A Review of the Capstone Depleted Uranium Aerosol Characterization and Risk Assessment Program

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ABSTRACT

The Capstone Program consisted of the Capstone Depleted Uranium (DU) Aerosol Study, which characterised aerosols produced when DU munitions penetrate armoured vehicles, and its related risk assessments. The Capstone Human Health Risk Assessment (HHRA) applied the results to calculate radiation doses and peak uranium kidney concentrations to personnel in a struck vehicle and those who enter soon after (Level I exposures), and assessed the resulting radiation and chemical risks. Complementary assessments were made for personnel carrying out activities in and around struck vehicles afterwards, resulting from intakes of disturbed surface contamination (Level II and III exposures).

This review was conducted to assist the UK Ministry of Defence (MOD) in gaining an understanding of the implications of the Capstone Program, its results and interpretation, to identify any limitations of the studies and remaining data gaps, and to assess their relevance to MOD and the MOD DU Research Programme.

The Aerosol Study addressed two major data gaps: the source terms for exposure to airborne DU within a struck vehicle, immediately after impact and as a result of activities that resuspend surface contamination. It involved firing large calibre DU rounds mainly into the stripped shells of two types of US armoured vehicle inside an enclosure. It produced a wealth of information on the characteristics of aerosols produced when a DU penetrator pierces an armoured vehicle, and so enables more reliable assessments to be made of the hazards to personnel exposed to such aerosols than was previously possible.

From a UK perspective, the limitations largely relate to the scope of the studies, and major remaining gaps in data or understanding concern extrapolation to situations different from the test conditions.

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EXECUTIVE SUMMARY

Background
The first use by US (and UK) Armed Forces of large-calibre (LC), anti-armour depleted uranium (DU) kinetic energy (KE) penetrators was in the 1991 Gulf War (Operation Desert Storm, ODS). This demonstrated their effectiveness against armoured vehicles, and they have since been employed in conflicts in Bosnia (1994-5), Kosovo (1999), and Iraq (2003). However, since their use in 1991 there has been considerable discussion about the possible health effects resulting from the dispersal of uranium, because it is radioactive and chemically toxic. In particular, during ODS there were “friendly fire” incidents in which US armoured vehicles were struck by LC-DU munitions. These involved 6 Abrams tanks and 14 Bradley Fighting Vehicles (BFV) from which 104 crew survived. When a DU round penetrates armour, some of the penetrator metal burns or wears away forming DU oxide dust to which personnel can be exposed.

The Preface to the Capstone Summary Report states that: “The purpose of the Capstone effort was to provide a peer reviewed, rigorous scientific estimate of the health risks to military personnel in and around armoured vehicles perforated by a large caliber DU munition”. The Capstone Program had two main components: the Capstone DU Aerosols Study and the Human Health Risk Assessment (HHRA).


This review was conducted to assist the Ministry of Defence (MOD) in gaining an understanding of the implications of the Capstone studies, their results and interpretation, to identify any limitations of the report and remaining data gaps, and to assess their relevance to MOD and the MOD DU Research Programme. It was therefore carried out specifically from a UK perspective. Like the study itself, the review has limitations, partly arising through the desirability of producing it in a reasonably short time scale. It was also carried out from a position of having access only to the published Capstone Report and other information in the public domain, and was not refined, e.g., through discussion with those involved in the Capstone Program. Hence it is possible that the reviewer misunderstood aspects of the studies. The review does not aim to judge the Capstone Program against its own objectives, but against the wider requirements of assessing exposures to DU resulting from its use in weapons.

It is also influenced by the reviewer’s own research background, which is predominantly related to understanding the behaviour of inhaled radioactive particles. The reviewer was a member of the Royal Society’s Working Group (RSWG) on the health hazards of depleted uranium munitions, and within that group was particularly involved in assessing potential exposures to DU from its use on the battlefield, and the resulting uranium concentrations in tissues and radiation doses. Much of the Capstone Report is directly relevant to these matters, and therefore comparisons are made with the RSWG assessments, and the results were partly viewed in the light of the extent to which they filled research needs identified by the RSWG.
A feature of the programme was that it involved experts from different backgrounds and incorporated peer review at all stages. This combination of military and independent experts enabled very strong teams of expertise to be brought to bear on the problem, and also strengthened its credibility.

The Capstone Aerosols Study

The Capstone Aerosols Study involved the generation and characterisation of DU aerosols created by the perforation of an Abrams tank and a BFV with LC-DU penetrators. A series of tests was carried out in which LC-DU penetrators impacted target vehicles inside an enclosure (Main Text, Table 1). Phases I-III used a “Ballistic Hull and Turret” (BHT), a vehicle shell stripped of flammable material, instrumentation etc. In particular, the BHT had no ventilation system. Phase IV used an operational Abrams tank.

Phase I (Abrams tank BHT with conventional armour) consisted of seven shots. Four shots crossed the turret (two of them 13 minutes apart in a single test, i.e., a double shot), two were fired into the gun breech (to maximise aerosol formation), and one was fired into the hull.

Phase II (BFV BHT) consisted of three shots: two of them 14 minutes apart in a single test through the scout compartment, and one through the turret to maximise aerosol formation.

Phase III (Abrams tank BHT with DU armour) consisted of two shots, both through the DU armour fitted to the turret.

Phase IV (operational Abrams tank with DU armour) consisted of four shots. Three were firings of non-DU munitions. One was more relevant, involving a DU penetrator fired through DU armour. It therefore enabled a comparison to be made of a BHT (Phase III) with an operational vehicle.

Three shots were retrospective, simulating ODS incidents, while the others were prospective, providing information for possible future incidents.

Extensive sampling and aerosol characterisation were carried out. In Phases I-III, there were four main sampling positions within the vehicle, corresponding to the four tank crew: commander, driver, gunner, and loader. At each position nine pairs of air samplers were run in a pre-set time sequence starting 5 seconds after impact (to avoid damage from blast and fragments). Each pair consisted of a filter that collected total aerosol (all the airborne particles in the volume of air drawn through it), and a cascade impactor (CI) which separated the particles collected into nine fractions according to their “aerodynamic” diameter (which takes account not only of physical dimensions but also density and shape). Thus DU air concentrations and aerodynamic size distributions were obtained as functions of time.

In addition, two other types of air sampler were operated inside the vehicle. One was a moving filter sampler (MVF), which collected particles on a tape of filter that was wound past the sampler inlet, and which started immediately after impact. The other was a cascade cyclone, which provided much larger amounts of sized material than the CI, but collected a single set of samples over the entire period from 5 seconds to 2 hours after
impact. The Phase IV tests were not designed specifically to evaluate DU aerosols, and space for samplers was restricted. Some sampling was carried out in three tests. Typically five CI were attached to mannequins at the driver and loader positions, with the MVF and cyclone in the driver’s compartment.

To provide information on particle shape, structure and composition, some samples were analysed by x-ray dispersion (XRD), others by scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS). To provide material-specific information to characterise absorption of uranium into circulating body fluids from particles deposited in the lungs, in vitro dissolution tests were carried out on 27 samples, mainly from cascade cyclone stages.

Aerosol measurements were also carried out during recovery operations several hours after impact. Some personnel wore personal CI, and for two shots (in Phase I) the loader’s sampling array was used. Some personnel also wore cotton gloves, which were measured to provide information for assessing inadvertent ingestion through hand-to-mouth transfer.

Extensive wipe sample surveys were conducted inside and outside the vehicle to assess removable surface contamination. Some were complemented by surveys using portable radiation monitoring instruments to evaluate their capability for monitoring DU contamination. Some were carried out after decontamination procedures to evaluate their effectiveness.

Some air sampling was conducted outside the vehicle, using high volume air samplers and CI, but only a few samples were taken in each test. The priority of the study was to obtain information on aerosols within the vehicle, and this determined its location within an enclosure. However, the presence of the enclosure limited the value of aerosol data collected outside the vehicle.

The Capstone Aerosol Study mainly addressed what were recognised to be two of the main data gaps for the assessment of the hazards of the use of DU munitions: the source terms for exposure to airborne DU within a penetrated vehicle, immediately after impact, and as a result of later activities that resuspend surface contamination.

Although it was based on recommendations from assessments made by the US military authorities, the study directly addresses the first two recommendations of the RSWG’s first report (Royal Society, 2001):

- “further test firings under realistic conditions into heavily- armoured vehicles to provide better estimates of the levels of DU, and the properties of DU aerosols, within and released from struck vehicles;
- experimental information on resuspension from surfaces in contaminated vehicles to enable reliable assessments to be made of exposures resulting from various forms of entry into struck vehicles and enable recommendations to be made for appropriate precautions to be taken by service personnel and civilians”

The study produced a wealth of information on the characteristics of aerosols produced inside an armoured vehicle when pierced by a DU penetrator. It is far more comprehensive than all other published studies put together. It thereby enables more
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reliable assessments to be made of the hazards to personnel exposed to such aerosols than was hitherto possible. Major achievements and findings included:

- Development of systems to characterise the aerosol produced inside an armoured vehicle when pierced by a DU penetrator, taking account of the hostile environment directly after the penetrator impact (blast, heat, fragments etc), the high initial air concentration and its rapid decrease.

- Successful collection of data on DU air concentration and size distribution as a function of time after impact and position within the vehicle, for several different shot lines within the same vehicle, and for a few different vehicle types. The comprehensive data collected from each shot, and the combination of results from different shots carried out within a co-ordinated programme enables inferences to be made about variability in concentration and size distribution that can arise.

- The initial DU air concentrations in the test vehicle configurations without ventilation were very high, of order grams per cubic metre, consistent with the results of previous, but more limited, impact tests.

- For the Abrams tank with its ventilation/air filtration system operating, the initial concentration was about two orders of magnitude lower than for an unventilated tank.

- The initial DU air concentration in the vehicle increased (as expected) with the hardness of the target, but over a relatively small range.

- The exposure from a ‘double shot’ (two hits which both penetrate the vehicle armour) can be assessed simply as twice that from a single shot.

- The fraction of the penetrator converted to DU aerosol was estimated to range between a maximum of 1% for the lighter armoured BFV to a maximum of 7% inside the heavily armoured Abrams tank, consistent with results of other more recent studies, and making the earlier estimates above 10% seem less likely to be realistic.

- For all the configurations there was not much difference between the average DU air concentrations at 10 seconds, 30 seconds and 1 minute after impact. The concentration at 30 minutes was much lower: by a factor between 10 and 300 times.

- The first measurements of aerosol size distribution, made within the first minute, showed most of the DU to be associated with particles of a few microns or a few tens of microns diameter, which would be largely non-respirable. However, most subsequent measurements showed most of the DU to be associated with particles of about 1 micron diameter, which would be largely respirable. Again, this is consistent with the results of previous, but more limited, impact tests.

- Extensive complementary measurements were made of particle structure and composition, and properties such as dissolution rate.

- Measurements of the dissolution of samples showed that a fraction (1-28%) dissolved rapidly (in about a day) and the rest with half times between 70 and 1700
days. Again, this is broadly consistent with the results of previous, but more limited, impact tests.

- Measurements were made of ventilation rates in vehicles, according to the extent of natural and forced ventilation. It was inferred that vehicle ventilation is probably a major factor in reducing the DU air concentration, and hence the exposure of personnel.

- Measurements were made of aerosols formed by resuspension of surface deposits, as a result of activities carried out by personnel a few hours after an impact. DU air concentrations resulting from recovery activities were found to be very variable, and related as much to the activities being carried out as to the level of surface contamination.

- Extensive measurements of surface contamination were made, and good correlation was found between the results of wipe tests and radiation survey instruments.

- Presentation of the study and its results in full detail, including description of problems (and occasional errors) with remarkable candour. This detailed reporting and openness increases confidence in the results, and provides valuable information for those carrying out assessments based on the results and for those who might be involved in conducting similar tests in future.

In considering what might be regarded as ‘limitations’ or ‘shortcomings’ of the Aerosol Study, it should be recognised that resources and time-scale for completion and reporting were finite. As noted above, the review does not judge the Capstone Program against it own objectives, but against the wider requirements of assessing exposures to DU resulting from its use in weapons, and from a UK perspective. Priority in the Capstone Study was presumably given to what were regarded as the most important data gaps relevant to US interests, which included situations that might lead to the highest exposures in future. In the opinion of this reviewer, the main limitations of the Capstone Aerosol Study relate to its scope:

- The Capstone Study tested only large calibre DU rounds, and no consideration is given in the report to the small calibre rounds such as those fired from aircraft.

- Most of the aerosol data were obtained in the “Ballistic Hull and Turret” (BHT, stripped shell) of a US Abrams Tank and a Bradley Fighting Vehicle (BFV). Extrapolation to operational vehicles in general, and to UK vehicles in particular remains an issue.

- The RSWG recommendation: “the development and validation of models to enable DU exposures to be predicted in a wide range of circumstances”, was only addressed to a limited extent. (It is more important in the UK context, because of the need to extrapolate to vehicles different from those used in the tests.) One test (Phase IV) made in an operational Abrams tank gave much lower DU concentrations than in the corresponding BHT, and this was attributed to operation of its ventilation/air filtration system. As noted above, measurements were made of ventilation rates in different vehicle configurations, although attempts to measure ventilation rates in vehicles after DU penetrator impacts were unsuccessful. To
make best use of the results in assessing exposures in other situations requires a model of some sort, but none is presented as part of the Aerosol Study. A simple model to take account of vehicle ventilation is presented in the HHRA report. It appeared to work well when tested against the trial on a ventilated vehicle. However, it was not applied in the HHRA to produce estimates of exposure in ventilated vehicles.

- Ideally the Capstone Report would have included a comparison with previous studies of the characteristics of aerosols formed when a DU penetrator impacts on armour plate. (It is a common feature of the “Discussion” section of a research report.) The authors were well placed to do this, especially as some were involved in the previous studies.

In the opinion of this reviewer, the studies were well conducted, especially considering the constraints imposed by the experimental conditions. A number of problems were identified by the Capstone team, which led to changes in procedures during the course of the study. They are described in the Capstone Report (and summarised in Section 2.10.1 of this review). While the comment is made here that some of these might have been avoided (i.e., the revised procedures implemented from the outset) if it had been possible to conduct a pilot trial (or trials) in advance of the main programme, none would appear to have an important effect on the results or their application in risk assessments. Some other issues were identified by the reviewer and for completeness they are summarised in Section 2.10.2 of this review. Again, most are not expected to have an important effect on the results or their application. However, two issues are noted here as being of greater significance and so meriting further attention:

- Reliance was placed on in vitro dissolution tests to quantify DU particle dissolution in the human lung. Although dissolution rates were measured for twenty-seven samples, which usefully covered a range of sizes and times after impact, the measurements were all made in “simulated lung fluid”, and over a relatively short period (46 days), at the end of which most (50-90%) of the sample remained undissolved. The issue of extrapolation to human lung clearance was not discussed. It was noted in the RSWG Report, which recommended: “long-term in vivo studies of the dissolution of DU oxides formed from penetrator impacts and fires involving DU. These are needed to assess doses from inhalation prospectively, and, more importantly, to assess intakes and doses (especially lung and thoracic lymph node doses) from urine samples. Doses to thoracic lymph nodes are especially sensitive to the long-term dissolution rate of DU oxides in the lungs and lymph nodes”. This issue therefore remains open.

- Measurements of DU air concentrations produced by resuspension of surface contamination showed great variability, a lack of correlation between surface and air contamination levels, and in particular a large difference between measurements made with personal samplers worn by the recovery personnel, and those measured by static arrays. These measurements were much more comprehensive than any others previously available, but the main finding seems to be the extent of the variability, rather than reliable representative values for dose and risk assessment purposes.
EXECUTIVE SUMMARY

The Capstone Human Health Risk Assessment (HHRA)
The overall objectives of the HHRA were to give guidance on whether the health risks to Level I personnel are high enough to warrant changes in medical policy or in personal protective measures. This involved several steps:

- Developing exposure scenarios for the Level I exposure group.
- Developing intake parameters, source terms (from the Capstone Aerosol Study) and physiological data (breathing rates) for use in modelling.
- Using current internationally recognised models to calculate radiation doses and peak uranium kidney concentrations.
- Using information from the published literature to establish the relationships between doses/concentrations and health effects.
- Assessing the chemical and radiological risks for the Level I scenarios using appropriate risk models.
- Making recommendations for military risk management and for further actions.
- Using good risk communication to provide the estimated risks of DU exposure so that appropriate decisions can be made.

A complementary assessment (Attachment 4) applied data from the Aerosol Study to calculate corresponding outcomes for personnel carrying out activities later, as a result of inhalation of resuspended surface contamination and ingestion through hand-to-mouth transfer (Level II and III).

Generally, the HHRA and Attachment 4 used standard, internationally recognised methods and relevant parameter values to assess radiation doses and associated risks, and peak uranium kidney concentrations. These are the current ICRP (International Commission on Radiological Protection) biokinetic models (which describe quantitatively the distribution and retention of uranium in different body tissues after inhalation or ingestion) the current ICRP dosimetric models (which identify target cells within tissues, and quantify the amount of ionising radiation energy absorbed in the target tissues from the radioactive decay of uranium in the source tissues where it is located), and ICRP risk factors for the irradiated tissues, where available. The reviewer considers this to be current best practice, as used for example by the RSWG in its assessments, and that indeed any other approach would be difficult to justify at this time.

