control of parameters including the mass and enrichment of the fissile material, the facility geometry, the concentration of fissile material if in solution, the available moderator and the presence of absorbers. A summary of IAEA requirements specific to conversion and enrichment facilities is given in [7].

Fuel Fabrication

Materials in the process could be in various physical forms, powders, solutions, solids including fissile uranium ^{235}U and/ or mixtures of ^{239}Pu, ^{240}Pu and ^{241}Pu. Control parameters for fuel fabrication are similar to those cited above for fuel enrichment and indeed for most stages in the fuel cycle. Main parameters include degree of moderation, control of reflectors, geometry and fissile mass with commercial fuel production relying heavily in limiting moderators as a primary control parameter. Controls are required for production operations involving material cross-over, for machining, grinding and cutting and the handling and storage of fresh fuel. IAEA requirements for uranium fuel fabrication are summarized in [8], with some specific requirements for Mixed Oxide (MOX) fuel given in [9].

Spent Fuel Operations

The criticality control parameters described above for earlier fuel cycle operations still apply here but spent fuel operations require special considerations as they involve the management and retention of large quantities of fissionable materials within highly irradiated fuel, which is now extremely radioactive. There are potential accident conditions associated with remote handling and storage of spent fuel [10], loss of soluble or fixed absorbers e.g. in fuel ponds [11], re-racking of fuel, changes in irradiated fuel composition and mis-loading. Safety measures include robust engineering design of structures, restriction on fuel and other structures' movements and robust administrative arrangements to ensure the control parameters above are maintained under normal and accident conditions.

Burn-up Credit

In principle it is possible to take advantage of a potential reduction in spent fuel k_{eff} relative to fresh fuel i.e. take advantage of burn-up credit. In practice, however, it is necessary to determine fully the changes in fuel composition during its irradiation. In order to demonstrate an adequate criticality safety margin, it is therefore necessary to make allowances for the increased complexity and uncertainty surrounding the irradiation phase, by making suitably conservative assumptions on initial enrichment, the amount of burn-up, the effects of burnable poisons, fuel temperature, coolant temperature and density, power history and cooling time. It is also important to justify modeling assumptions, including the validation of codes used for analysis. Further information on burn-up credit is given in [12].

Reprocessing

Reprocessing involves a wide range of operations involving various chemical and physical processes including fissionable material. This can be in different forms e.g. fuel rods and assemblies, fines, solutions of uranium and/ or plutonium salts and uranium/ plutonium or their mixed oxides. Issues to be addressed in the safety case include mobility and possible mis-direction of solutions, inadvertent hold-up and accumulation and maintaining control of the usual criticality parameters. A review of the status and trends in reprocessing is given in [13].

Waste Management and Decommissioning

Waste management operations include packaging, interim storage and disposal operations. They involve different facilities, materials and processes [14]. Control is based on the limits and design of waste packages and the arrangements of disposal in the relevant facility. Consideration must be given to changes in configuration, particularly in the degradation of engineered safety features over long time-scales. Decommissioning operations, involving fuel removal will require criticality controls as above, otherwise the issues are only generally concerned with the management of low fissile inventory materials and of less significance from the point of view of criticality. [15].

Transport

Transport criticality controls are even more stringent than those for facilities since there is potential for closer contact with the public [3], [4]. It is necessary to demonstrate the maintenance of sub-criticality under both normal and accident conditions, including leakage of water into or out of the package, rearrangement of contents, damage to the package, reduction of packing space or immersion in water or snow.

Research and Development

There are a number of facilities e.g. laboratories that are concerned with research and development (R & D) into processes and products containing fissile materials [3]. These may have low fissile material inventories enabling a reasonable degree of flexibility in their activities but they may also have to accommodate fuel experiments and associated waste handling. Depending on the nature of the R & D, there may be a diverse range of fissionable or non-fissionable isotopes of uranium, plutonium together with moderator, absorber, poisons and other material. Because of the range of activity, care has to be taken in interfacing with other criticality controlled areas to avoid any unintended consolidation of fissile materials or other unexpected criticality hazards.

