The status of criticality accident dosimetry in the UK

C. L. Wilson[1], L. N. Buchanan[1], D. Spencer[2], M. S. Peace[3]
[1]*AWE, Aldermaston, Reading, RG7 4PR*
[2]*Nuvia Ltd., Dounreay, KW14 7TZ*
[3]*Sellafield Ltd., Seascale, CA20 1PG*

Criticality accident dosimetry is required under the Ionising Radiation Regulations 1999 in environments where there is a risk that persons may be exposed to a high dose of ionising radiation from a critical assembly. The infrequency of criticality accidents has resulted in a dwindling of expertise in the area of Criticality Accident Dosimetry (CAD) over the past decades.

New technologies and methodologies, and renewed regulatory interest in the area of criticality accidents, has highlighted a need to modernise CAD systems and the techniques used in dose assessment. The history of CAD is reviewed and the current state-of-the-art in the UK is examined and compared to other dosimetry services around the World.

Key words: Criticality dosimetry, CAD, CADUG, neutron dosimetry, accident dosimetry

1. Introduction

The manufacture of complex nuclear devices, from warheads to fuel pins for power plants, relies on industrial processes involving the aggregation and manipulation of fissile material. The history of the handling of fissile material, both in industrial manufacture and in research, is scarred by inadvertent occurrences of nuclear criticalities, which are referred to as criticality accidents.

The chronicle of McLaughlin *et al*. (2000) details how multiple process criticality accidents occurred in the 1950s and 1960s when criticality safety programmes were in their infancy and when operator training was often overlooked. A period of relative calm prevailed after 1970 as strict mass controls and administrative procedures were introduced together with criticality education programmes. However, the incidents at Sarov in 1997 (IAEA 2001) and Tokai-mura in 1999 (IAEA 1999, Inaba 2000, Endo 2010) demonstrate that a fatal accident can occur even in a mature nuclear infrastructure with well-defined safety parameters.

This paper summarises the lessons learned from the history of criticality accidents and the philosophy and development of criticality accident dosimetry. Where possible, comparisons are sought between the approaches adopted by different nations to satisfy the need for accurate dose assessment following criticality accidents. This includes workers in the immediate area, other peripheral personnel and the public living in the vicinity of a facility.

2. Criticality accidents

A study of the history of process criticality accidents (McLaughlin *et al* 2000) reveals that failures in administrative controls, human error and equipment malfunction, lead to the mass of a fissile isotope becoming concentrated in such a way that the critical mass is exceeded for the geometry and matrix of the material. The result is a critical assembly, which has an exponentially increasing fission rate for a short time, before thermodynamic processes intervene to reduce the reactivity.

The chronology of a criticality accident can be complex and is a function of the material, matrix and environment (IAEA 1982). In general, the critical assembly will be powered by a total of $\sim 10^{16}$-10^{19} fissions and will produce an intense field of mixed photon/neutron radiation.

The danger to personnel from a criticality accident is principally in the initial pulse of the assembly, which has a rise time and duration of a few seconds or less. The pulse triggers Criticality Accident Area Monitors, which alarm and initiate an immediate evacuation of a facility. The rapid evacuation of personnel reduces the risk of over exposure to ionising radiation however the initial pulse alone generally involves $\sim 10^{15}$-10^{16} fissions. The ionising-radiation field generated by the assembly in this initial pulse is capable of delivering an absorbed dose in body tissue of tens of Gy before the workers are able to reach a safe distance. History has shown that any workers within the immediate vicinity of a criticality accident are likely to be severely over exposed, and fatalities arising from these incidents are not uncommon.

3. Criticality accident dosimetry

Mass control systems and strict working practices have been designed to mitigate the threat of criticality accidents, but the employer of radiation workers still has a duty to ensure that, in the event of an incident, the dose received by workers is assessed accurately and in a timely fashion (UKP IRRs 1999). Criticality accident dosemeters were developed for the purpose of post-incident dose assessment and are routinely worn by radiation workers in facilities where fissile materials are handled.

In the United Kingdom a dosimetry service may be approved by the Health and Safety Executive (HSE) to provide Special Accident Dosimetry in order to assess whole-body dose exceeding 0.5 Gy (HSE 2008 p.2). The requirement for the approval of such dosimetry is that the system used must be capable of assessing dose exceeding 1 Gy within 8 hours of exposure. In addition the system must be capable of determining any dose exceeding 0.25 Gy, with an uncertainty no greater than 30 %, within 1 week of an incident (HSE 2008 p.33).