In some respects the Capstone assessments go beyond what might be regarded as minimum requirements for applying the ICRP methodology, but do so in a way consistent with the ICRP principles and guidance on applying the models to specific situations. These are regarded by the reviewer as specific achievements, made feasible by the comprehensive data obtained in the aerosol study, and include the following:

- For convenience, the ICRP Human Respiratory Tract Model (HRTM) provides values of the fraction of inhaled material deposited in each region of the respiratory tract, for aerosols with log-normal size distributions (as functions of the characteristic parameters, the median and geometric standard deviation, GSD of the distribution).
However, the aerosols produced in the Capstone Aerosol study were not well fit by lognormal particle size distributions. To calculate respiratory tract deposition with the HRTM, the masses of uranium collected on each size-specific stage of the cascade impactors were used directly. The aerosol was thus treated as a combination of nine aerosols: one for each stage. This required more calculations, but made best use of the available information, and the approach might well be applied elsewhere.

- The HRTM recognises that dissolution of material deposited in the lungs is time dependent, and represents this simply by assuming that a fraction dissolves relatively rapidly, at one constant rate, and the rest dissolves more slowly at another lower rate. Provision is made in the HRTM for two fractions, to avoid undue complexity, because it was considered that there would not normally be sufficient information to justify more. However, the Capstone dissolution data were usually represented by three components, and additional calculations were made to use that information.

- A sophisticated Bayesian approach was used to calculate distributions of possible doses to personnel, based on the results of the Capstone Aerosol Study. This included calculating doses for each shot and sampling position.

- The HHRA concluded that the most important factor for reducing exposure and dose discovered in the analysis was the use of onboard vehicle ventilation.

- The HHRA concluded that because of differences in individual exposures for crew in a perforated vehicle, DU bioassays are needed to establish individual dose estimates. The report provides information that can be used for deciding when individual monitoring (bioassay) should be implemented.

- Although the HHRA used internationally recognised (ICRP) risk factors where available for assessing radiation-induced cancer risks for each tissue considered important (in terms of radiation exposure or sensitivity), special consideration (by review of the current literature) was given to lung cancer risks, because risks to other tissues were calculated to be much lower. Risks of radiation-induced cancer were also assessed for kidney and the extrathoracic airways, although ICRP has not provided specific risk factors for these tissues.

- The HHRA recognised that the risks needed to be put into an appropriate framework that applies to the various risks of combat, so that field commanders can include them in mission risk analysis and management. The existing Radiation Exposure Status (RES) categories used to track the total radiation dose received by a combat unit are based on external gamma exposures. The HHRA modified the RES approach to make it applicable to internal DU deposition and its related dose, by comparing the calculated risks of cancer from external gamma and internal alpha radiation from DU.

- To assess the chemical toxicity risks, the HHRA extended and developed the approach taken by the RSWG, which was to correlate observed renal effects in humans after acute exposures with the calculated peak kidney uranium concentrations. Some additional cases were added, and the results used to develop a set of “Renal Effects Groups (REGs)” correlating uranium concentration in the
kidneys with renal effects. Because there is no system similar to the RES categories developed for chemical toxicity, the HHRA used the REG chemical risk model to perform a similar function.

As noted above with regard to the Aerosol Study, in considering what might be regarded as ‘limitations’ or ‘shortcomings’ of the HHRA (Level I) and the Attachment 4 risk assessments (Level II & III), it should be recognised that resources and time-scale for completion and reporting were finite. Similarly, this review judges the assessments against the broad requirements of assessing exposures to DU resulting from its use in weapons from a UK perspective. In this reviewer’s opinion, as for the Aerosol Study, limitations of the HHRA relate more to the scope, than to the methods used:

- The assessment does not consider exposures and risks to personnel (or the public) outside the struck vehicle from the initial plume (dust cloud) produced by the impact, except to note that they would be lower than to those inside the vehicle. This is of greater importance since the 2003 Iraq war, because of the public perception, at least, that there was more use of DU weapons in urban areas than there was in ODS. From a UK perspective, the ability to make such assessments is limited by the “restricted” distribution of the report on the study most relevant to this issue.

- Evaluation of the health risks from embedded fragments and wound contamination was stated to be beyond the scope of the HHRA. However, these are potential exposure pathways for Level I personnel, and so for completeness they would have been addressed, at least by a comprehensive review of the current literature.

- The assessments are restricted to the situations (shots, vehicles ventilation, sampling positions) actually investigated in the Capstone Aerosol Study. Most of these seemed to have been designed to maximise the DU air concentration within the vehicle by maximising aerosol production through hitting a particularly massive target, and minimising dilution through ventilation. Although a simple model is described to estimate the reduction in DU air concentration resulting from ventilation, it is not applied to assess the likely range of exposures that might occur in practice as a result of ventilation.

- Thus the modelling considers worst-case exposures and intakes, but the subsequent stages of the HHRA (calculations of doses and risks from the intakes) appear to be based on modelling using central estimates of parameter values. Care is therefore needed to interpret what is meant by e.g. "Most likely scenario", which is used to refer to a short stay time, but no ventilation.

- The only factors included in the HHRA uncertainty analysis were those that could readily be quantified from the Capstone Aerosol Study: measurement uncertainties and variability in the measured data. It did not for example include modelling uncertainties. A full uncertainty analysis would be needed to assess the overall distributions of potential doses and risks, and would also be useful in identifying the contributions to overall uncertainty made by all the factors involved and hence providing guidance on options for reducing uncertainties by further study.

- Although reviews were conducted of the literature relating to radiation and chemical effects, these were limited to reasonable complementary studies, consistent with
their role in support of the main effort, which was to apply the results of the Capstone Aerosol Study. The reviewer’s opinion is that they are not exhaustive studies, as for example recommended by the RSWG with respect to the lymph nodes: a thorough review of the effects of radiation from radioactive particles retained in lymph nodes, including any possible carcinogenic effects. Thus the need remains for a project on Health Effects identified in the MOD DU research programme.

- Although the HHRA concluded that because of differences in individual Level I exposures for crew in a perforated vehicle, DU bioassays are needed to establish individual dose estimates, no similar recommendation is made with regard to Level II exposures. Nevertheless, the lack of correlation between surface contamination and airborne activity demonstrated the difficulty in assessing potential exposures from surface contamination measurements, and the potential intake from an hour’s exposure based on the area monitor measurements is of the order of 10 mg, leading to a committed effective dose of about 1 mSv.

There are similarities in scope and approach to the assessment carried out by the RSWG. Both assessments set up a set of exposure scenarios; estimated intakes and exposure parameter values based on available experimental data; used the same current international models to calculate tissue concentrations of uranium and radiation doses; reviewed the literature to assess radiation and chemical risks associated with DU intakes; assessed risks to exposed personnel; and made recommendations for further action and research. The HHRA was narrower in scope in that the Royal Society assessment considered Level I, II and III exposures. The Royal Society assessment considered all routes of intake, external exposure, etc. It also addressed, in Part II, the longer term environmental impact resulting from the dispersal of DU from both penetrator impacts and penetrators that missed their targets. The HHRA, however, went deeper, in having the comprehensive Aerosol Study database to draw on, and assessed doses and risks for each scenario, shot, and sampling position. It was thus able to build up distributions of intakes, doses and risks, based on the distributions of original data; and measurement uncertainties.

Comparison of the results is not straightforward, because there are differences in what is meant by “central estimate” and “worst case” by the RSWG and the HHRA.

The Capstone Aerosol Study clearly provides scope for updating the RSWG assessment, using its more robust and comprehensive data for the source terms for both Level I and Level II exposures. It is quite possible that this would result in lower assessed intakes and risks. For example, in the RSWG Level I “worst case”, the initial concentration assumed (50 g m⁻³) is a few times higher than the highest measured, even though shots were designed to maximise aerosol production (although this might be partly offset by consideration of multiple hits). However, the filling of this data gap shifts the emphasis onto another major source of uncertainty, that of extrapolation to other vehicles, the effect of ventilation, etc. The Capstone Study identified ventilation as probably a major factor determining the rate of decrease in concentration within a vehicle, and this would have implications for the central estimate.
The conclusions of this review essentially reflect the reviewer’s opinions of achievements and the limitations of the Capstone Program as listed above.

Its recommendation is an extension of one of those made by the RSWG in Part 1 of its report in 2001: “An independent and fully resourced assessment of the risks, particularly from Level I and II exposures, ensuring that all of the data are available, including restricted material not available to us, and data from any new test firings.”

Consideration should be given to updating the assessments carried out by the RSWG but this should take into account not only the results of the Capstone Program, but those of other studies carried out in the last few years, and in particular those from the MOD’s own research programme on DU, which is due to be completed in March 2006. The RSWG assessment made “central” estimates of exposure for each scenario, which might be used to assess the overall impact on health, and “worst case” estimates, which it was unlikely that any individual would exceed. Since the Capstone Aerosol Study aimed to maximise aerosol production, re-assessment of “worst case” estimates should be relatively straightforward. Reassessment of the “central” estimate making best use of the available information, however, should include consideration of extrapolation of the results to UK vehicles, and issues such as ventilation rates in operational vehicles. Hence a multi-disciplinary team involving both independent expertise (on e.g. biokinetics and risks) and military expertise (on e.g. armoured vehicle operation) might be most effective to conduct such a reassessment. Such a team could well consider the remaining data gaps, and the studies required to address them.
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1 INTRODUCTION

1.1 Background

The use of depleted uranium (DU) munitions in the 1991 Gulf War (Operation Desert Storm, ODS) demonstrated their effectiveness against armoured vehicles, and they have since been employed in conflicts in Bosnia (1994-5), Kosovo (1999), and Iraq (2003). However, since their use in 1991 there has been considerable discussion about the possible health effects resulting from the dispersal of uranium, because it is radioactive and chemically toxic.

The relevant DU munitions are kinetic energy penetrators, which are rods of DU metal (alloyed with 0.75% titanium), with a nose cone and tail fins for stability in flight, fired at very high velocity (up to 1800 m s\(^{-1}\)). Large calibre (LC, 100- or 120-mm) rounds fired by tanks have DU masses of 4-5 kg. Small calibre rounds are also used, notably the 30-mm rounds used by the GAU-8 Gatling gun of the US A-10 aircraft, which have masses of about 0.3 kg.

During ODS, there were “friendly fire” incidents in which US armoured vehicles were struck by large calibre depleted uranium (LC-DU) rounds. These involved 6 Abrams tanks and 14 Bradley Fighting Vehicles (BFV) from which 104 crew survived. When a DU round penetrates armour, some of the penetrator metal “erodes” (burns or wears away) forming DU oxide dust to which crew are exposed.

Detailed assessments of the exposure of personnel on the battlefield have been carried out, notably by the Royal Society’s Working Group (RSWG) on the health hazards of depleted uranium munitions (Royal Society, 2001, 2002), and by the US Army Center for Health Promotion and Preventive Medicine (USACHPPM, 2000) directed by the US Office of the Special Assistant to the Deputy Secretary of Defence for Gulf War Illnesses (OSAGWI). Both these assessments, following a review by OSAGWI (2000), identified three broad classes of potential exposure.

Level I includes exposures of personnel in or on a vehicle that is struck by a DU penetrator, or personnel (“first responders”) entering immediately, typically to assist injured comrades. It is assumed that exposure is dominated by inhalation of the aerosol generated by the impact, and by embedded DU fragments (“shrapnel”).

Level II exposures occur after the initial aerosol generated by the impact has dispersed and settled. It includes exposures of personnel working in or on contaminated vehicles, typically to carry out repairs. It is assumed that exposure is dominated by inhalation of aerosols resuspended by their activities, but ingestion through hand to mouth transfer from contaminated surfaces is also considered.

Level III includes all other exposures, for example inhalation downwind of an impact or fire, or brief entry into a contaminated vehicle.

The USACHPPM (2000) assessment included identification of data gaps and determination of future research needs. It concluded that the personnel exposure data were relatively robust except for the data required to estimate exposures for those
personnel in, on, or near (within 50 metres) an armoured vehicle when it was perforated by a DU munition or DU armour perforated by any munition (Level I). To fill this gap, the US Army and OSAGWI sponsored the Capstone DU Aerosol Characterization and Risk Assessment Program.


As stated in the Preface to the Capstone Summary Report: “The purpose of the Capstone effort was to provide a peer reviewed, rigorous scientific estimate of the health risks to military personnel in and around armoured vehicles perforated by a large caliber DU munition”. There are, however, some differences in the objectives as stated in different places in the Capstone Report (here taken to refer to the set of documents posted at [wwwdeploymentlink.osd.mil/du_library/du_capstone/index.pdf](http://wwwdeploymentlink.osd.mil/du_library/du_capstone/index.pdf)). In the Capstone Program as reported, the emphasis was on exposures within the struck vehicle, and on shots intended to maximise aerosol production within it, and hence give guidance on the maximum potential exposure of personnel.

In the context of this review, the Capstone Program’s objectives are a part of the background to the work. The review does not aim to judge the Capstone Program against its own objectives, but against the wider requirements of assessing exposures to DU resulting from its use in weapons. It considers the results of the Capstone Program from a UK perspective, and thus the extent to which it fills gaps in information identified by assessments such as that carried out by the RSWG. A notable difference in perspective from that of the authors of the Capstone Report is that some of the important references cited are not available to the reviewer, because their distribution is “restricted”. Similarly, they were not available to the RSWG, as was noted in its reports. In particular, the report of Fliszar et al (1989), is often cited in the Capstone Report, and is regarded as the most valuable source of information on exposures downwind of a struck vehicle. The issue of restricted documents is discussed further in Section 3.17.2.

The Capstone Programme had two major components: the Capstone DU Aerosols Study and the Human Health Risk Assessment (HHRA). The Capstone DU Aerosols Study involved the generation and characterisation of DU aerosols created by the perforation of an Abrams tank and a BFV with a LC-DU penetrator. The HHRA estimated the radiation doses and uranium concentrations in the body resulting from exposure to such aerosols using internationally recognised models, and from them estimated the resulting risks to health.

A feature of the programme was that it involved experts from different backgrounds and incorporated peer review at all stages. Thus, the Summary to Attachment 1, Pages iv-v, states: “The project staff... consisted of Army health physicists and engineers ... Collaborators from outside the Army included health physicists, aerosol specialists, and instrument engineers from Lovelace Respiratory Research Institute (LRRI), Los Alamos National Laboratory (LANL), and PNNL. An Army steering committee ... guided the overall test objectives and test implementation. The US Army Medical Command (MEDCOM) developed a set of Data Quality Objectives (DQOs) for the specific
information to be derived from this testing program. An independent nine-member peer review panel provided technical feedback on the project plans and the draft report."

This combination of military and independent experts enabled very strong teams of expertise to be brought to bear on the problem, and also strengthened its credibility. Several members of the peer review panel and some of the report authors are known to this reviewer by their reputations outside the topic of DU.

1.2 The Capstone DU Aerosols Study

A series of tests was carried out in which LC-DU penetrators impacted target vehicles inside an enclosure (the “Superbox” facility at Aberdeen Proving Ground, MD). The tests were divided into four Phases (I – IV), each with a different target vehicle. Phases I-III used a “Ballistic Hull and Turret” (BHT), a vehicle shell stripped of flammable material, instrumentation etc. In particular, the BHT had no ventilation system. Phase IV used an operational Abrams tank with DU armour. There were between two and seven shots fired in each Phase (Table 1). Thus PI-6 refers to shot 6 from Phase I.

- Phase I (Abrams tank BHT without DU armour). Seven shots: PI-1, PI-2, PI-3/4 (two shots 13 minutes apart), crossed turret; PI-5, PI-6 into gun breech, PI-7 into hull.
- Phase II (BFV BHT) Three shots: PII-1/2 (two shots 14 minutes apart) through scout compartment, and PII-3 through turret.
- Phase III (Abrams tank BHT with DU armour). Two shots: PIII-1 and PIII-2, both through the DU armour fitted to the turret.
- Phase IV (operational Abrams tank with DU armour). Four shots: PIV-1 to PIV-3 Non-DU munitions; PIV-4 DU penetrator on DU armour.

Shots PI-7, PII-1/2, and PII-3 were retrospective, simulating ODS incidents (Attachment 1 Table 5.1). Others were prospective, providing information for possible future incidents. Some were intended to provide reasonable upper bounds of aerosol concentration.

Extensive aerosol sampling and characterisation was carried out. In Phases I-III, there were four sampling positions within the vehicle. In Phases I and III they corresponded to the four tank crew: commander, driver, gunner, loader. In Phase II the right and left scout positions replaced (but in sample identification are referred to as) “gunner” and “loader” respectively. At each position, nine sequential filters (total aerosol) and nine (8-stage) cascade impactors (CI) to provide size distributions, including activity median aerodynamic diameters (AMAD), were run, starting 5 seconds after impact. In addition, a moving filter (MVF) sampler (which started immediately after impact), and a cascade cyclone (providing larger amounts of sized material) were run.