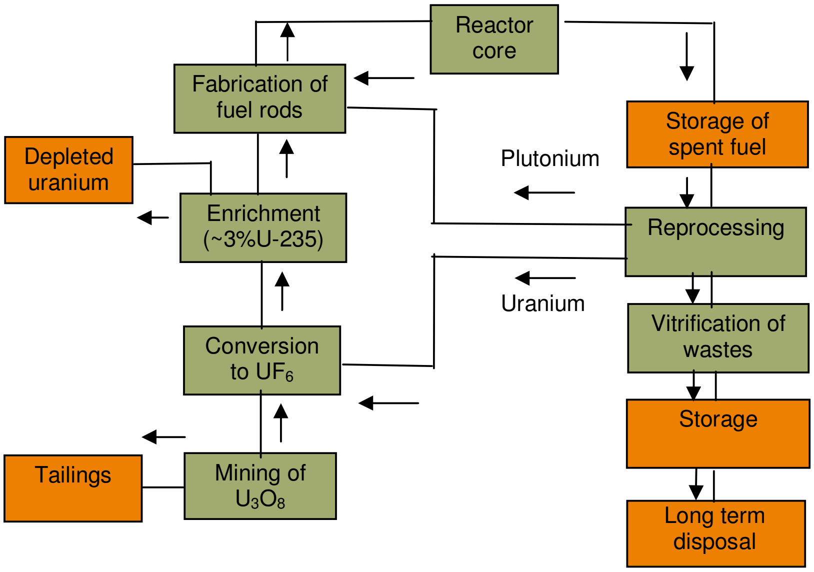

Figure 1: Stages of the fuel cycle

4 AREAS OF CRITICALITY SUPPORT

Serco (and its pre-cursor organizations) provide criticality services and consultancy to nuclear industry in many fields of activity. These include operational safety, nuclear science disciplines, safety methodology and international standards, emergency planning and professional development including training. Some examples of recent activities are given in this Section.

Operational Safety

As discussed above, there are operational criticality safety issues across all stages of the fuel cycle and some specific Serco activities in some of these stages are referred to in Section 5. Technical assessments are generally carried our using the ANSWERS codes; in particular the MONK Monte Carlo criticality code [16] and also, for some criticality applications, the WIMS reactor physics code [17]. Some details on these codes are given in Section 6.

Nuclear Science, Code Development and Validation

- Serco has developed new criticality safety handbook style curves through the development of the Improved Critical and Safe Parameters Algorithm (ICASPA) [18]. This method can be used to calculate the critical (or safe) ‘size’ of systems for given fissile material geometry; an example application might be to calculate the safe payload for transport containers.

- Contribution to experimental data-base for criticality safety via data from earlier experimental reactors at Winfrith, e.g. DIMPLE, ZEBRA. DIMPLE provides reactor physics data for thermal nuclear reactor methods validation; ZEBRA providing physics data for fast reactors.

- Recent MONK developments include the ICASPA method above, a Genetic Algorithm search engine and other detailed MONK code developments and improvements. These are described in several other Serco papers to be presented at the ICNC 2011 conference [19], [20].

Safety Methodology and International Standards

Serco routinely carries out safety case support and criticality design assessments for new plant and major modifications of plant for both normal and fault conditions. Activities include the development and assessment of methods (including burn-up credit and ALARP), performing periodic safety reviews, transport operations, waste management and disposal, decommissioning, peer review and Independent Nuclear Safety Assessments (INSAs).

To retain state-of-the art expertise, Serco engages in various international activities, associated with:

- ICSBEP: International Criticality Safety Benchmark Evaluation Programme;
- IRPhE: International Reactor Physics Benchmarks;
- JEFF: Nuclear data; and
- IAEA: International Atomic Energy Agency.

Emergency Planning

In performing criticality plant safety and transport safety case assessments of accident conditions, Serco also covers:

- Review of Criticality Incident Detection Systems (CIDAS) and CIDAS omission cases; and
- Emergency planning arrangements.

Professional Development

Serco carries out various criticality training programmes:

- Training of criticality assessors;
- Criticality awareness training;
- Training in the use of ANSWERS criticality codes; and
- Support to university programmes.

5 OPERATIONAL CRITICALITY SAFETY

In this Section are listed some recent specific examples of Serco activities in support of operational criticality safety at different stages of the fuel cycle:

- **Support to fuel fabrication activities at the Sellafield MOX plant.** This plant was designed to produce MOX fuel as an alternative to low enriched uranium fuel for use in light water reactors. Serco have carried out a number of criticality INSAs for various operations, including the residual fuel store.

- **Sizewell-B fuel ponds (Figure 2) safety case.** Work has been carried out to support the verification of MONK models and modelling methods for the Sizewell-B ponds. The code has then been used to support the safety case for different fuel loadings.