The largest uncertainty in any dose assessment for a criticality accident arises from the inexact knowledge of the radiation quality experienced by the exposed person. There is wide variation found in the average tissue kerma per unit fluence for neutrons from assemblies with different compositions (IAEA 1982, Table VI). This is linked to the non-linear relationship between neutron energy and surface absorbed dose per unit fluence, which is ~10 times greater for 1 MeV neutrons than for thermal neutrons (Jones *et al.* 1971, ICRU 2001). The ratio of γ-to-neutron dose also varies, having a value ~0.1 for a bare metal system and up to 3 for an aqueous or highly moderated system (IAEA 1982, p. 39). In addition the orientation of the dosemeter to the radiation field introduces uncertainty on the dose assessment due to the attenuation of radiation in the body of the wearer and the anisotropy of response of the dosemeter. In order to determine the dose within the uncertainty stipulated by the HSE, a dosemeter must be capable of measuring photon dose, neutron fluence as a function of energy, and the orientation of the wearer with respect to the field.

The Approved Dosimetry Service (ADS) provided to the Atomic Weapons Establishment (AWE) by Analytical Sciences (ASc), has approval to provide and assess a dosemeter supplied by Nuvia Ltd, Dounreay. The dosemeter design was conceived in the 1960s at the Atomic Energy Research Establishment, Harwell (Dennis 1963, Smith *et al.* 1965) and later adopted by the UK Atomic Energy Authority. Since 1986 the technical maintenance and development of the dosimetry system has been overseen by the Criticality Accident Dosimetry Users Group (CADUG, formerly NADUG); a collaboration of a small number of institutions within the UK. As such a single design of dosemeter is used across the UK and the maintenance and development of the device is a collective activity.

4. The CADUG dosimetry system

The CADUG dosimetry system (Delafield *et al.*, 1973) is based on the use of passive detectors for neutron fluence measurements (Holt 1985) coupled with a standard thermoluminescent detector for γ-ray dose determination. Sulphur, gold and indium are used to sample the neutron field through multiple capture and scattering processes. The activation products resulting from these reactions are β and/or γ emitters, with half-lives sufficiently long to enable measurement of their activities following the post-incident recovery of the dosemeters.

Sulphur and indium have threshold reactions; so called because beneath certain energies the cross-section for the reaction with neutrons is negligible. Analysis of these materials allows a determination of the fast component of the neutron field. Two gold foils, separated by cadmium, are used in a complex process to estimate the thermal and epithermal components of the neutron field and subtract the contribution from neutrons reflected from the body (Adams and Dennis 1963).

The activation of indium is analysed using high-resolution γ spectrometry, and has thus improved as this technology has developed. In contrast the β emission from the sulphur and gold components are counted using end-window Geiger-Muller tube detectors in large lead shields. These devices are dedicated to the CAD process; maintaining them is increasingly difficult as parts become obsolete, and calibration is costly, especially as neutron irradiation facilities become increasingly scarce. A programme is currently underway within CADUG to identify new instrumentation for the gross β counting of gold and sulphur and to implement a sustainable calibration methodology to ensure the continued viability of the dosimetry system.

The final component of the neutron dosemeter is a silicon diode (Harshaw type DN-156), the forward voltage of which is increased if exposed to neutrons due to the displacement of silicon atoms from their lattice sites, which increases electrical resistance across the diode (Swaja 1986). This device is easily and rapidly processed on a PIN diode reader manufactured by J Caunt Scientific Ltd. and can provide an assessment of the fast neutron dose in seconds. Unfortunately there are now no suppliers for new diodes since the commercial requirement has become too limited to support a manufacturing line.

The results from the dosemeter can be combined with biological assessments of dose, such as body sodium activation (Anderson 1964) and activation of body hair and clothing (Delafield 1985) however these aspects of the dosimetry system are not formally approved by the HSE.

The dose from photons is measured with a standard Harshaw Type 8814 thermoluminescent detector issued routinely to classified workers at AWE. The TLD is capable of responding linearly to dose up to 10 Gy and supra-linear corrections can be made beyond this dose.