Additional measurements were made, including: deposition in trays, wipe tests, aerosols resuspended by personnel entering the vehicles to collect samples etc., ventilation rates, and some sampling outside the vehicle. Some samples were analysed by x-ray dispersion (XRD), others by scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS). In vitro dissolution tests were carried out on 27 samples, mainly from cyclone stages and back-up filters. Retention of undissolved DU was fit by two- or three-component exponential functions.
## Table 1: Overview of Capstone test shots (based on Attachment 1, Tables 5.1, 5.4, and Appendix A, Table A1.)

<table>
<thead>
<tr>
<th>Shot</th>
<th>Shot type</th>
<th>Retro- / Prospective</th>
<th>IOM Intact/total</th>
<th>Cy-clone</th>
<th>MVF</th>
<th>Resuspension</th>
<th>Vehicle venting (hatches opened)</th>
<th>External CIs</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase I A</td>
<td>Abrams Ballistic Hull and Turret (BHT) without DU armour</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PI-1</td>
<td>Turret cross</td>
<td>P</td>
<td>18/36</td>
<td>36</td>
<td>1</td>
<td>Part</td>
<td>No</td>
<td>Driver’s</td>
<td>Commander and Gunner IOMs damaged. Longest sampling duration</td>
</tr>
<tr>
<td>PI-2</td>
<td>Turret cross (as PI-1)</td>
<td>P</td>
<td>20/36</td>
<td>36</td>
<td>1</td>
<td>0</td>
<td>No</td>
<td>Loader’s</td>
<td>One or more IOMs damaged in each array</td>
</tr>
<tr>
<td>PI-3/4</td>
<td>Turret cross</td>
<td>P</td>
<td>30/36</td>
<td>36</td>
<td>1</td>
<td>Part</td>
<td>No</td>
<td>Loader’s (rose and fell)</td>
<td>Two shots on similar lines, 14 minutes apart. Loader shield opened too soon. Samplers damaged.</td>
</tr>
<tr>
<td>PI-5</td>
<td>Into breech</td>
<td>P</td>
<td>27/27</td>
<td>27</td>
<td>0</td>
<td>0</td>
<td>No</td>
<td>Commander’s, loader’s open a crack</td>
<td>1</td>
</tr>
<tr>
<td>PI-6</td>
<td>Into breech (as PI-5)</td>
<td>P</td>
<td>27/27</td>
<td>27</td>
<td>1</td>
<td>0</td>
<td>Yes</td>
<td>Commander’s, loader’s open a crack</td>
<td>2</td>
</tr>
<tr>
<td>PI-7</td>
<td>Through hull</td>
<td>R</td>
<td>35/36</td>
<td>36</td>
<td>1</td>
<td>0</td>
<td>Yes</td>
<td>Commander’s raised an inch</td>
<td>2</td>
</tr>
<tr>
<td>Phase II B</td>
<td>Bradley Fighting Vehicles (BFV) BHT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PII-1/2</td>
<td>Scout compartment</td>
<td>R</td>
<td>36/36</td>
<td>36</td>
<td>1</td>
<td>0</td>
<td>No</td>
<td>Hatches intact, small venting losses</td>
<td>2</td>
</tr>
<tr>
<td>PII-3</td>
<td>Turret</td>
<td>R</td>
<td>36/36</td>
<td>36</td>
<td>1</td>
<td>1</td>
<td>No</td>
<td>TOW missile</td>
<td>Right scout shield opened only partially.</td>
</tr>
<tr>
<td>Phase III A</td>
<td>Abrams BHT with DU armour</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PIII-1</td>
<td>Turret/DU armour</td>
<td>P</td>
<td>36/36</td>
<td>36</td>
<td>1</td>
<td>1</td>
<td>No</td>
<td>Loader’s hatch perimeter, Gunners Primary Sight (GPS)</td>
<td>2</td>
</tr>
<tr>
<td>PIII-2</td>
<td>Turret/DU armour</td>
<td>P</td>
<td>35/36</td>
<td>36</td>
<td>1</td>
<td>1</td>
<td>No</td>
<td>Loader’s hatch briefly (GPS)</td>
<td>2</td>
</tr>
<tr>
<td>Phase IV</td>
<td>Operational Abrams tank with DU armour. Information taken from Attachment 1, Section 4.4. These tests were not designed specifically to evaluate DU aerosols, and space for samplers was restricted. Some sampling was carried out in three tests. Typically 4 or 5 CI attached to mannequins at driver and loader positions. Moving filter (MVF) and cyclone in driver’s compartment.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PIV-1</td>
<td>Non-DU munition</td>
<td>P</td>
<td>0</td>
<td>9</td>
<td>1</td>
<td>1</td>
<td>No</td>
<td>As planned, target not penetrated</td>
<td>0</td>
</tr>
<tr>
<td>PIV-2</td>
<td>Non-DU munition</td>
<td>P</td>
<td>0</td>
<td>9</td>
<td>1</td>
<td>0</td>
<td>No</td>
<td>Crew compartment not penetrated</td>
<td>0</td>
</tr>
<tr>
<td>PIV-3</td>
<td>Non-DU munition</td>
<td>P</td>
<td>0</td>
<td>9</td>
<td>1</td>
<td>1</td>
<td>No</td>
<td>Crew compartment perforated</td>
<td>0</td>
</tr>
<tr>
<td>PIV-4</td>
<td>DU munition</td>
<td>P</td>
<td>0</td>
<td>5/9</td>
<td>0</td>
<td>1</td>
<td>No</td>
<td>Perforated DU armour and entered crew compartment</td>
<td>0</td>
</tr>
</tbody>
</table>

IOM = Institute of Medicine personal air sampler. CI = Cascade impactor. MVF = Moving filter.
1.3 Human Health Risk Assessment (HHRA)

The stated overall objective of the Human Health Risk Assessment (HHRA) was to use the data generated in the Capstone study to develop health risk assessments that the Department of Defense (DoD) could use in answering three primary questions as it reviews its internal policies. Are the health risks to the following groups high enough to warrant changes in the medical policy, in the medical treatment and medical monitoring, and in personnel protective measures for soldiers potentially exposed to DU?

- Personnel in, on, or near an armoured vehicle at the time the crew compartment is perforated by DU munitions,
- Personnel who enter the armoured vehicle still with residual aerosolised DU and also resuspended DU in the air following the initial perforation of an armoured vehicle crew compartment,
- Personnel who entered an armoured vehicle well after the vehicle was perforated by DU munitions and who re-suspended DU into the air.

The HHRA involved the assessment of radiation doses and maximum kidney concentrations to personnel exposed inside vehicles to the aerosol produced by the impact (“Level 1”). (No specific assessments were made in the HHRA of exposures outside vehicles.) For this purpose five Level 1 exposure scenarios were defined (Table 2). Four (A – D) were for crew inside the vehicle at the time of impact, with exposure duration before exit of 1 minute, 5 minutes, 1 hour or 2 hours. The fifth (E) was for first responders entering 5 minutes after impact and exiting 10 minutes later. The Capstone DU Aerosol Study provided values of DU air concentration as a function of time after impact, and properties of the aerosol (size distribution and dissolution rate) determining the deposition pattern in the respiratory tract and the clearance of uranium from it.

Table 2 HHRA Scenario exposure times and durations

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Exposure time</th>
<th>Duration</th>
<th>Breathing rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crewmembers inside vehicle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Most likely scenarios</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario A</td>
<td>From impact to exit 1 min post shot</td>
<td>1 minute</td>
<td>3 m³/h</td>
</tr>
<tr>
<td>Scenario B</td>
<td>From impact to exit 5 min post shot</td>
<td>5 minutes</td>
<td>3 m³/h</td>
</tr>
<tr>
<td>Upper bound scenarios</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario C</td>
<td>From impact to exit 1 hour post shot</td>
<td>1 hour</td>
<td>3 m³/h for first 15 min 1.5 m³/h thereafter</td>
</tr>
<tr>
<td>Scenario D</td>
<td>From impact to exit 2 hours post shot</td>
<td>2 hours</td>
<td>3 m³/h for first 15 min 1.5 m³/h thereafter</td>
</tr>
<tr>
<td>First responders</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario E</td>
<td>Entry 5 min post shot, exit 15 min post shot</td>
<td>10 minutes</td>
<td>3 m³/h</td>
</tr>
</tbody>
</table>

The HHRA used current ICRP biokinetic models for the respiratory tract (Publication 66, ICRP, 1994) gastrointestinal (GI) tract (Publication 30, ICRP, 1979) and for the systemic behaviour of uranium that has been absorbed from the respiratory and GI tracts into body fluids (Publication 69, ICRP, 1995a). These models were used to calculate radiation doses to tissues and maximum kidney concentrations, for the various scenarios.
The HHRA considered the potential health risks in detail. Calculated doses to the lungs were higher than those to any other organs known to be sensitive to induction of cancer by radiation. Current sources of information for both radiation–induced lung cancer and chemical toxicity to the kidney were reviewed. Radiation risks were based on the linear, no-threshold (LNT) model, and considered human data relating to long-lived alpha-emitting radionuclides. For chemical toxic effects on the kidneys, the model proposed by the RSWG (Royal Society, 2002) which correlates maximum uranium kidney concentration to categories of health effects observed in human beings exposed to uranium, was developed further. Kidney concentrations are divided into four categories termed “Renal Effects Groups” (REGs), based on the severity of effect and predicted outcome.

The assessments of radiation doses and maximum kidney concentrations to personnel who enter later, resulting from aerosols resuspended by their activities, and ingestion through hand to mouth contacts (Level II and III exposures) were considered separately (Attachment 4).

1.4 Objectives of this review

The overall objectives were:

- To produce a detailed analysis of the Capstone Report and its data to assist the Ministry of Defence (MOD) in gaining an understanding of the implications of the trials and their results and interpretation;
- To identify any limitations of the report and remaining data gaps and assess their relevance to MOD and the MOD DU Research Programme.

Specific objectives included:

- To comment on the scientific and technical quality of the experimental work and associated data and findings, from the standpoint of (a) what was achieved given the constraints (blast, fragments etc.) and (b) what might have been achieved under ideal conditions (which would include more time and resources).
- To assess and report on the uncertainties in extrapolating from the measured data to intake.
- To compare and contrast the results of the Capstone work with the results of other studies such as those cited in the Royal Society’s DU reports; to report on any similarities and discrepancies between the findings of the various studies, and to comment on possible reasons (such as differences in methodology) that might account for these.
- To comment on the scientific and technical aspects of the methodology used in the Capstone risk assessment, to review the findings and conclusions of the US work and to compare and contrast the Capstone and Royal Society methodologies.
- To assess the implications of the Capstone data for the health risk assessments described in the Royal Society’s report, and if necessary to update the Royal Society source term and risk assessments to take account of the Capstone findings.
- To identify and report on any data or knowledge gaps that still exist in relation to the Capstone and Royal Society work, and, as far as possible, to make recommendations and quantify the resources required to address these data gaps.
It should be noted that the present document is a review of the Capstone Report from a particular perspective, and includes some comments that are necessarily subjective to some degree. Readers interested in specific aspects or issues are strongly advised by the reviewer to consult the original documents.

1.5 Outline of the Capstone Report


_Depleted Uranium Aerosol Doses and Risks: Summary of US Assessments._ (Parkhurst et al 2004a)

This provides an overview of the whole project in about 70 pages, and itself begins with a 3-page Preface and 7-page Executive Summary. Since this provides three summaries of the project at different levels of detail, another is not given here beyond those already included in the Abstract, Executive Summary and Introduction.


Attachment 1 describes the experimental studies: the test facility, vehicles, air sampling techniques, characterisation etc., and gives a summary of the results. Far more detail is given than would be possible in, for example, a journal publication. It runs to about 250 pages, beginning with its own 8-page summary. It is complemented by Attachment 2.


Attachment 2 consists of seven appendices (A – G) which give further information about the experimental studies, including detailed tables of results.

Appendix A: Capstone Data Summaries. This has further information about how the DU mass concentrations in air were measured (30 pages), and tables of individual air sampler data etc. (120 pages).

Appendix B: Particle Size Distribution—Cascade Impactor Summary Data. This gives full details of the measurements of aerodynamic size distributions within the vehicle using cascade impactors (CI). Fitted AMADs as a function of time after impacts are tabulated and shown graphically.

Appendix C: X-Ray Diffraction Patterns of Uranium Aerosols. Following a description of methods, 25 XRD patterns are shown.

Appendix D: Particle Morphology and Composition. Particle morphology and chemical composition of selected samples were examined by SEM (particle shape and structure). Chemical compositions of particles were determined qualitatively by energy dispersive spectroscopy (EDS). Following a description of methods, about 150 SEM images are shown.
Appendix E: *In vitro* Solubility of Aerosol Samples. Dissolution of 27 samples in a simulated lung fluid was followed for 46 days. Details are given of the methods, retention curve fitting and results.

Appendix F: Wipe Surveys. Wipe surveys were conducted inside target vehicles and on exterior surfaces to evaluate surface deposition. Some instrument surveys were taken in conjunction with them to evaluate how well they are correlated. It gives example schematics of the sampling locations and lists of the uranium masses in the samples.

Appendix G: Target Vehicle Ventilation. To assist extrapolation of results to functional vehicles, the volume change per hour was measured in BHTs and in functional Abrams tanks and a BFV. For the functional vehicles, air changes were measured with and without ventilation systems operating and hatches open.

*Attachment 3. Human Health Risk Assessment of Capstone Depleted Uranium Aerosols. (Guilmette et al 2004)*

Attachment 3 describes the Human Health Risk Assessment: exposure scenarios, input data, modelling, assessed doses and uranium concentrations, radiological and chemical risks, medical management, etc. The main text runs to about 200 pages, beginning with its own 16-page summary. It is complemented by two appendices, which are within Attachment 3.

Appendix A: Tables of dose and kidney uranium concentration for various scenarios, sampling positions and times.

Appendix B: Summary of a literature review of animal studies related to uranium toxicity.

*Attachment 4. Level II and Level III Inhalation and Ingestion Dose Methodology: Calculations and Results (Szrom et al 2004.)*

Attachment 4 uses information in Attachments 1 – 3 to estimate potential DU inhalation and ingestion exposures for personnel who enter or work around the perforated vehicle hours to days after the impact (Levels II and III).

*Attachment 5 Data Quality Objectives for the Capstone Depleted Uranium Aerosol Study and the Human Health Risk Assessment of Capstone Aerosols.*

The US Army Medical Command (MEDCOM) developed a set of Data Quality Objectives (DQOs) for the specific information to be derived from this testing programme. The DQOs, which specify the objectives of the project, are reproduced in Attachment 5. They were used in planning the Capstone DU Aerosol Study and guided the HHRA. (It was not clear to this reviewer to what extent the DQOs were “for guidance” or to what extent they were “mandatory”, but as noted in Section 1.1, this review considers the Capstone Report from a UK perspective, rather than on the light of its own objectives.)

The level of detail provided in the Capstone Report is remarkable in a number of respects. It is unusual for such detailed information relating to sophisticated weapon systems to be put in the public domain. The level of detail and in some places comments on problems that arose, is far more than could be provided in a journal paper, and more than often given in laboratory reports. It does however add confidence to the assessments and the conclusions drawn from the study, since the scientific basis (and
its limitations) are given in full to support them. It will also enable others to make risks assessments from the data for other scenarios or using different approaches.

2 CAPSTONE DEPLETED URANIUM AEROSOLS: GENERATION AND CHARACTERISATION

2.1 Aerosol terminology and deposition mechanisms

Informed discussion of the Capstone DU Aerosol Study requires a basic understanding of aerosol terminology and dynamics, which is therefore presented first. (Much of this Section is based on text prepared by the reviewer for Annexe B of ICRP, 2002, and reproduced here by kind permission of the ICRP.) A brief explanation is also given of the types of instruments used in the Capstone Study, particularly the cascade impactor (CI).

The behaviour of an airborne particle depends on its size, shape and density. If the particle is spherical, its size can be uniquely defined by its geometric diameter. If it is not spherical its size is usually described in terms of an ‘equivalent diameter’ – the diameter of a sphere (or circle) which gives the same result as the particle when measured in the same way. For example, the volume equivalent diameter, $d_v$, is the diameter of a sphere with the same volume as the particle.

There are three main mechanisms that determine the behaviour of airborne particles in the ambient air, respiratory tract, and air sampling instruments: gravitational sedimentation, inertial impaction and diffusion (Figure 1). (For further information see eg IAEA, 1973; Hinds, 1982; ICRP Publication 66, 1994 Annexe D.)

2.1.1 Gravitational sedimentation

The gravitational force, $F_g$, on a particle of equivalent volume diameter $d_v$ is given by:

$$F_g = g \rho \frac{\pi}{6} d_v^3$$

(1)

Figure 1 Main mechanisms of particle deposition in the respiratory tract (ICRP, 2002, after Yeh et al., 1976)
where $g$ is the acceleration due to gravity, and $\rho$ is the particle density (strictly, the particle density minus the density of air).