- **Transport assessments for spent fuel.** Serco (and its pre-cursor organisations) have performed spent fuel criticality assessments for fuel transport from UKAEA sites to storage locations in the UK. Similarly criticality assessments have been carried out for the handling and transport of irradiated fuel from some Magnox stations (e.g. Chapelcross).

- **Support to reprocessing operations.** Recent activity has been contribution to the Long Term Periodic Review (LTPR) to provide the criticality safety case for the Sellafield Thermal Oxide Reprocessing Plant (THORP); this covered several different plant and process areas including fuel dissolution and chemical separation plant.

- **Criticality assessments in regard to geological disposal.** Various projects have been carried out to investigate safe fissile material limits on Intermediate Level waste (ILW) storage in a Geological Disposal Facility. A representative calculation is described in Section 7.

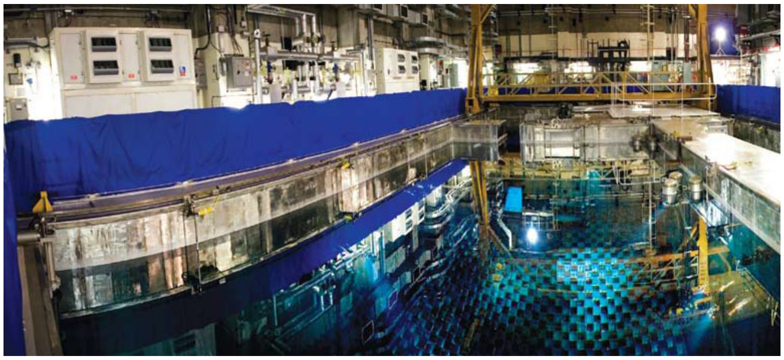

Figure 2: Fuel Ponds (Sizewell-B)
(Courtesy of British Energy Group plc)

6 CRITICALITY ASSESSMENTS

There are a range of different types of activities that can contribute to overall criticality assessments such as:

- COSR safety case production for major facilities.
- Criticality safety case review.
- Technical criticality safety assessments across all operations.
- Fissile material transport assessment.
- Design assessments of facilities processing or storing fissile materials.
- Criticality incident detection system advice and assessment.
- HAZOP studies.

Technical criticality assessments utilise computer models that enable detailed and precise models to be made of the various components of the facility geometry or transport flask packages etc. As stated earlier, in Serco, the methodology is based the ANSWERS the MONK and WIMS codes; these can be supplemented by other codes to provide specialist features. Section 7 shows the capability of these ANSWERS codes in modelling the detailed features of a representative waste package.

MONK is a 3-D continuous energy Monte Carlo code which can also be used with a broad group structure for comparison with deterministic codes, such as WIMS [17]. It can allow for a large number of discrete energy groups (13193 groups) to be included. Figure 3 shows a 3-D MONK model of fuel elements, which uses the ANSWERS Integrated Development Environment (IDE), Visual Workshop [21] to display the model with results superimposed, if required. MONK has been well validated over many years for a very wide range of applications and is capable of high accuracy, only limited by the number of samples tracked in MONK and fidelity of the nuclear data library used. Since it is a Monte Carlo code, it can however make heavy demands on computer power if distributed parameters such as burn-up, are to be scored but this is less of a problem in the age of modern super-fast computers. Recent developments in MONK are for it to take advantage of parallel processor architectures.

WIMS is a deterministic multi-group code with a choice of 69, 172 and 1968 group schemes. It is a 3-D code with many different methods available for calculating the neutron flux and multiplication factor, including: diffusion, method of characteristics, collision probabilities and discrete ordinates. It is not as extensively validated for criticality applications as MONK, but it is faster running for prediction of distributed parameters, such as flux maps and is not subject to the statistical errors of the Monte Carlo method. WIMS is used for burn-up analysis and to calculate input conditions such as temperature feedback coefficients for transient criticality calculations. WIMS is also used for sensitivity analyses to find “worst case” conditions.

Figure 3: Fuel Elements and a Transport Container

7 GEOLOGICAL DISPOSAL

Serco has performed criticality assessments in regard to the safe disposal of waste and other materials at the back end of the fuel cycle.

The company has a capability to deliver criticality safety cases in support of flask development for transport of canisters to the disposal site and to carry-out assessments of handling, emplacement and long-term storage.