The results from all components of the dosimetry system are input into a computer programme known as CRISIS (UKAEA 1992). This programme uses measurement and contextual data to determine the dose to individuals based on the derived radiation quality and orientation of the individual, and removes the necessity for a highly trained analyst to compute multiple equations.

5. Intercomparison of dosimetry systems

During the development of criticality dosimetry systems intercomparisons were relatively frequent; four were conducted under the aegis of the International Atomic Energy Agency in the early 1970s (Gibson *et al.* 1976). In the past 20 years the SILENE reactor at IRSN, Valduc has been host to a number of international intercomparisons. The European Dosimetry Group (EURADOS) organised an exercise in 1993, another was organised in 2002 motivated by the Tokai-mura incident and a third occurred in 2010.

Participants from around the World use dosimetry systems based on the same principles as described above, although some place greater reliance on biological dosimetry (Roy 2004). Somewhat surprisingly, laboratories and facilities in the United States do not have a common system though there are similarities between sites (Ward 2010, Hill and Conrady 2010, Delafield 1985).

The results from the recent intercomparisons intimate that further development of dosimetry systems may be required. In 2002 86 % of participants reported their neutron dose to within ±25 % of the reference value but only 73 % reported the photon dose within the same range (Médioni and Delafield 1997). In 2007 the results were similar; 80 % of participants reported neutron dose within ±25 % and 71 % reported within this range for the photon dose (Médioni *et al.* 2004). These cumulative results hide a wealth of data that shows that some dosimetry systems do not perform well in particular fields. The most recent exercise again highlighted issues with the accurate determination of photon dose, which tends to perform poorly due to neutron-induced signal in the photon dosemeter (Savanier 2011, Ward 2010).

6. Monte Carlo computational techniques

The dosimetry systems extant today were mostly developed in the 1960s using analytical techniques to derive the neutron fluence based on the integral cross sections of reactions in different materials. Much of the development work of the past 20 years has focussed on the increasing capacity of computers to model the response of dosemeters, especially using Monte Carlo techniques. Devine (2004) compared analytical techniques to Monte Carlo calculations to determine cross sections in common materials used in CAD, and Takada *et al.* (2011) combined experiment with Monte Carlo calculations to refine the expected response of indium to a neutron field. In addition, Endo (2010) illustrates how Monte Carlo techniques can be used to simulate the dose distribution in the body of an exposed worker. These techniques could be expanded to create neutron dose maps for the environment around a criticality accident, to ensure that lightly exposed personnel on the periphery of the accident zone are assigned a conservative dose.

Monte Carlo techniques should also be utilised to design new criticality accident dosemeters that are easier and cheaper to deploy and have calculated responses for a wide variety of fields. Calculations are also being performed at AWE to aid understanding of the response of thermoluminescent detectors in mixed photon-neutron radiation fields.

7. Conclusions

The Sarov and Tokai-mura accidents of the 1990s taught the World that the threat of criticality accidents cannot be dismissed because of their relative rarity. Criticality accident dosimetry remains essential for employers of radiation workers who process or handle fissile materials. Most CAD systems in use today were developed in the 1960s and, though they still perform satisfactorily in exercises, there is clearly a need to review and update the field using modern computational techniques combined with new technologies.

In the UK the Atomic Weapons Establishment in collaboration with the Criticality Accident Dosimetry Users Group is embarking on a programme of research and development to ensure that criticality accident dosimetry continues to meet the demands of the nuclear manufacturing industries and the national regulators.

8. References

Adams, N. and Dennis, J. A., *"A new method of using gold foils for the investigation of the leakage spectra from critical assemblies"*, IAEA, Vienna (1963)

Anderson, J. et al. *"Neutron-activation analysis in man in vivo"*, The Lancet, December 5th, 1964, pp. 1201-1205

Delafield, H. J., *"Nuclear accident dosimetry"*, Radiat. Prot. Dos., **10**, pp. 237-249 (1985)

Formatted: Font: Bold

Formatted: Font: Bold

Formatted: Font: Bold

Delafield, H. J. *et al.*, *"Nuclear accident dosimetry: Part 1 – General principles"*, Report AERE-R7485, HMSO, London (1973)

Dennis, J. A., *"Neutron dosimetry using activation techniques"*, Report AERE–R4277, HMSO, London (1963)

Devine, R. T., *"Computation of cross sections and dose conversion factors for criticality accident dosimetry"*, Radiat. Prot. Dos., **110** (1-4), pp. 491-495 (2004)