As the particle falls, it experiences an opposing force due to viscous drag, which increases with particle velocity, $u$. For a spherical particle of diameter $d$, it is given approximately, by Stokes’ law, as $3\mu ud$, where $\mu$ is the viscosity of air. For particles with dimensions less than about 0.1 µm the molecular structure of the air becomes noticeable, and it acts less like a continuous fluid. As a result the drag is reduced, and this is taken into account using the Cunningham slip correction factor $C(d)$, which has a value of 1 for large particles and increases with decreasing size (ICRP Publication 66, Section D.4.1.1). The drag on an irregular particle is usually greater than that on a sphere of the same volume, and this is taken into account using the ‘dynamic shape factor’ $\chi$, which has a value between 1 (for spheres) and about 2 (Hinds, 1982). (The HRTM uses default value of 1.5 for $\chi$, typical of compact, irregular, ie, non-spherical particles). Hence the drag force $F_D$ on an irregular particle is given by:

$$F_D = \frac{3\pi \mu ud_x \chi}{C(d_x)}$$

(2)

When the gravitational and drag forces are equal the particle falls at a constant rate $u_g$, known as the terminal or settling velocity. From equations 1 and 2, putting $u = u_g$ gives:

$$u_g = \frac{\rho \frac{d_x^2}{18} C(d_x) g}{\mu x}$$

(3)

This is used to define the aerodynamic equivalent diameter, $d_{ae}$ or AD, which is widely used in occupational health, and in both the HRTM and the ICRP Publication 30 (1979) lung model. It is the diameter of a unit density (1 g cm$^{-3}$) sphere with the same settling velocity as the particle:

$$u_g = \frac{\rho \frac{d_x^2}{18} C(d_x) g}{\mu x} = \frac{d_{ae}^2 C(d_{ae}) g}{18 \mu}$$

(4)

Hence $d_{ae}$ is given by:

$$d_{ae} = d_x \left( \frac{\rho}{X} \right) \frac{C(d_x)}{C(d_{ae})}$$

(5)

For larger particles, $C(d_x)$ and $C(d_{ae})$ are both approximately 1:

$$d_{ae} \approx d_x \left( \frac{\rho}{X} \right)$$

(6)

Hence for DU oxides, with bulk densities of about 10 g cm$^{-3}$, $d_{ae}$ is a few times greater than $d_x$.

### 2.1.2 Inertial impaction

When an airstream changes direction, the inertia of the particles in it makes them tend to follow their original trajectories. It can be shown that if a particle with velocity $u_0$
enters still air it will come to rest in a distance \( L_s \), known as the stop distance, which is given by:

\[
L_s = \frac{u_g u_g}{g}
\]  

(7)

Since \( u_g \) is a function of \( d_{ae} \) (Equation 4) aerodynamic diameter is also a useful indicator of deposition by impaction. The importance of inertia is also measured by the dimensionless Stokes’ Number, \( St = \frac{L_s}{L} \), where \( L \) is a ‘characteristic length’ of the system, such as the diameter of an obstacle or aperture.

### 2.1.3 Diffusion

Collisions with gas molecules give rise to the random (Brownian) motion of a particle in a fluid, with average kinetic energy in each direction of \( \frac{1}{2}kT \), where \( k \) is Boltzmann’s constant and \( T \) is the absolute temperature. The motion is opposed by viscous drag, i.e. subsequent collisions with air molecules. A useful measure of the effect of diffusion is the diffusion coefficient, \( D \), which for a sphere of diameter \( d \), is given by:

\[
D = \frac{k T C(d)}{3\pi \mu d}
\]  

(8)

Thus \( D \) increases with decreasing particle size, but not with particle density. So aerodynamic diameter is not appropriate when diffusion dominates. Since diffusion is a ‘thermodynamic’ process, the particle’s behaviour is described by means of its thermodynamic diameter, \( d_{th} \), which is the diameter of a sphere with the same diffusion coefficient as the particle. In the HRTM, for simplicity, \( d_{th} \) is taken to be equal to the volume equivalent diameter, \( d_e \), although in practice \( d_{th} \) would be determined by measuring the diffusion coefficient (ICRP Publication 66, Paragraph D30). On this basis, \( d_{th} \) can be related to the aerodynamic diameter, \( d_{ae} \), using equation 5:

\[
d_{th} = d_e = d_{ae} \left( \frac{\rho \chi}{C(d_{ae})} \right)
\]  

(9)

For larger particles, \( C(d_{ae}) \) and \( C(d_e) \) are both approximately 1:

\[
d_{th} \approx d_{ae} \left( \frac{\chi}{\rho} \right)
\]  

(10)

Sedimentation and impaction are important above about 0.1 µm and increase with increasing size, while diffusion is important below about 1 µm and increases with decreasing size (Figure 2). In the range 0.1–1 µm all are important.
Figure 2  Relative importance of gravitational sedimentation and diffusion as a function of particle size (for unit density spheres (ICRP 2002), data taken from Raabe, 1994). For gravitational sedimentation the displacement is the vertical distance the particle falls in 1 second. For diffusion the displacement is the root mean square distance the particle travels as a result of Brownian (random) motion in 1 second.

The rapid increase of sedimentation velocity, $u_g$, with increasing diameter has important implications for the change in concentration with time of the DU dust cloud formed in relatively still air. For 3 µm-$d_{ae}$ particles $u_g$ is about 0.3 mm s$^{-1}$, so it takes 30 seconds to fall 1 cm, and such particles (and smaller ones) are quite stable in air. However, for 10 µm-$d_{ae}$ particles $u_g$ is about 3 mm s$^{-1}$, and such particles (and larger ones) deposit rapidly.

In the Capstone study, aerodynamic diameters (or specifically aerodynamic size distributions, see Section 2.2) were measured directly using cascade impactors (Section 2.2.3), which separated the airborne particles collected into fractions, using inertial impaction. In applying the results to calculation of deposition in each part of the respiratory tract, all three deposition mechanisms described above are considered. The contributions of gravitational sedimentation and inertial impaction are based on aerodynamic diameter. Thus particle density and shape are automatically taken into account in calculating their contributions. Assumed values of density and shape factor are, however, required to estimate the corresponding thermodynamic diameter, and hence the contribution of diffusion to deposition, but this is likely to be a minor component given the size ranges measured in the Capstone Study. In addition, in the ICRP Human Respiratory Tract Model (HRTM, ICRP, 1994), as used in the HHRA, it is assumed that some of the material deposited in the bronchial tree clears slowly, and that the fraction depends on the geometric size of the particles, which is calculated in the same way as the thermodynamic diameter. The effects of uncertainties in density and shape factor on assessed intakes and doses could be addressed in a study of overall uncertainty (Section 3.15), but in this reviewer’s opinion would be likely to make only small contributions, given the likely uncertainty in the exposure (time-integrated air concentration) itself.
2.2 Particle size distributions

The particles produced by any source will generally have a wide range of sizes. A collection of airborne particles (solid or liquid) is known as an aerosol. In order to describe the ‘size’ of the whole aerosol, and its behaviour, it is useful to represent it by a mathematical function. The one most frequently used for aerosols is the ‘log-normal’ distribution. Its use was recommended by the ICRP Task Group on Lung Dynamics (TGLD, 1966), and it is assumed by both the ICRP Publication 30 lung model and the HRTM.

2.2.1 The log-normal distribution

The log-normal distribution is often found suitable for describing the distribution of a parameter that shows a wide range of values. Moreover, although the function that represents it is complex, it easy to apply the distribution in practice using software or suitably formatted graph paper (see below). If a parameter \( y \) is normally distributed, then the probability of a value lying between \( y \) and \( y + dy \) is given by \( P(y)dy \), where:

\[
P(y)dy = \frac{1}{\sigma_y \sqrt{2\pi}} \exp \left[ -\frac{(y - \bar{y})^2}{2 \sigma_y^2} \right] dy
\]

where \( \bar{y} \) is the (arithmetic) mean value of \( y \) and \( \sigma_y \) is its standard deviation.

If a parameter \( x \) is such that the logarithm of \( x \), \( \ln x \), is normally distributed, then \( x \) is said to be log-normally distributed. Substituting \( y = \ln x \) and \( dy = dx/x \) in equation 11 gives the probability, \( P(x)dx \), of a value of the log-normally distributed parameter, \( x \), lying between \( x \) and \( x + dx \):

\[
P(x)dx = \frac{1}{x(\ln \sigma_g) \sqrt{2\pi}} \exp \left[ -\frac{(\ln x - \ln x_{50})^2}{2(\ln \sigma_g)^2} \right] dx
\]

where \( x_{50} \) is the median (50% of values lie below the median) and \( \sigma_g \) is the geometric standard deviation (GSD) of the distribution. A log-normal distribution is usually characterised by its median and GSD. Thus \( \ln \sigma_g = \sigma_y \) and \( \ln x_{50} = \bar{y} \). However, whereas for a normal distribution the median, arithmetic mean and mode (most likely value) are all the same, for the log-normal distribution they are different, as the distribution is skewed. The mode \( \hat{x} \) and arithmetic mean \( \bar{x} \) are given by:

\[
\hat{x} = x_{50} \exp\left[-\left(\ln \sigma_g\right)^2\right]
\]

\[
\bar{x} = x_{50} \exp\left(0.5\left(\ln \sigma_g\right)^2\right)
\]
These quantities are shown in Figure 3 for a distribution with $x_{50} = 1 \mu m$ and $\sigma_g = 2$.

![Figure 3. Log-normal distribution of particle sizes with median, $x_{50} = 1 \mu m$ and GSD ($\sigma_g$) = 2 (ICRP 2002).](image)

For a radioactive aerosol, the amount of activity per unit size, rather than the number of particles, is usually considered. For particles of about 1 µm or larger, when sedimentation and impaction are important, and aerodynamic diameter, $d_{ae}$, is the appropriate measure of behaviour, the aerosol would be characterised by the activity median aerodynamic diameter, AMAD: 50% of the activity is associated with particles larger than the AMAD. For smaller particles, for which diffusion dominates, and thermodynamic diameter, $d_{th}$, is the appropriate measure of behaviour, the aerosol would be characterised by the activity median thermodynamic diameter, AMTD: 50% of the activity is associated with particles larger than the AMTD.

In practice, the parameters describing the distribution, the median and GSD, can easily be found graphically, using paper with a logarithmic scale on the x-axis, and with a ‘probability’ scale on the y-axis. The (cumulative) percentage of activity associated with particles below a given diameter is plotted against the diameter. On these scales, a log-normal distribution is easily fitted as it gives a straight line. The median is read from the x-axis, at the point corresponding to 50% on the y-axis. Similarly the GSD can be found from the relationship:

$$\sigma_g \approx \frac{x_{84.13}}{x_{50}} \approx \frac{x_{50}}{x_{15.87}}$$  \hspace{1cm} (14)

The diameter corresponding to 84.13% or 15.87% of the activity is read from the x-axis, and $\sigma_g$ calculated from that and $x_{50}$. Before the wide availability of personal computers, this was the usual approach taken to analysing cascade impactor data.
2.2.2 Measurement of aerodynamic size distribution
In principle the aerodynamic size of a particle can be determined from measurement of its physical dimensions (e.g., by electron microscopy), and its estimated density. However, in practice, it is generally more effective to use an air sampling instrument that measures aerodynamic diameter directly, or that classifies (separates) the aerosol according to aerodynamic diameter.

2.2.3 The cascade impactor
In the Capstone Study, cascade impactors were used to determine the aerodynamic size distributions of the aerosols generated inside and outside the struck vehicles.

The cascade impactor has long been the most widely used instrument for measuring aerodynamic size distributions, and was the natural choice for the Capstone Study. Suction is used to draw air through one or more orifices in a plate, producing a high velocity jet (or jets). A collection plate perpendicular to the jet creates a rapid change in direction. The inertia of larger particles causes them to impact on the collection plate, while the air and smaller particles flow around it. In a cascade impactor there are several such stages in series, each consisting of an orifice plate and a collection plate. The collection plate may have a removable ‘substrate’ to improve retention of particles that impact on it, and to facilitate measurement of the deposited material. The collection efficiency of each stage is characterised by an ‘effective’ cut-off diameter (ECD), corresponding to the particle aerodynamic diameter that is collected with 50% efficiency. This is determined by the orifice diameter, the spacing between the plates, and the flow-rate. Thus each stage has a smaller ECD than the preceding stage. After sampling, the device is dismantled and the mass or activity on each stage measured.

Advantages of the cascade impactor are that it measures aerodynamic diameter directly and is relatively simple and robust. It can classify aerodynamic diameters between about 0.5 and 15 µm, and the stage cut-offs are reasonably sharp. Disadvantages (which are recognised in the Capstone Report) include:

- ‘wall losses’ - particle deposition on components other than the collecting plate substrates;
- ‘particle bounce’ and re-entrainment – particles impacting on the collecting plate, but not being retained; the collecting substrate can be chosen to reduce it;
- ‘stage overloading’ – if deposition on a plate is high enough it will alter the collection characteristics.

2.2.4 The cascade cyclone
A cascade cyclone, or ‘cyclone train’ was also used to collect aerodynamically separated fractions for analysis. A cyclone, like an impactor, uses inertia to separate the aerosol into aerodynamic size fractions. The air is drawn tangentially into a tapered cylinder, and as the air flows round the circumference, the larger particles impact on the inner surface, from where they fall into a collecting chamber. The air and smaller particles are drawn from the axis of the cylinder to the next stage. Its main advantage over the cascade impactor is its higher capacity: much larger masses can be collected.
for further study without overloading. Its main disadvantage is that the stage cut-offs are less sharp – there is much more overlap in the particle sizes collected in each stage. It is also bulkier.

2.2.5 Aspiration efficiency
A related issue is the ‘aspiration efficiency’ of the air sampling device, which is a measure of the extent to which the inlet to the device collects a representative sample of the particles in the volume of air sampled. Particles with aerodynamic diameters smaller than a few microns will readily follow the airstream into the device inlet. However, larger particles, may not, because of their inertia, depending on the particle size, air velocity and inlet aperture (Equation 7), and so there is a tendency to underestimate the concentration. In still air gravitational effects may also reduce the concentration of particles entering the inlet, depending on its orientation. In moving air the situation is further complicated: if the air moves towards the sampler inlet, particles, may, in effect be blown in, rather than, as normal, sucked in. In the Capstone Study tests this could occur as a result of the initial pressure pulse and turbulence, and the effect was evaluated through the use of “field blanks”, samplers through which air was not drawn (e.g. Attachment 3, Page 3.12). Similar effects arise when particles are inhaled into the nose and mouth, where the fraction of particles in the inhaled air that enters the nose or mouth is termed ‘inhalability’. It is taken into account in the HRTM (ICRP 1994), in which inhalability is taken (based on experimental data) to be 100% for particles of $d_{ae}$ smaller than about 5 µm, reducing to about 50% for particles of $d_{ae}$ greater than about 30 µm.

2.3 Scope
The Capstone DU Aerosol Study involved firing LC-DU rounds so that they penetrated armoured vehicles within the Superbox, a structure built to contain the blast, fragments, and DU aerosol produced by such tests. Table 1 lists the 13 firings of DU rounds. The aerosol characterisation carried out, although subject to some limitations (to be discussed later) was remarkably impressive (a) because it was so comprehensive and (b) because of the extremely difficult conditions (blast, fragments etc.) for sampling following penetration of the vehicle armour. Before going into details, limitations of the scope are noted from the perspective of this review. The issue of scope is related to the extent to which the study was prospective, going beyond the simulation of the actual ODS friendly-fire incidents, to provide information to assess possible exposures in future incidents.

2.3.1 Type of DU penetrator
Only Large Calibre DU rounds, as typically fired from tanks, were used, although DQO 3 (Attachment 5, page 3) refers to both long-rod and short-rod penetrators. In fact, little information is given about the penetrators that were fired, even though OSAGWI (2000) gives details of various rounds. From the perspective of this review, the obvious omission is of the small calibre (30-mm) rounds fired by aircraft. Most of the DU fired in ODS, and all of that used in the Balkans, was fired from aircraft. As noted below, even before Capstone there was far less information publicly available about the aerosols...
formed by impact of small-calibre penetrators than for LC-DU penetrators. This limitation is not addressed in the Capstone Report: there is no discussion of why small calibre rounds were not included in the tests or how the results might be extrapolated to them (or to any other type of DU penetrator). A possible explanation is that the Capstone study focussed on the ODS “friendly fire” DU incidents, which all involved LC-DU penetrators, and on shots designed to maximise aerosol production.