Figure 4 below shows an illustrative analysis which demonstrates:

- Application of the Serco ANSWERS Monte Carlo MONK code to the calculation of safe fissile material limits for representative intermediate level waste (ILW) packages.

- The variation of the multiplication factor, k-effective, as a function of uranium particle size and ^{235}U composition for a low enriched uranium waste package.

- That, by way of an example, in a particular model with a fissile mass of 810g of ^{235}U, with a nominal graphite reflector of 1kg mass, and for a worst-case heterogeneous 4% uranium enrichment, the reactivity is maximized when the particle size is approximately 0.35cm with a fissile concentration of 0.05g ^{235}U/cc.

Calculations have been carried out for a number of different waste compositions including Pu contaminated material, irradiated natural U, low enriched U and high enriched U and more specific wastes, e.g. from decommissioning activities.

The methodology enables calculations of both lower and upper fissile limits for waste packages to be performed for various scenarios. It therefore enables calculation of critical and safe parameters for realistic and highly pessimistic scenarios. This type of analysis can provide input into ‘risk-informed’ decision making and also ALARP arguments. Long term, post-closure criticality safety of a geological disposal facility has also been considered, as described in [22], [23].

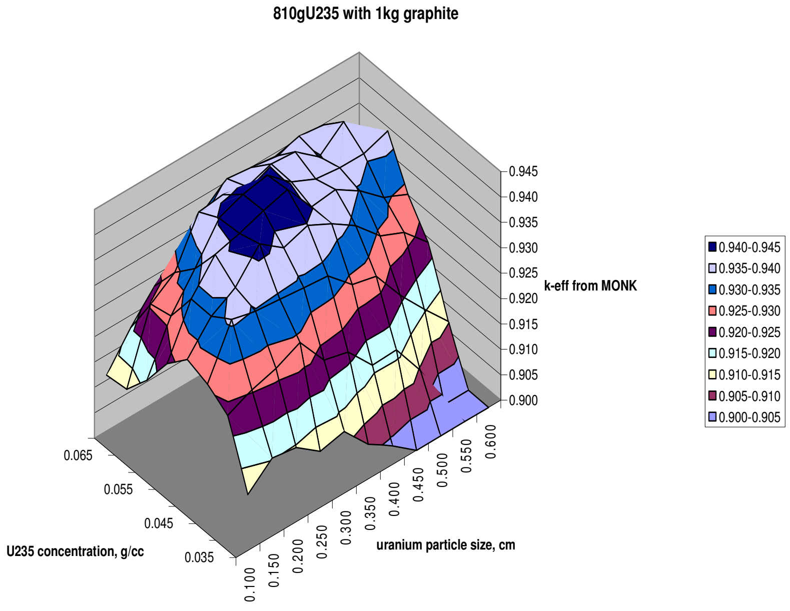

Figure 4: Geological Disposal

8 CONCLUSIONS

The UK SAPs are not prescriptive but the principles are consistent with international practice e.g. IAEA standards. For the transport of fissile materials, UK requirements conform to IAEA RAM Transport Regulations. Serco staff are very experienced in regulatory compliance against these requirements and standards.

Apart from early stages of the fuel cycle that involve natural uranium prior to enrichment, almost all stages across the fuel cycle involve fissile fuel operations, namely enrichment, fabrication of fuel, fuel handing transport and storage, spent fuel reprocessing (if required), processing of waste and its final disposal. Criticality controls must be in place at each stage.

Criticality safety is achieved by careful control of a number of parameters including the mass and enrichment of the fissile material, the facility geometry, the concentration of fissile material if in solution, the available moderator and the presence of absorbers. There are numerous IAEA documents as cited in this paper that describe in detail how criticality is controlled at each stage.

Serco (and its pre-cursor organizations) have provided criticality services and consultancy to the nuclear industry over many years. Current areas and items of interest cover: nuclear science disciplines, including code development and validation, safety methodologies and international standards, emergency planning and professional development, including training, knowledge management and succession planning.

A key part of our work includes software services and related consultancy centered on our ANSWERS business and the maintenance, development and application of the MONK Monte Carlo criticality code, and for some criticality applications, the WIMS reactor physics code.

Serco has gained a large body of expertise in performing criticality assessments in all areas across the fuel cycle, experience that has been honed over many years. The application of codes and methodologies developed within the ANSWERS framework enable safe fissile limits to be established.

9 ACKNOWLEDGMENTS

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