Endo, A., *"Dose assessment in the criticality accident in Tokai-mura"*, Radiat. Meas., **45**, pp. 1484-1489 (2010)

Gibson, J. A. B. *et al.*, *"Nuclear accident dosimetry – Report on the 4th IAEA intercomparison experiment at Harwell, UK – 7th-18th April 1975"*, Report AERE-R8520, HMSO, London (1976)

Health and Safety Executive, *"Requirements for the approval of dosimetry services under the Ionising Radiations Regulations 1999, Part 1: External radiations"*, RADS 1/2008, HSE (2008)

Hill, R. L. **and Conrady**, M. M., *"PNNL results from 2009 SILENE criticality accident dosimeter intercomparison exercise"*, Pacific Northwest National Laboratory, PNNL-19503 (2010)

Holt, P. D., *"Passive detectors for neutron fluence measurement"*, Radiat. Prot. Dos., **10**, pp. 251-264 (1985)

Inaba, J., *"Radiological and environmental aspects of the criticality accident in Tokai-mura"*, Radiat. Prot. Dos., **92** (1-3), pp. 239-246 (2000)

International Atomic Energy Agency, *"Dosimetry for Criticality Accident: A manual"*, Technical Report Series No. 211, IAEA, Vienna (1982)

International Atomic Energy Agency, *"Report on the preliminary fact-finding mission following the incident at the nuclear fuel processing facility in Tokaimura, Japan"*, IAEA, Vienna (1999)

International Atomic Energy Agency, *"The Criticality Accident in Sarov"*, IAEA STI/PUB/1106, IAEA, Vienna (2001)

International Commission on Radiation Units and Measurements, *"Determination of operational dose equivalent quantities for neutrons"*, ICRU 66 (2001)

Jones, T. D. *et al.*, *"Absorbed dose, dose equivalent and LET distributions in cylindrical phantoms irradiated by a collimated beam of mono-energetic neutrons"*, Health Phys., **21**, pp. 253 (1971)

McLaughlin, T. P. *et al*., *"A Review of Criticality Accidents"*, Los Alamos National Laboratory, Los Alamos, LA-13638 (2000)

Médioni, R. **and Delafield**, H. J., *"Criticality Accident Dosimetry: An international intercomparison at the SILENE reactor"*, Radiat. Prot. Dos., **70** (1-4), pp. 445-454 (1997)

Médioni, R. *et al.*, *"Criticality accident dosimetry systems: An international intercomparison at the SILENE reactor in 2002"*, Radiat. Prot. Dos., 110 (1-4), pp. 429-436 (2004)

Formatted: Font: Bold

Roy, L. *et al.*, *"International intercomparison for criticality dosimetry: The case of biological dosimetry"*, Radiat. Prot. Dos., **110** (1-4), pp. 471-476 (2004)

Formatted: Font: Bold

Savanier, L. *et al.*, *"Criticality accident dosimetry: International intercomparison exercises around SILENE and CALIBAN reactors"*, Proceedings of the International Conference on Nuclear Criticality (2011)

Formatted: Font: Bold

Smith, J. W. *et al.*, *"A criticality dose assessment system"*, IAEA, Vienna (1965)

Formatted: Font: Bold

Swaja, R. E. *et al.*, *"Performance characteristics of a high-level solid-state personnel dosimetry system in pulsed radiation environments"*, Radiat. Prot. Dos., **15**, pp. 109-115 (1986)

Formatted: Font: Bold

Takada, C. *et al.*, *"Recalibration of indium foil for personnel screening in criticality accidents"*, Radiat. Prot. Dos., **144** (1-4), pp. 575-579 (2011)

Formatted: Font: Bold

United Kingdom Atomic Energy Authority, *CRISIS: An expert assistant in criticality accident dosimetry assessment – User guide version 1.1"*, AEA Environment and Energy (1992)

Formatted: Font: Bold

United Kingdom Parliament, *"Ionising Radiations Regulations 1999*", HMSO, London (1999)

Formatted: Font: Bold

Ward, D. C., *"Sandia National Laboratory results for the 2010 criticality accident dosimetry exercise at the CALIBAN reactor, CEA Valduc, France"*, Sandia National Laboratories, Albuquerque, SAND2011-6416 (2010)

Formatted: Font: Bold