2.3.2 Type of target vehicle
The target vehicles represented Abrams tanks and BFVs as used by US forces, eg in ODS. Extrapolation to other vehicles is not discussed. This raises the issue of application of the results to vehicles used by UK forces. However, as will be discussed later, there was a relatively small range in uranium air concentrations between the different vehicle arrangements and shot lines, suggesting (at least to this reviewer) that the results might be extended to other armoured vehicles relatively easily. Furthermore, for most of the tests, and all those for which full sets of measurements were made, the vehicles were BHTs, vehicle shells stripped of flammable material, instrumentation etc. This will give rise to differences from an operational vehicle: the air volume would be greater (decreasing the initial concentration), the surface area less (decreasing the rate of deposition); there was no ventilation or fire suppression system, and in most cases nothing to ignite and burn. Furthermore, in the one test in which the EC/NBC ventilation system was operating, air concentrations were much lower. This raises the possibility that the ventilation rate may be a more important factor than the type of armour penetrated.

2.3.3 Type of shot line and distribution of exposures
The choice of ‘shot line’, ie, the point and direction of entering the vehicle, would be expected to determine the extent to which the penetrator erodes, and hence the formation of the DU oxide aerosol. (Here “erodes” refers to the loss of material from the penetrator surface as it interacts with the armour.) Three of the shots (PI-7, PII-1/2, and PII-3) were retrospective, simulating ODS incidents. The others were stated to be prospective, providing information for possible future incidents. Attachment 1 page 3.1 notes that the Phase I BHT was a circa-1991 Abrams tank without DU armour. The Abrams tanks used in ODS were M1A1 (with or without DU armour.) The M1A2 series has largely replaced the M1A1, but the turret side armour is similar, and so the Phase I results should still be relevant to future scenarios.

This raises the issue of where they fit in the distribution of possible future impacts with respect to aerosol generation, and whether they provide enough information about that distribution.

The following is extracted from Data Quality Objective (DQO) 1 for the Aerosol study (Attachment 5, Page 2):

*Develop an experimental scenario that provides the data required for bounded (upper-bound, lower-bound and most probable) estimates of the inhalation and ingestion in the crew compartments of Bradley Fighting Vehicles (BFV) and Abrams tanks (with and without DU armour) at the time the vehicles are struck by DU munitions. The design*
must allow for reasonable extrapolations to less or more severe scenarios. For example, the definition of normalisation factors such as the percentage of the penetrator aerosolised would allow for follow-on estimates of other scenarios. The following variables need to be considered: Type of vehicle (Abrams, Bradley (infantry or scout), type of armour perforated, air handling system, fire suppression system, type of DU round (length and mass), shot lines (angle of perforation, impact location on vehicle, impact velocity, etc.

It is instructive to compare statements made in the Capstone Report about the selected test shots with the approach adopted by the RSWG.

The RSWG assessment aimed to develop a ‘central estimate’ and a ‘worst case’, and these were carefully defined:

A ‘central estimate’, intended to be a central, representative value, based on likely values of all parameters that determine the intake according to the information available, or where information is lacking, values that are unlikely to underestimate the exposures greatly. The central estimate is intended to be representative of the average individual within the group (or population) of people exposed in that situation. However, the term average is not used, because the central estimates are not based on statistical analyses of data. It is recognised that for individuals in each group values could be greater than (or less than) the central estimate.

A ‘worst-case’ estimate was calculated using values at the upper end of the likely range, but not extreme theoretical possibilities. The aim was that it should be unlikely that the value for any individual would exceed the worst-case. Thus the worst-case should not be applied to the whole group to estimate, for example, the number of excess cancers that might be induced. One aim of the worst-case assessments is to try to prioritise further investigation. If even the worst-case assessment for a scenario leads to small exposures, then there is little need to investigate it more closely. If, however, the worst-case assessment for a scenario leads to significant exposures, it does not necessarily mean that such high exposures have occurred, or are likely to occur in a future battlefield, but that they might have occurred, or might occur in future conflicts, and further information and assessment are needed.

According to Attachment 1, Page 2.2: The test shots received by the Abrams tank “in Phase I were more severe than the shots received during actual Gulf War/ODS incidents. Four of the seven Phase-I shots were crossing shots in which the round was fired at and perforated the side of the turret, and exited through the opposite side. Two of the remaining three shots purposely were fired into the gun breech to maximize the amount of aerosol generated. In the final Phase-I test, the shot was fired through the hull within the turret basket to more closely represent the upper bound of aerosol production for Gulf War/ODS incidents.”

According to Attachment 1, Page 3.4: “For testing purposes, shot lines were selected to simulate the Gulf War/ODS shot lines believed to have had the highest potential for aerosol generation. Additionally, two separate shots into the gun breech of the Abrams tank and one shot into the turret gun feeder of the Bradley vehicle were conducted to enhance the generation of aerosols and provide an estimate of an upper bound of DU aerosol production.” These were shots PI-5 and PI-6 (Abrams tank) and PII-3 (BFV).
Since the vehicles had hatches closed and no ventilation systems, these would seem to provide reasonable upper bounds for the initial aerosol concentration produced from a single shot.

What is not so clear is which shots (if any) might be regarded as providing a typical “central” estimate for a shot that actually penetrates the crew compartment.

2.3.4 Aerosol outside the vehicle
Measurements were made of the aerosols generated outside the vehicle, but it is noted in the Capstone Report (e.g., Attachment 2, Section 3.6) that there were limitations imposed by the test facility.

- The dimensions of the Superbox limit the distance at which measurements can be made. The fragmentation shield around the vehicle was 12 m long by 12 m wide by 7.6 m high (Attachment 1, Page 2.3). Thus only dispersal within a few metres could be measured.
- The penetrator exiting the vehicle struck a solid “catch-plate”, which acted as a second aerosol source.
- For the first 2 hours after the shot, the Superbox ventilation was turned off (to avoid interference with the aerosol inside the vehicle). Hence there was less dispersal of the aerosol outside the vehicle than would be expected outdoors, where some wind is likely.

It is noted (eg Attachment 1, Page 2.3) that “The data obtained in Fliszar et al. (1989) for exposure outside of the struck vehicle were sufficiently robust for use in human health risk assessments.” However, the report by Fliszar et al. (1989) is of restricted distribution and not in the public domain (it was not available to the RSWG), although extensive reference is made to it in USACHPPM (2000), which is in the public domain.

2.3.5 Comparison of scope with that of other studies such as those used by the RSWG
The studies used by the RSWG (Royal Society, 2001) to estimate the properties of the source term were summarised in Annexe G to Part 1 (Bailey, 2001) and are listed in Table 3. A brief summary of each follows. Detailed comparisons of results (air concentrations, fractions of penetrator aerosolised, size distributions, dissolution characteristics, chemical composition, particle morphology) are made in Section 2.13 and Tables 7 - 10.
Table 3 Summary of information in source documents used by the RSWG (Table G1 of Bailey, 2001)

<table>
<thead>
<tr>
<th>Report</th>
<th>Amount/mass concentration</th>
<th>Dissolution characteristics</th>
<th>Chemical composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reports obtained</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hanson et al 1974</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Glissmeyer and Mishima 1979</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Patrick and Cornette 1978</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Chambers et al 1982</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scripsick et al 1985(a,b)</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Brown 2000</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Reports not obtained (OSAGWI 2000, Tab L)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gilchrist et al 1979</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fliszar et al 1989</td>
<td>✓</td>
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</tr>
<tr>
<td>Parkhurst et al 1990</td>
<td>✓</td>
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</tr>
</tbody>
</table>

2.3.5.1 Reports available to the RSWG

Hanson et al (1974). Five shots were fired at armour plate, of which four penetrated. The penetrator mass was about 270 grams, suggesting small-calibre DU rounds. Enclosures in front of, and behind, the target contained the aerosol for measurement of concentration and size distribution (by cascade impactor).

Glissmeyer and Mishima (1979). Five shots (3.4-kg penetrator mass) were fired at armour plate in the open, from a 105-mm gun at 200-m range. Air was sampled above the targets and at various distances: within ~50 m of target and ~0.8, 3 and 9 km for measurement of concentration and size distribution (by cascade impactor).


Chambers et al (1982). Nine shots (2.27-kg penetrator mass) were fired at armour plate in an enclosure. Air samples were taken 1.5 – 15 m from target, for measurement of concentration and size distribution (by cascade impactor).

Scripsick et al 1985(a,b). Study of *in vitro* dissolution of DU dusts. Two of the samples were from a USAF test bunker following penetrator impacts (one from an air filter, the other material into which the penetrators were fired), but no details are given.

Brown (2000) reported measurements of concentration and size distribution (by cascade impactor) made during UK tests in the 1980s, but no details of the arrangements are given.

Thus the studies of which reports were available to the RSWG did not involve impacts on vehicles, but on pieces of armour plate, and so the resulting aerosols were not measured inside a vehicle. Where feasible, estimates were made of the fraction of the penetrator mass that was aerosolised, and the RSWG assumed this to be dispersed within the vehicle. Furthermore these tests were carried out for different purposes: not in
general to provide information for battlefield health risk assessments (although in some cases to help assess exposures of personnel conducting the tests). Clearly the Capstone study is far more appropriate for this task, at least with respect to personnel exposed within the vehicle.

2.3.5.2 Reports not available to the RSWG: summaries are given in OSAGW1 (2000) Tab L, from which the following information was obtained.

Gilchrist et al (1979). Research Report Summary #11 in OSAGWI, 2000, Tab L. Similar test arrangement to Glissmeyer and Mishima (1979). Shots (2.2-kg DU penetrator mass) were fired at armour plate in the open, from a 105-mm gun at 200-m range.

Fliszar et al (1989). Research Report Summary #27 in OSAGWI, 2000, Tab L. Measurements were made of aerosols generated inside and outside an Abrams tank with DU armour struck by various rounds in the open air. (Hence the study was similar to Phase IV, but carried out in the open air, rather than in a containment structure.) Of them one (Test 5A) was a 120-mm DU penetrator. (The final test caused a fire that “consumed” the vehicle, which was loaded with DU munitions.) Aerosol size distributions were measured near the point of impact and up to 100 m away. Air concentrations were measured up to at least 200 m away. Air within the vehicle was sampled during the last three tests, when break-through occurred. However, there were difficulties determining the times during which the samplers actually operated. The first of these used the DU round, the NBC air filtration was running and the loader’s hatch opened on impact. The second was a non-DU (tungsten) round, the NBC system was off, and no hatches opened. The samplers were all destroyed in the fire caused by the final test. One team member wore a personal air sampler to evaluate resuspension at the test site and while working inside the crew compartment. Air samples were also taken during welding operations, such as might take place on the battlefield.

Jette et al (1990). Research Report Summary #31 in OSAGWI, 2000, Tab L. Aerosol concentrations were measured after complete and partial penetration of armour by both DU and non-DU rounds. (Few details are given in this summary.) Estimates were made of the fraction of penetrator aerosolised, and in vitro dissolution tests were carried out.

Parkhurst et al (1990). Research Report Summary #29 in OSAGWI, 2000, Tab L. 25-mm DU rounds tested against hard armour. Estimates were made of the fraction of penetrator aerosolised, and in vitro dissolution tests were carried out. (Few details are given in this summary.)

2.3.5.3 More recent studies

Chazel et al (2003) reported on studies of aerosols produced during two firings of DU rounds against the glacis (sloping armour) and turret of a tank, carried out by the French Army. The glacis and turret were placed on a chassis in front of a sand box (presumably in the open.) Nine air samplers ran outside the vehicle (1 – 4 m away), and one was inside the structure. A single CI measured the size distribution (outside) at 2.5 m from the tank. Various measurements were made on the samples collected, including in vitro dissolution tests. Little information is given about the firing and impact itself.
Mitchel and Sunder (2004) followed urinary excretion of uranium for 7 days after intratracheal instillation into rats of the <50-µm fraction of dust obtained from impact of DU munitions on armour plate. No information at all is given about the test firing or how the material was collected. However, the large size suggests that the material was from surface deposits rather than air samples, and may not be representative of dust that might be inhaled.

2.3.6 Summary
Clearly the Capstone aerosol study is of much greater scope and depth than any other known studies, at least with respect to personnel exposed within the vehicle.

The studies of which reports were available to the RSWG did not involve impacts on vehicles, but on pieces of armour plate, and so the resulting aerosols were not measured inside a vehicle. Where feasible, estimates were made of the fraction of the penetrator mass that was aerosolised, and the RSWG assumed this to be dispersed within the vehicle. Furthermore these tests were generally carried out for different purposes: not to provide information for battlefield health risk assessments.

Two other known studies (Fliszar et al 1989; Chazel et al, 2003) involved impacts on vehicles. However, as noted above, the report by Fliszar et al (1989) is not available, and that of Chazel et al (2003) has only a brief summary of information relating to the impact conditions and arrangements. With regard to exposures inside the vehicle, the scope of the Capstone study greatly exceeds all others together. Chazel et al ran only one sampler within the vehicle for each shot, and one of those was destroyed. Fliszar et al took more samples, though far fewer than Capstone, and there are doubts about their interpretation, because of uncertainties in the time periods for which air samplers ran, and damage to filters (USACHPPM, 2000).

2.4 Achievements of the Capstone DU Aerosols Study

Most of these issues relate to the experimental work undertaken, some to analysis in terms of the processes involved (rather than the risk assessment, which is considered later) and a few to the report on the studies. The following sections (2.5-2.8) consider each aspect. As indicated by the title, these sections summarise aspects of the study considered “positive” by the reviewer. Thus, to avoid repetition, it can be assumed that throughout these Sections (2.4–2.8) the reviewer considers the approach taken to be reasonable, unless comment is made. In a number of cases where the reviewer has been particularly impressed such comments are complementary.

2.5 Experimental work

2.5.1 Aerosol sampling inside the vehicle
Systems were successfully developed for collecting samples to characterise the DU aerosol within a vehicle struck by a DU penetrator. As outlined on page 2.5 of Attachment 1, the aerosol collection system needed to:
function in a high-temperature, high pressure environment;
- survive damage from fragments;
- provide sample collection redundancy, confidence in timing, adequate flow rates, and sufficient sample collection for chemical analysis of selected samples;
- collect aerosols inside the vehicle as a function of time, position, and shot line

A very comprehensive sampling schedule was carried out in Phases I–III. Four custom-designed arrays of sampling heads were built, each with nine 25-mm Institute of Occupational Medicine (IOM) filter cassettes and nine ‘Marple’ cascade impactors (CIs). For the Abrams BHTs (Phases I and III) the arrays were mounted in locations approximating to the breathing zones of the commander, loader, gunner, and driver. However, for shots PI-5 and PI-6, which were into the gun breech, the gunner’s array was removed to avoid damage.

For the BFVs (Phase II) the loader’s and gunner’s arrays were placed behind the left and right ‘scout’ positions respectively. Samples were nevertheless identified as ‘L’ and ‘G’ respectively.

The CIs and IOM filters were operated in pairs; eight in sequence, to give concentration and size distribution as a function of time between 5 seconds and 2 hours after impact. The ninth was a ‘field blank’, with no air drawn through it. The sampling times were logarithmically spaced. Lists are given in Attachment 1 (Phase I: Table 4.7, page 4.25; Phase II: Table 4.12, page 4.34. Phase III: Table 4.16, page 4.41).

In Phase IV, Capstone sampling arrays could not be placed in the vehicle because of other requirements. The primary samplers were Marple CIs attached to the uniform jackets of mannequins placed at the driver’s and loader’s positions (four and a field blank) (Shots PIV-1, 3, 4).

In addition, a single cyclone train, and moving filter (MVF) were placed together about 0.3 m above the floor in a suitable but ‘survivable’ location near the sampling arrays. (Both were also used in Phase IV, Shots PIV-1, 3, 4.) The cyclone ran from 5 seconds after impact for about 2 hours.

For reasons of availability and cost, to enable many samples to be collected after each shot, the air samplers were essentially off-the-shelf, commercially available devices.

The IOM filter cassette holds a 25-mm diameter filter (sampling flow rate 2 litres per minute, Lpm). A detailed description is not given although a photograph is. It appears to be a personal air sampler with the filter held in place by an open mesh grid, with a wide short inlet.

The CIs were eight-stage, stainless steel, 34-mm Marple (Model 298), sampling rate 2 Lpm, (presumably manufactured as personal air samplers). Nominal stage cut-offs are about 21, 15, 10, 6, 3.5, 1.6, 0.9, and 0.5 µm, respectively. The substrate was a cellulose ester impaction medium of 0.8-µm pore size. The backup filter was polyvinyl chloride (PVC) of 5-µm pore size. A silicone-adhesive coating was applied to the first-stage substrate to minimise particle bounce.
A five-stage, SRI cyclone train collected size-selected aerosol material for studies of chemical and physical characteristics and in vitro dissolution. Plans called for the cyclone to be operated at a flow rate of 10 Lpm, giving cut-off diameters for stages 1 – 5 of approximately 10, 4.3, 2.9, 2 and 1.2 µm. The actual flow rates ranged from 9.0 to 13.4 Lpm. The cutoff diameters for Stages 1 through 5 at 14 Lpm were 7.8, 3.2, 2.3, 1.2, and 0.7 µm, respectively, and so the size fractions actually collected were not very different from those planned. Normally this is followed by a back-up filter, to collect particles which penetrate stage 5 (i.e., less than about 1 µm). For Shot PI-1 the back-up filter was replaced by a parallel-flow diffusion battery (PFDB) to fractionate the sub-micron particles (see below).

A Merlin-Gerin auto-advance moving filter (MVF) collected aerosols during the first few seconds after impact, before the other samplers were activated, and during pre-selected sampling time intervals (eg in Phase IV, to coincide with the CI measurements). Aerosol was drawn through the sampling inlet and collected on the filter through a 25-mm square aperture. The filter advanced from one spool to another at a controlled speed. A critical orifice controller maintained the nominal sampling flow rate of 28.3 Lpm. The device was placed inside a stainless steel box with the sampling inlet outside the box.

2.5.2 Computer control system

A sophisticated computer-controlled system was designed and built to control the operation of the various samplers, and to ensure that timings were accurate and flow rates were monitored. Considerable detail is given. QA was an important feature. For example (Attachment 1 page 3.28) the pressure drop across each filter was monitored to document the exact start and end of sampling, and changes that would indicate either damage to the filter or overloading.

In addition, for most tests, there was an impressive array of other instruments to provide supplementary information:

- Sensors to measure the temperature and pressure pulses and their rapid decreases after perforation within the turret, usually at aerosol sampler locations.
- An x-ray image of the residual penetrator exiting the vehicle was captured on film for use, if possible, in qualitatively evaluating the extent of penetrator erosion.
- A high-speed video camera (nominally 1000 frames per second) pointing into the turret.

Real-time video captured exterior and interior views. Two external cameras mounted above the vehicle provided views of the aim point on the side of the turret facing the gun and on the opposite side of the turret. Inside the turret, two cameras pointed toward the gunner’s position. For example, the external cameras showed when hatches popped open briefly during shots, and dispersion of aerosol through the hatch in those cases when it remained open.

2.5.3 Ventilation rates

The ventilation rates of the Abrams and BFV targets vehicles were measured using sulphur hexafluoride (SF₆) gas dilution. This involves introducing a small amount of the
inert tracer gas, and measuring the SF$_6$ concentration using an electron-capture gas chromatograph. The rate of decay of the concentration gives the air-exchange rate.

This was carried out before, during, and after vehicle penetration. These rates were compared with rates tested in operational Abrams tanks and in a BFV under three conditions:

1) internal fan off and the hatches closed,
2) internal fan on and the hatches closed,
3) internal fan off and the commander’s hatch open.

Attachment 1, pages 4.49-4.51 gives the dimensions (volumes) of operational and BHT versions of Abrams tanks and BFVs. It also gives air exchange rates in functioning vehicles, and results of the pre-shot ventilation rates in the test BHTs.

As summarised in Table 4, ventilation rates were higher when either the fan was on or the hatch was open. Of the Abrams tanks, the M1A1 and M1A2 had much lower ventilation rates than the M1 model when the hatches were closed.

Table 4 Summarised ventilation rates in operational vehicles (based on Attachment 1, Table 4.23)

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Volumes exchanged per hour (approximate)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fan OFF, Hatches closed</td>
</tr>
<tr>
<td>Abrams M1</td>
<td>5</td>
</tr>
<tr>
<td>Abrams M1A1</td>
<td>1.1</td>
</tr>
<tr>
<td>Abrams M1A2</td>
<td>0.25</td>
</tr>
<tr>
<td>BFV</td>
<td>10</td>
</tr>
</tbody>
</table>

Ventilation in the BFV (hatches closed, internal fan off) was greater than in the Abrams tanks. Turning on the internal fan increased the ventilation rates significantly, but opening hatches did not.

During the penetrator tests inside the Superbox, SF$_6$ was released about an hour before the shot. For the first 20 min, the concentration increased with time. Then it decreased as expected, because of the air exchange. Exchange rates were similar to those in corresponding functional vehicles. However, after each shot was fired, the SF$_6$ concentration measurements increased and therefore the ventilation rates could not be estimated. Further details are given in Attachment 1, Appendix G.

2.5.4 Air sampling outside the vehicle

Total particulate aerosol concentration was measured with four high-volume Staplex air samplers, (referred to as ‘Hi-Vols’) fitted with 10-cm sampler heads and operated at nominal flow rates of 560 Lpm. Except for the Hi-Vol positioned ~0.5 m above the ground under the catch plate during the first two shots, the sampler heads were located 1.5 m above the floor at designated points around the target vehicle. They provided 1-h baseline evaluations before all shots. They also collected total particulate aerosol after impact following the first five shots.
Beginning with PI-5, two Andersen ambient CIs were used to provide data on particle size distributions. Once available, they replaced the Hi-Vols as the primary samplers. The Anderson CIs used 81-mm cellulose ester substrates and operated at a nominal flow rate of 28 Lpm. They were located 1.5 m above floor level in a horizontal orientation. They were activated 10 sec after impact and ran for 2 min during all subsequent shots in all three test phases, with two exceptions: in PI-7 they ran for 1 min; and in PIII-2 one ran for 5 hours.

There was no exterior air sampling in Phase IV, because the Superbox ventilation system was operating throughout.

2.5.5 Aerosol deposition and resuspension sampling

Particles produced in the impact will deposit on surfaces inside and outside the vehicle and become a potential source of internal exposure through resuspension into the air or hand-to-mouth contact.

Comprehensive surveys of removable contamination were conducted in and on damaged vehicles, using wipe samples and deposition trays to collect the deposited material. The surveys followed a systematic protocol, i.e., samples were taken at predetermined locations: at least 30 wipe locations and four deposition trays inside and outside the vehicle in Phases I-III.

Surveys were also conducted with portable radiation survey instruments to evaluate the correlation between instrument responses and the DU contamination present.

The aerosol levels remaining during recovery activities and resuspended by them were evaluated in several limited exercises in which IOM and CI personal air samplers were worn. Cotton gloves worn over protective gloves by selected recovery personnel provided a method to collect the deposited material and evaluate the amount available for transfer. These took place several hours after impact following shots PI-6 and PI-7. For those shots the sampling array at the loader’s position remained shielded until shortly before recovery operations started. Its samplers were run before, during and after the recovery operations.

Wipe test surveys were conducted first to measure levels of removable contamination, and secondly to determine the effectiveness of the decontamination procedures used by Battlefield Damage Assessment and Repair Personnel. Radiation monitoring instrument surveys were also performed.

2.6 Results

In large part the Capstone Study was successful in obtaining and measuring samples according to the programme outlined above. Given the difficult conditions, it probably came as close as could be expected to meeting its objectives. The main findings are summarised in Attachment 1 (Summary) pages vi-x, from which much of the following is drawn but with additional comments.
The study obtained a wealth of information about the DU aerosol formed within Abrams tanks and BFVs (or at least BHTs), following the impact of an LC-DU penetrator. Phases I - III involved 10 shots. Two of these (PI-3/4 and PII-1/2) were double shots, with two rounds fired along similar trajectories 10-15 minutes apart. For these 10 shots, apart from some lost samples, mainly in the early shots, comprehensive measurements were made of the DU mass concentration and size distribution, typically at eight time points between 5 seconds and 2 hours after impact, and at four locations within the vehicle, corresponding to the breathing zones of four crew members.

It is noted that although the costs of the tests prevented reruns, there was a degree of duplication, which helps to confirm reliability. Thus measurements at the commander and loader positions in Phases I and III, and at the right and left scout positions in Phase II were expected to be broadly similar. Shots PI-1 and PI-2, and PI-5 and PI-6 were essentially replicates. The IOM and CI samplers both measured total concentration, and at some times there were also measurements from the MVF for comparison. The cyclone samples could give a measure of the time-integrated concentration. There is reasonable consistency (sometimes good agreement, see eg Attachment 1 page 5.29) between comparable measurement results, which in this reviewer’s opinion adds confidence to the findings.

Uranium masses were determined for a very large number of samples. For each Phase I-III shot there were up to four Capstone arrays, each with nine 8-stage cascade impactors and IOM filters, more than 60 wipe samples, and others. As shown in Attachment 1, Table 3.4, more than 6,000 samples were analysed.

Comprehensive QA and QC procedures were applied to the various analyses, and are described in some detail (eg, Attachment 1, pages 3.52-3.54; 5.2-5.3). For example, all IOM filters were photographed before counting. It was also noted that QA and QC procedures were especially important because thousands of samples had to be processed.

### 2.6.1 DU aerosol concentration

While recognising that DU concentrations varied between shots and crew positions, Table S.1 of Attachment 1 gives average values for each vehicle configuration. These are reproduced in Table 5, which is based on Table S.1, but with shot numbers added.
Table 5  Summary of DU aerosol mass concentrations (Based on Attachment 1, Table S.1)

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Mean DU concentration (g m⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retrospective (no ventilation)</td>
<td></td>
</tr>
<tr>
<td>Abrams BHT crossing hull</td>
<td></td>
</tr>
<tr>
<td>PI-7</td>
<td>11</td>
</tr>
<tr>
<td>Shots</td>
<td>10 sec</td>
</tr>
<tr>
<td></td>
<td>9.0</td>
</tr>
<tr>
<td></td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>0.057</td>
</tr>
<tr>
<td>Bradley BHT</td>
<td></td>
</tr>
<tr>
<td>PI-I/2&amp;3</td>
<td>3.0</td>
</tr>
<tr>
<td>Shots</td>
<td>1 min</td>
</tr>
<tr>
<td></td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>0.049</td>
</tr>
<tr>
<td>Prospective (no ventilation)</td>
<td></td>
</tr>
<tr>
<td>Abrams BHT crossing turret</td>
<td></td>
</tr>
<tr>
<td>PI-1,2,3/4</td>
<td>8.8</td>
</tr>
<tr>
<td>Shots</td>
<td>30 sec</td>
</tr>
<tr>
<td></td>
<td>7.9</td>
</tr>
<tr>
<td></td>
<td>5.7</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>0.064</td>
</tr>
<tr>
<td>Abrams BHT crossing turret into breech</td>
<td></td>
</tr>
<tr>
<td>PI-5&amp;6</td>
<td>16</td>
</tr>
<tr>
<td>Shots</td>
<td>30 min</td>
</tr>
<tr>
<td></td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>6.4</td>
</tr>
<tr>
<td></td>
<td>0.020</td>
</tr>
<tr>
<td></td>
<td>0.029</td>
</tr>
<tr>
<td>Abrams BHT into DU armour</td>
<td></td>
</tr>
<tr>
<td>PI-II-1&amp;2</td>
<td>10</td>
</tr>
<tr>
<td>Shots</td>
<td>1 h</td>
</tr>
<tr>
<td></td>
<td>7.9</td>
</tr>
<tr>
<td></td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>0.049</td>
</tr>
<tr>
<td></td>
<td>0.017</td>
</tr>
<tr>
<td>Prospective (with ventilation)</td>
<td></td>
</tr>
<tr>
<td>Abrams tank into DU armour</td>
<td></td>
</tr>
<tr>
<td>PIV-4</td>
<td>0.092</td>
</tr>
<tr>
<td>Shots</td>
<td>10 sec</td>
</tr>
<tr>
<td></td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>0.011</td>
</tr>
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<td>-</td>
</tr>
</tbody>
</table>

Several important general points can be seen from this summary (most but not all are noted in the Capstone report as indicated below):

- For all the configurations without ventilation, the initial concentrations are remarkably similar. For times up to 1 minute, there is only a factor of 3-5 between the lowest and the highest. There is a wider range at 30 minutes, but at 1 hour it is again only a factor of four. Thus while, as expected, it is higher for the Abrams tank than for the BFV (with lighter armour), it is only a few times higher. Attachment 1, page 2.3, notes that: “LC-DU munitions easily penetrate the Bradley’s light armor, and they generally traverse the vehicle with little penetrator erosion.” Similarly, the initial concentrations following the shots intended to give “upper bound” concentrations, are only a few times higher than the others, and the DU armour has little effect. The Capstone Report itself does not emphasise this narrow range. However, Attachment 1 page 6.33 notes: “Surprisingly, the DU aerosol concentrations reached during the hull shot (PI-7), in which the penetrator traversed the thinnest armor of the Abrams tank shots, were similar to the turret shots.”

- For all the configurations without ventilation, the initial concentrations are very high: the range is 3 – 16 grams per cubic metre. (As discussed in Section 2.7.1 below with regard to the size distribution, a “typical” pattern is for the AMAD for the first measurement to be a few (or a few tens of) microns, with subsequent values around 1 micron. Thus with the exception of the time of first measurement (10 seconds) most of the airborne DU would be considered respirable).

- For the Abrams tank with ventilation, the initial concentration is far lower: by about two orders of magnitude.

- For all the configurations there is not much difference between the average concentrations at 10 seconds, 30 seconds and 1 minute. The concentration at 30 minutes is much lower: by a factor between 10 and 300 times.

- For all the configurations without ventilation, the concentrations at 30 minutes and 1 hour, although far lower than during the first minute, are still high: tens of milligrams per cubic metre.

It should be noted that while there are 10 shots into BHTs without ventilation (Phases I-III), there is only one of a DU round into a vehicle with its ventilation system running (PIV-4). Furthermore, sampling following shot PI-V was limited compared to that in Phases I-III (Table 1). With these provisos, it does appear that operation of the vehicle ventilation system can have a dramatic effect on the DU air concentration. Indeed, it
appears that it might well have more effect than the type of armour penetrated or whether or not the DU penetrator hits a massive object like the gun breech.

An overall conclusion of the Capstone Study from the report is advice to turn on vehicle ventilation as soon as possible after an impact, if it is not already operating, as a means of reducing exposure to the DU aerosol.

Two tests consisted of double shots. It was found that for these, the aerosols formed were essentially independent: the aerosol formed by the second shot was not significantly influenced by the first. It was not significantly increased as a result of resuspension of contamination from the first shot, nor reduced by ventilation through the apertures created by the first shot. Thus the exposure from a double shot can be simply assessed as twice that from a single shot.

2.6.2 Aerosol particle size distributions
Aerosol size distributions were based on measurements of the radioactivity on each collecting stage substrate of the Marple and Anderson Cascade Impactors, and therefore relate to DU only. As noted below, measurements of mass were unreliable because in many cases the substrate weighed less after sampling than before. The analysis of the measurements is described below (Analysis of Results).

2.6.3 Aerosol outside the vehicle
Some aerosol measurements were made outside the vehicle but these were much more limited: typically two CIs at a single time outside, compared to four CIs at eight time points inside. It was considered in the Capstone Report (Attachment 2, Page 3.31) that these were likely to overestimate concentrations that would arise in the open, because of confinement by the Superbox structure and aerosol generation from impact of the residual penetrator on the catch plate.

2.6.4 Other characteristics of the DU aerosol particles
In addition to the measurements of uranium mass, on which air concentrations and size distributions were based, a range of other measurements was made on selected samples (Attachment 1, pages 5.58-5.72). These were mainly from the cyclone stages and their back up filters, because larger masses were available. They were collected over the whole 2-hour sampling time and were size fractionated. However, Attachment 1, page 5.59, notes that “Cost considerations limited the number of cyclone samples characterized to one from each phase.” Samples were selected from PI-3/4, PIi-1/2 and PIII-2. In addition, PI-7 was analysed because it was most representative of an Abrams/ODS scenario.

2.6.5 Chemical composition
Analysis of the cyclone samples showed that a high percentage of the mass of material collected was uranium: approximately 40-70% for the Abrams BHT and about 25% for the BFV BHT. Aluminium and iron were the other main metals. Aluminium varied the
most by Phase, being highest in Phase-II and lowest in Phase-III. Other major constituents included titanium, zinc, and copper.

X-ray diffraction (XRD) patterns were evaluated for selected samples (Attachment 1, pages 5.65-5.68 and Appendix C), to identify crystalline uranium oxides, and for semi-quantitative analysis of their relative proportions. This showed that the predominant uranium oxide phase consisted of U₃O₈/UO₃. (It was not possible to distinguish between U₃O₈ and UO₃.) Its presence increased as particle size decreased. The percentage of U₄O₉, which was highest with the large particles, decreased as particle size decreased. Although the presence of UO₂ could not be ruled out because of the overlap in the XRD patterns for UO₂ and U₄O₉, it was not specifically detected. A small amount of UO₂•2H₂O (schoepite) was detected in several cyclone stages and in backup filter samples. For most samples it was not feasible to determine the percentages of the uranium compounds present, and therefore only ratios are presented for U₄O₉ compared to U₃O₈/UO₃.

Attachment 1, page 5.65, notes that some of the XRD patterns contained a broad diffraction profile indicative of amorphous (non-crystalline) materials, which cannot be identified by XRD. This amorphous material probably contains oxide phases of target metals and amorphous uranium oxides.

2.6.6 SEM/EDS Particle morphology and composition

Particle morphology (particle shape and structure) was examined by SEM. Chemical compositions of individual particles were determined qualitatively by energy dispersive spectroscopy (EDS), which is limited to elements of atomic number greater than 6 (carbon). (No attempt was made to assess the composition of an entire sample.) A summary is given in Attachment 1 pages 5.68-5.69, with further details in Appendix D, including about 150 micrographs (Appendix D, pages D.13-D.41, Figures D.1-D.29).

The samples analysed were one set of cyclone residues and backup filters from Phase I shots 3/4 and 7, Phase II Shots 1/2 and Phase III Shot 2; moving filters; four PFDB filters; and the “DU cone”. This was formed when a metal fragment ignited and burned on the floor of the Abrams BHT following Shot PI-5.

SEM showed the diversity of particle shapes and the degree of agglomeration. Descriptive terms used included: “Amorphous looking” meaning lacking faceted particle shapes characteristic of crystals; “Agglomerate” meaning any group of particles; which were subdivided into “Aggregates” (relatively loose) and “conglomerates” (cemented together).

The particles examined by SEM had a complex, heterogeneous structure. The uranium particles displayed many different shapes, from spheres to fractured grains, suggesting that they were formed by several different mechanisms. A useful categorisation appears in Appendix E, page E.12, which states that review of SEM showed several discrete forms of uranium:

- Irregularly shaped particles with sizes in the tens of µm and with surfaces that appeared to be fractured (Figure D.2). These particles typically had very high
uranium and low oxygen contents, and are believed to be uranium metal particles that were spalled from the surface of the DU penetrator during perforation.

- Typically spherical particles between 1 and about 12 µm in diameter, and with high uranium and oxygen contents, with what appeared to be highly vesiculated or compartmented surfaces with well-defined, cell-like features (see, eg Figure D.3). The surfaces of these particles were often irregularly coated with relatively electron-lucent material having the appearance of a "moldy growth". This latter material had little or no uranium elemental signature.

- Ill-defined agglomerates of relatively electron-lucent materials (Figure D.13, a-d), which predominated in number particularly in cyclone Stages 4 and 5. Embedded within this flocculent-appearing matrix were numerous micrometre- and submicrometre-sized spherical uranium particles. The physical sizes of the aggregates ranged from a few micrometres to several tens of micrometres.

EDS analysis suggested that all samples were composed of U, Al, Fe, and O (oxide) with lesser amounts of other elements. Uranium was associated with almost every particle or particle matrix evaluated, either as pure or nearly pure uranium oxide, or as an agglomerate with other metals. Uranium combined with aluminium predominated. Iron and elements associated with steel were also present. Titanium was consistently identified as a minor constituent. Samples from Phase II contained a much higher aluminium content, as expected because of the composition of the BFV armour penetrated.

These measurements supplement other analyses of chemical composition and size distribution, and can assist in understanding the processes involved and interpreting the results. For example, it is stated (Attachment 1 page 6.50): "From the perspective of the future needs of the dose/risk assessor, knowledge of how the DU aerosols were formed is useful. For example, the lack of vaporization/condensation aerosols is important in modeling the deposition and dissolution/retention of the inhaled DU-containing aerosols, because this particle size range need not be considered. Second, the extreme heterogeneity of the aerosol particles also presents a difficulty in interpreting the particle-size-specific data, particularly the relationship between particle size and solubility."

### 2.6.7 In vitro dissolution

*In vitro* dissolution tests were carried out on 27 samples, mainly from cyclone stages and back-up filters. A summary is given in Attachment 1, page 5.70, and full details in Appendix E. Dissolution was measured at 17 times up to 46 days in simulated lung fluid. For analysis of the results, see below.

### 2.6.8 Surface contamination

An extensive database of analysed wipe samples was developed that provides values (probably near the upper end of the range, because some of the tests were designed to maximise aerosol production and hence contamination) for surface deposition inside and outside the vehicle. This provides information about the amount of uranium potentially available for resuspension. Amounts of uranium on the wipe media and on the cotton gloves provide information about amounts potentially available for hand-to-mouth transfer.
The Capstone Report notes that good correlations were observed between the removable beta activity and measurements with the two types of beta-gamma probe tested. (Attachment 1 pages 5.38-5.39 and Appendix F).

2.6.9 Aerosols during recovery activities
Recovery activities started several hours after each shot (or double shot). Some information was obtained on aerosols present, which included residual airborne material from the shot and deposited material resuspended by the actions of recovery personnel (Attachment 1, pages 5.39-5.44).

During shots PI-6 and PI-7, the loader’s array was used to monitor the aerosol concentrations before, during, and after recovery activities. Based on these, following PI-6, the concentration rose from about 3 mg m\(^{-3}\) before entry, to a peak of about 30 mg m\(^{-3}\), and fell when they left, reaching about 7 mg m\(^{-3}\) 30 minutes afterwards. However, following PI-7, the concentration fell during the recovery activities suggesting, as noted in the Capstone Report, that they resulted in little resuspension of deposited material.

Two recovery personnel each wore two personal air samplers, an IOM and a Marple CI following the Phase I-III shots. Measured uranium air concentrations were in the range from about 60 to 1000 µg m\(^{-3}\) (Attachment 1, Table 5.22), lower than measured by the arrays.

2.7 Analysis of results
2.7.1 Aerosol particle size distributions
Aerosol size distributions were based on measurements of the radioactivity on each collecting stage substrate of the Marple and Anderson cascade impactors, and therefore relate to DU only.

The net mass of uranium for each stage was entered into a computer program (SigmaPlot 2000) which fit the data by one (unimodal) or two (bimodal) log-normal distribution functions (Attachment 1, page 5.45). This determined the AMAD, the geometric standard deviation (GSD), the R\(^2\) value (measures goodness-of-fit), and fraction of the mass in the first peak (for bimodal distributions). The software used a transformation equation that employed the effective cut-off diameters (ECDs) for the Marple CIs. (However, it is not explained how the size-dependence of the cut-off, which is a function of aerodynamic diameter, was taken into account). A multi-lognormal regression was used to fit the data to unimodal and bimodal distributions. Almost 400 sets of CI data were analysed.

Thus, as expected, a sophisticated procedure was applied to analyse these results. It is commendable that statistical analysis was undertaken to demonstrate that departures from the unimodal distribution (the simplest assumption) were not due to chance. However it is not clear from the description whether uncertainties in the ECDs were taken into account in the statistical analysis.

Examples are given in Fig 5.28 – 5.35. The Capstone Report notes that for most aerosols the distribution was bimodal, rather than unimodal, with a small particle size mode in the range 0.2 – 1.2 µm and a large size mode in the range 2 – 15 µm.
However, the Capstone Report also notes that the distributions were not well fit by log-normal distribution functions, even using bimodal models. For the HHRA the individual stage data were used to calculate amounts of DU deposited in each region of the respiratory tract using the HRTM. The Capstone Report points out that this approach makes best use of the original data, and might well find application elsewhere. The reviewer agrees: it is entirely consistent with the principles on which the HRTM is based. The assumption of a log-normal distribution by the HRTM with deposition related (to a first approximation) to the AMAD and GSD was for ease of application. The use of the individual stage data requires nine calculations instead of one, but with the availability of suitable software nowadays that is not a problem. Nevertheless, the fitted AMADs and GSDs are useful to summarise the distributions. Appendix B gives more details. Figures B1-B7 (pages B.2-B.7) show AMAD as functions of time for each shot and sampling position (for the unimodal distributions): also listed in Table 5.25. Table B1 (pages B.8 – B.33) tabulates AMAD and GSD for each shot, position and time, for both unimodal and bimodal lognormal distributions.

As noted, it would be expected that since settling velocity increases rapidly with diameters above 0.5 µm, the AMAD would decrease with time, and generally this was seen. A "typical" pattern is for the AMAD for the first measurement to be a few (or a few tens of) microns, with subsequent values around 1 micron. However, there are exceptions. In particular, for the PIII-2 gunner position, several results, including those at 1 and 2 hours are >40 µm. For Phase IV there are only three results (driver position) and these show an increase in AMAD from 0.6 µm at 1 minute to 4 µm at 25 minutes.

The Capstone Report explains that: “The GSDs provide a description of how wide the size distribution is around the aerodynamic median diameter—the larger the number, the wider the distribution. A monodispersed particle size distribution (ie, one diameter only) would have a GSD of 1.0. A GSD of greater than 5 or 6 is considered to be a ‘broad’ peak. A GSD of greater than 20 is considered to be one that is not realistically connected to a ‘peak’. The HRTM assumes by default a GSD of 2.5 for aerosol AMADs greater than a few µm as typical for a single source. This in itself represents a broad distribution, with about 33% of activity associated with particles less than 0.4 times the AMAD or greater than 2.5 times the AMAD (Equation 14). The Capstone Report observes that the derived GSDs are very variable.

### 2.7.2 Aerosols produced by resuspension in the vehicle

Particle size distributions obtained by the loader’s array in PI-6 and PI-7 relating to resuspension during recovery activities are given in Table 5.27 (pages 5.56-5.57) and Figure B6. Values of AMAD fluctuate between about 1 and about 10 µm, which is presumed by the reviewer to reflect activities taking place.

### 2.7.3 Aerosols produced outside the vehicle

Aerosol size distribution parameter values obtained from analysing the results of the two Anderson CI for shots PI-5 to PIII-2 are listed in Attachment 1, Table 5.28, page 5.56. The results are extremely variable, although, taking the unimodal fits, they fall into two groups: six AMADs are less than 2 µm (five of them less than 1 µm, while the other nine are in the range 12 – 27 µm. The discussion is illustrated with reference to PI-5 CI-1.
The bimodal fit has 74% in the first peak (AMAD 2.0 µm, GSD = 48) and 26% in the second peak (AMAD 9.3 µm, GSD = 1.13). The reviewer considers that both GSDs are unrealistic: the first being too large to represent a “peak”, the second too small for an aerosol produced by such a process (specialised laboratory techniques are needed to produce an aerosol of this size with such a narrow distribution). The Capstone Report suggests that air movements within the enclosure may have caused the wide variability. This all indicates to the reviewer that the limited sampling did not give reliably representative results, and so the results are not useful for risk assessment purposes.

2.7.4 In vitro dissolution

*In vitro* dissolution tests were carried out on 27 samples, mainly from cyclone stages and back-up filters. A summary is given in Attachment 1, page 5.70, and full details in Appendix E. Dissolution in simulated lung fluid was measured for 46 days.

Time-dependent retention of undissolved DU was fit by two- and/or three-component exponential functions. Table 6 summarises the parameters of the fitted functions. Based on the two-component fits, there was a rapidly dissolving fraction of 1-28% (geometric mean, GM, 12.5%), with an associated rapid dissolution rate of 0.1-30 d⁻¹ (GM 6 d⁻¹; corresponding half-time, t₁/₂ = 0.12 d). The remaining fraction dissolved at a slow rate of 0.0004-0.0095 d⁻¹ (GM 0.0026 d⁻¹; t₁/₂ = 268 d).

Thus there was considerable variation between samples, especially in the fraction that dissolved rapidly. There appeared to be some correlation between the initial and final dissolution rates: The higher the dissolution in the first day, the faster the long term dissolution rate. In the Capstone Report the dissolution characteristics were compared with both the ICRP 30 lung model defaults (Classes D, W and Y) and HRTM defaults (Types F, M, S). For the former, each sample tested is assigned proportions to each Class (Table 5.37). For the latter, the Capstone Report notes qualitatively that most samples resemble Type M, but some (e.g. PI-3/4 cyclone back-up filter, and the “DU cone”) Type S. It points out (Appendix E, page E.11) that such variation is not surprising given the heterogeneity of both physical and chemical forms of the U-containing aerosols. ICRP Publication 71 (ICRP, 1995b) gives quantitative criteria for assigning materials to Types F, M and S. Based on these criteria, for *in vitro* dissolution tests, a material would be assigned to Type F if the amount remaining undissolved at 30 days was less than 13%, and to Type S if the amount remaining undissolved at 180 days was more than 84%. Otherwise it is assigned to Type M. These amounts are given in Table 6 (calculated by the reviewer from the fitted functions: the amounts at 180 days are predicted values, since the tests stopped at 46 days). On those criteria, no samples would be assigned to Type F, but in addition to the two identified in the Capstone Report, PIII-2 cyclone stage 4 would be assigned to Type S. The rest would be assigned to Type M. Note, however, that comparisons with the ICRP default values are only to put the results in perspective. The HHRA, like the RSWG assessment, used parameter values based on information available about the DU aerosols that might be inhaled.
Table 6 Results of *in vitro* dissolution tests

<table>
<thead>
<tr>
<th>Phase</th>
<th>Shot</th>
<th>Sample Description</th>
<th>Two-component A$_i$ (%) B$_i$ (d$^{-1}$)</th>
<th>Three-component exponential retention function A$_i$ (%) B$_i$ (d$^{-1}$)</th>
<th>R(30) %</th>
<th>R(180) %</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>2</td>
<td>driver IOM filter, sampling period 1</td>
<td>E.2 7.8 2.1 0.0014</td>
<td>E.7 5.7 4.7 0.18 0.00091</td>
<td>88.2</td>
<td>76.9</td>
</tr>
<tr>
<td>I</td>
<td>2</td>
<td>driver IOM filter, sampling period 3</td>
<td>E.3 13.8 2.4 0.0033</td>
<td>E.8 8.2 8.8 0.2 0.0022</td>
<td>77.9</td>
<td>56.0</td>
</tr>
<tr>
<td>I</td>
<td>2</td>
<td>driver IOM filter, sampling period 4</td>
<td>E.4 18.5 4.1 0.0034</td>
<td>E.14 6.2 7.5 0.14 0.0018</td>
<td>73.6</td>
<td>56.1</td>
</tr>
<tr>
<td>I</td>
<td>2</td>
<td>driver IOM filter, sampling period 6</td>
<td>E.5 13.6 1.9 0.0028</td>
<td>E.8 5 8.7 0.15 0.0016</td>
<td>79.2</td>
<td>62.2</td>
</tr>
<tr>
<td>I</td>
<td>2</td>
<td>driver IOM filter, sampling period 7</td>
<td>E.6 9.2 3.9 0.0039</td>
<td>E.7 6.2 4.2 0.13 0.0032</td>
<td>80.6</td>
<td>49.8</td>
</tr>
<tr>
<td>I</td>
<td>2</td>
<td>cyclone stage 2</td>
<td>E.7 13.9 13.7 0.0014</td>
<td>E.12 17.1 3 0.14 0.00073</td>
<td>82.4</td>
<td>73.8</td>
</tr>
<tr>
<td>I</td>
<td>3/4</td>
<td>cyclone stage 3</td>
<td>E.8 27.5 11 0.0069</td>
<td>E.22 21.7 13.5 0.15 0.0032</td>
<td>58.5</td>
<td>36.1</td>
</tr>
<tr>
<td>I</td>
<td>3/4</td>
<td>cyclone stage 4</td>
<td>E.9 21.6 26.1 0.0080</td>
<td>E.20 31.5 21 0.043 0.0021</td>
<td>61.2</td>
<td>40.4</td>
</tr>
<tr>
<td>I</td>
<td>3/4</td>
<td>cyclone stage 5</td>
<td>E.10 27.2 31.7 0.0095</td>
<td>E.11 63 8.2 1.9 0.0084</td>
<td>55.0</td>
<td>15.6</td>
</tr>
<tr>
<td>I</td>
<td>3/4</td>
<td>cyclone back-up filter</td>
<td>E.11 25.7 0.0009</td>
<td>E.12 25.7 0.0009</td>
<td>96.5</td>
<td><strong>84.8</strong></td>
</tr>
<tr>
<td>I</td>
<td>7</td>
<td>cyclone stage 1</td>
<td>E.12 28.2 4.1 0.0033</td>
<td>E.13 5.1 10.2 0.084 0.00067</td>
<td>64.4</td>
<td>57.5</td>
</tr>
<tr>
<td>I</td>
<td>7</td>
<td>cyclone stage 2</td>
<td>E.13 11.8 14.2 0.0018</td>
<td>E.14 21.8 5 0.11 0.00062</td>
<td>83.4</td>
<td>75.8</td>
</tr>
<tr>
<td>I</td>
<td>7</td>
<td>cyclone stage 3</td>
<td>E.14 25.9 4.5 0.0006</td>
<td>E.15 11.4 12.9 0.21 0.0025</td>
<td>64.0</td>
<td>44.0</td>
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<tr>
<td>I</td>
<td>7</td>
<td>cyclone stage 4</td>
<td>E.15 25.7 8.1 0.0050</td>
<td>E.16 16.2 10.9 0.19 0.0026</td>
<td>63.9</td>
<td>43.2</td>
</tr>
<tr>
<td>I</td>
<td>7</td>
<td>cyclone stage 5</td>
<td>E.16 21.9 21.8 0.0059</td>
<td>E.17 29.2 12 0.083 0.0024</td>
<td>64.7</td>
<td>44.5</td>
</tr>
<tr>
<td>II</td>
<td>1/2</td>
<td>cyclone stage 2</td>
<td>E.17 10.5 4.2 0.0019</td>
<td>E.18 14.5 6.4 0.19 0.001</td>
<td>84.3</td>
<td>72.5</td>
</tr>
<tr>
<td>II</td>
<td>1/2</td>
<td>cyclone stage 3</td>
<td>E.18 18.9 6.7 0.0033</td>
<td>E.19 7.8 4.7 0.091 0.0022</td>
<td>73.2</td>
<td>52.4</td>
</tr>
<tr>
<td>II</td>
<td>1/2</td>
<td>cyclone stage 4</td>
<td>E.19 19.8 6.6 0.0039</td>
<td>E.20 15.8 7.6 1.1 0.0035</td>
<td>71.3</td>
<td>42.2</td>
</tr>
<tr>
<td>II</td>
<td>1/2</td>
<td>cyclone stage 5</td>
<td>E.20 27.1 6.4 0.0068</td>
<td>E.21 16.2 16.8 0.039 0.0024</td>
<td>58.8</td>
<td>37.4</td>
</tr>
<tr>
<td>II</td>
<td>1/2</td>
<td>cyclone back-up filter</td>
<td>E.21 10.5 0.0066</td>
<td>E.22 12.2 11.2 0.055 0.0034</td>
<td>58.9</td>
<td>34.1</td>
</tr>
<tr>
<td>II</td>
<td>1/2</td>
<td>cyclone back-up filter</td>
<td>E.22 6.7 0.0029</td>
<td>E.23 7.7 8.8 0.039 0.001</td>
<td>77.6</td>
<td>64.5</td>
</tr>
<tr>
<td>III</td>
<td>2</td>
<td>cyclone stage 4</td>
<td>E.23 4 1.8 0.0013</td>
<td>E.24 2.7 3.8 7.5 0.044 0</td>
<td>91.8</td>
<td><strong>89.8</strong></td>
</tr>
<tr>
<td>III</td>
<td>2</td>
<td>cyclone stage 5</td>
<td>E.24 4.6 2.8 0.0024</td>
<td>E.25 8.2 8.0 0.0029 4E-17</td>
<td>88.7</td>
<td>62.9</td>
</tr>
<tr>
<td>III</td>
<td>2</td>
<td>cyclone back-up filter</td>
<td>E.25 3.9 0.0014</td>
<td>E.26 4.8 4.5 0.061 0.00041</td>
<td>85.4</td>
<td>79.6</td>
</tr>
<tr>
<td>I</td>
<td>1</td>
<td>PFDB screen assembly 7</td>
<td>E.26 20.5 0.084 0.0014</td>
<td>E.27 2.9 24.6 0.049 0.000031</td>
<td>77.9</td>
<td>72.3</td>
</tr>
<tr>
<td>I</td>
<td>5</td>
<td>DU cone bulk powder</td>
<td>E.27 1.4 6.2 0.0004</td>
<td>E.28 5.7 20.7 1.3 0.23 0.0013</td>
<td>97.4</td>
<td><strong>91.6</strong></td>
</tr>
<tr>
<td>I</td>
<td>5</td>
<td>DU cone size separated</td>
<td>E.28 16.2 0.0015</td>
<td>E.29 11.3 10.1 8.6 0.1</td>
<td>TypeF&lt;13 TypeS&gt;84</td>
<td></td>
</tr>
</tbody>
</table>

Geometric mean

| 12.5 | 5.7 | 0.0026 | 11.3 | 10.1 | 8.6 | 0.1 |
The Capstone report noted that the absence of Type F behaviour suggested that the conditions were not conducive to the formation of highly oxidised forms of uranium such as UO$_3$ or UO$_4$. However, it also notes the possibility that further oxidation could occur as a result of weathering, and therefore the results apply “directly to exposures that occur relatively soon after a DU impact event (minutes to weeks)” (Attachment 1, Page 5.70).

Discussion in Appendix E considers the effect of particle size. It is summarised below here, and all seems reasonable to the reviewer. The simplest assumption is that dissolution at the particle surface is the rate-determining step. In that case, the dissolution rate depends on specific surface area (SSA), ie, the fractional dissolution rate should increase with decreasing particle size (Mercer, 1967).

Sets of cyclone stage data were measured from 4 shots (shown in Figs E.29-E.32):

- PI-3/4 Stages 2, 3, 4, 5, back-up.
- PI-7 Stages 1, 2, 3, 4, 5, back-up.
- PII-1/2 Stages 2, 3, 4, 5, back-up.
- PIII-2 Stages 4, 5, back-up.

If the dissolution rate increases with SSA, the rate should increase with each stage. However, this is not apparent from the cyclone samples.

- PI-3/4 dissolution rate: back-up <2 <3,4 <5. The back-up filter is slowest, but in theory should be fastest.
- PI-7 dissolution rate: back-up, 2 <1,3,4,5. Similar to PI-3/4. The main difference between samples is in the rapid fraction. The long-term rates were all similar.
- PII-1/2 dissolution rate: back-up, <2,3 <4,5. As above. Back-up low, but others as expected. Main difference in rapid fraction.
- PIII-2 dissolution rate: Stage 4 <5 <back-up, as expected.

The five IOM (PI-2 driver position) samples were collected in sequence (1) 5-35 sec; (3) 1.30-3.30 min; (4) 3.30-7.30 min; (6) 15.30-31.30 min; (7) 32.30-60.30 min; and would therefore be expected to have sequentially smaller particles, as the larger ones were removed by sedimentation. Hence expect rate 1<3<4<6,7, but observed rates (Fig E.33, Table E.4): 1<3,6,7<4: the order appears almost random.

Two tests were carried out on the “Cone sample”, which was almost entirely DU oxide: “Unseparated” was bulk powder, and “Separated” was size-segregated by sedimentation in alcohol. “Separated” had both a larger rapid fraction and higher slow rate, consistent with sedimentation removing larger particles, and size-dependent dissolution.

Thus there was no clear trend of dissolution with particle size. The Capstone Report noted two confounding factors were:

1) cyclone cut-offs are not sharp, so there was considerable overlap in size distribution between stages.
2) heterogeneity of particle composition, shape etc. A review of SEM results showed several discrete forms of uranium-bearing particle.
The effect of the target was also considered, by comparing the same cyclone stage from different shots (Figs E.35-E.39). For Stages 2 and 3 there were conflicting findings.

- Stage 2: PII (BFV) dissolved faster than both PI (Abrams), which were similar.
- Stage 3: PII (BFV) dissolved slower than both PI (Abrams). For BFV, Stage 2 and 3 similar; P-I different.
- Stage 4 and Stage 5: PI (shots 3/4 and 7) and PII (shots 1/2) similar, but PIII (DU-Abrams) dissolved slower.
- Back-up: PI (shots 3/4) least soluble.

Overall, it was "difficult to discern consistent trends". No consistent difference between side-armour of BFV and Abrams, but small PIII (DU on DU) aerosols seem to dissolve slower than those from side armour.

2.7.5 Analysis of aerosols with respect to shot characteristics

Chapter 6 of Attachment 1 is entitled "Aerosol data analysis", and discusses the results (which were previously described by type of result: concentration, size distribution, etc.) in relation to the mechanics of the impact and composition of the target.

Section 6.1 brings together all the results for each Shot.

In Section 6.2 the data from Section 6.1 are reorganised so that the aerosol properties are grouped by scenario and are discussed in terms of their general similarity and their distinctiveness. Sub-sections describe DU aerosol concentrations and settling times by shot lines and particle size distributions as a function of time. DU aerosol concentrations are considered over several time intervals:

- The first 5 seconds. The video taken inside the turret suggests that the aerosol created by vehicle perforation disperses instantly and that mixing continues by turbulence. The MVF was the only instrument that collected aerosol samples during the first 5 seconds. Peak concentrations ranged from 1.1 to 9.1 grams m$^{-3}$, about an order of magnitude difference, and occurred at a minimum of 1.4 seconds and a maximum of 13 seconds after impact. The shot through the Bradley (PII-3) provided the lowest DU aerosol concentration, and the shots through the DU armour (PIII-1 and 2) had the highest peak DU aerosol concentrations.

- The first few minutes. The IOM filters provided the main source of information. As for the MVF, concentrations were highest during the first sampling interval (from 5 seconds to between 10 and 30 seconds later) concentrations ranged from 0.5 grams m$^{-3}$ (BFV turret shot PII-3) to 36 grams m$^{-3}$ (Abrams DU armour PIII-2). It was noted that in several shots aerosol concentrations were similar at the different sampling positions, indicating that aerosol dispersion occurred quickly. There was a drop of a factor of about 2-5 by the second measurement (midpoint 0.75 – 3.25 minutes post shot).

- 30-60 minutes after impact. Aerosol concentrations fell by about two orders of magnitude by 20-30 minutes after impact and by another factor of two by an hour.

- 2-4 hours after impact. Measured concentrations before recovery operations started following PI-6 and PI-7 were about 3 mg m$^{-3}$ and 1 mg m$^{-3}$, respectively, providing additional time points (Attachment 1 page 6.39).

It is stated (Attachment 1 page 6.47) that “Although an assessment of the mechanisms of aerosol particle formation is outside the scope of this report, some speculation may
be useful." Section 6.4 does provide some interesting discussion of mechanisms, briefly summarised here by the reviewer. It notes that at high temperature and low water content, uranium oxidation proceeds as follows:

\[ \text{U}_{\text{metal}} \rightarrow \text{UO}_2 \rightarrow \text{U}_4\text{O}_9 \rightarrow \text{U}_3\text{O}_8 \rightarrow \text{UO}_3 \]

Schoepite (\(\text{UO}_3\cdot2\text{H}_2\text{O}\)) is likely to form at ambient temperatures, in the presence of moisture. The Capstone aerosols were formed at high temperatures. However, the variety observed in the morphology indicates a variety of temperatures of formation and cooling rates, and consequently mechanisms. Some particles showed signs of melting, others did not. The situation was complicated by the presence of other materials and the agglomeration and coagulation that took place. Temperatures were not measured at the site of formation (point of impact) but the presence of Fe, Al and U in droplet type particles suggests a temperature above 1500°C (melting point of Fe). Similarly the absence of SEM evidence that the DU had vaporised, suggests that the maximum DU-metal temperature was less than 4000°C. However, it was noted that the temperature was potentially in the range of 3000°C because a significant amount of aluminium is believed to have vaporised.

2.8 Report

A very comprehensive report was produced, giving full details. Problems (and occasional errors) are described with remarkable candour. Several are outlined below in the Section (2.10.1) on issues identified in the first few shots. Another example is described in Attachment 1 pages 3.41-3.42. It was intended to measure sample masses by comparing CI collection substrate masses before and after the test. However, in many cases the substrate weighed less after than before, although there was evidence of collected material. Despite intensive investigation, the cause was never identified.

In the reviewer’s opinion, this detailed reporting and openness increase confidence in the results, and potentially provide useful information for those carrying out assessments based on the results and those who might be involved in future similar tests.

2.9 What might have been achieved with more time and resources

As noted in the Introduction (Section 1.1), in this review the Capstone Program’s achievements and limitations are considered not in relation to the objectives of the Capstone Program itself, but in relation to the wider requirements of assessing exposures to DU resulting from its use in weapons, and from a UK perspective. Thus consideration is given to the extent to which the Capstone Program filled gaps in information identified by assessments such as that carried out by the RSWG.

In considering what might be regarded as ‘shortcomings’ or limitations of the study, it should be recognised that resources were finite, and also that many of the issues are fully recognised by the Capstone team and identified in the Capstone Report. However,
Attachment 5, Page 12 states: “Therefore, the focus and the primary reasons for ensuring the quality of this DU Exposure Assessment and Health Risk Characterization, updated with the DU Capstone Test data, are:

a) Trust of the soldier and DOD/DA civilian, his/her family, military commanders, the military veteran, US Allies (Coalition Forces), the media, the citizens of the United States, and the Congress.

b) Scientific credibility of the DU health risk assessment product.”

Since US Allies are recognised as being among those whose trust is sought, one option for increasing resources might have been to involve Allies as collaborators, e.g. in sample or data analysis.

As with the achievements, most of these issues relate to the experimental work undertaken, but some to analysis in terms of the processes involved (rather than the risk assessment, which is considered later) and a few to the report on the studies. The following sections (2.10-2.12) consider each aspect.

2.10 **Experimental work**

In view of the hostile conditions, and that relatively few attempts have previously been made to carry out air sampling under such conditions, it is not surprising that problems arose, some, but not all of which were overcome during the programme.

2.10.1 **Issues identified during the study.**

A number of issues were identified that led to changes in procedures during the course of the study, and these are listed first.

2.10.1.1 **Damage to sampling arrays.**

Attachment 1 page 3.6 onwards describes the development of the shielding of the main sampler arrays.

Initially, 0.64-cm thick steel louvres were used to protect the aerosol samplers from fragments, but some filters were damaged in the first shot, apparently by high pressure and temperature, and hot particles. In the second shot, a bottom-hinged flat metal plate covered the louvre at the gunner’s position in an attempt to improve filter survival; however, this plate, which was released shortly after the shot was fired, offered little or no improvement. Solid steel covers were employed and sample media were changed in subsequent tests to avoid this problem. These covers had drop-down doors that were remotely released 3 seconds after impact, and sampling was initiated 5 seconds after impact. The cyclone and moving filter (MVF) samplers were placed in a steel box in the crew compartment to allow for collection of aerosols through sample inlets.

2.10.1.2 **Sampler overloading**

For Shot PI-1, the sampling duration sequence was 0.5, 1, 2, 4, 8, 16, 32, 64 minutes. Because of some overloading, for later shots, the sampling times were reduced, eg for
PI-6 the sequence of sampling times was 10, 10, 10, 30 seconds, 1, 2, 4, 8 minutes (with intervals between).

2.10.1.3 Choice of filter material
Attachment 1 page 3.18 notes that the filters in the IOM samplers closest to the penetrator exit holes were damaged in the first two shots. Filters of a different material (Teflon) were substituted and used successfully in the remaining tests.

2.10.1.4 Cyclone train flow rate
It is noted (Attachment 1 p 3.20) that “Initial plans called for the cyclone to be operated at a flow rate of 10 Lpm so the cutoff diameter for Stage 1 would be approximately 10-\(\mu\)m aerodynamic diameter (AD), which is the cutoff diameter specified by Phalen et al. (1986) for thoracic deposition.” However, the actual flow rates ranged from 9.0 to 13.4 Lpm, so that the cutoff diameter for Stage 1 varied between about 8 and 10 \(\mu\)m. This was a minor problem, and it is commendable that it was recognised and reported.

2.10.1.5 Ultrafine particle sampling
The Capstone Report records (Attachment 1 p 3.20) that because of considerable uncertainty regarding the existence of an ultrafine particle fraction in the interior atmosphere, the exit filter of the cyclone train was replaced with a parallel-flow diffusion battery (PFDB) during the first shot. Few details of its design are given, but it does state that: “This seven-cell, screen-type diffusion battery has a useful range from 0.005- to 0.5-\(\mu\)m AD and collects particles that pass through Stage 5 of the cyclone. The PFDB with Supor filters was flowmatched and calibrated with the cyclone at 14 Lpm. Measurement of both total mass of particles (by gravimetric analysis) and DU concentration (by radiological and chemical analyses) was planned using these ultrafine particle size fractions. The PFDB is a complicated apparatus, and in spite of exceptional efforts to seal all components, a leak may have developed during the first shot. For the remaining tests, the standard backup filter apparatus (actually a set of four filters, nicknamed a “spider”) replaced the PFDB.” Thus it seems to the reviewer that a reasonable attempt was made to characterise the ultrafine fraction under very difficult circumstances.

The reviewer notes that in some previous tests (eg, Glissmeyer and Mishima, 1979, Chambers et al, 1982) a large fraction of the aerosol was found on the backup filter of the CI, and so was associated with particles of \(d_{\text{in}}\) less than about 1 \(\mu\)m. Also, Patrick and Cornette (1978), from SEM studies, drew attention to the presence of ultrafine particles usually on the surface of larger particles but also as agglomerates.

There is (as recognised in the planning as reported above) considerable interest in the significance of an ultrafine fraction. The reviewer notes that their lung clearance characteristics can be very different from those of larger particles, as noted in ICRP Publication 66, paragraph E.70 (Bailey and Roy, 1994):

- much slower clearance of particles from the deep lung to the GI tract via the bronchial tree
- significant direct transfer to blood for particles smaller than a few nanometres diameter.
There is also potentially faster dissolution because of their much higher surface area per unit mass (Section 2.7.4 above).

There is also an issue with regard to the toxicity of ultrafine particles per se, as physical rather than chemical agents. (In this context ultrafine particles are usually defined as particles with physical diameters less than 0.1 µm diameter.) There is current interest in ultrafine particles (mainly from fossil fuel combustion) in the ambient air, and their possible role in adverse health effects (e.g. Kreyling et al 2004).

Hence, it is understandable that plans would be made to investigate the sub-micron and ultrafine fractions. It is regrettable that a problem arose and this did not happen. As the problem was attributed to leakage, one would expect that given time and effort it might have been overcome. There is little discussion of the issue in the Capstone Report. There is some further information in Attachment 2 (page A.6). It is noted there that the PFDB collected aerosol normally, but it was thought that a leak developed that made flow rates and hence size selection of each collector unreliable. Attachment 1 page 4.6 states that the leak may have been responsible for a measured flow rate of 31 Lpm, compared to the intended 14 Lpm.

It is however noted (Attachment 1, page 5.23) that “Analysis by SEM later revealed that material on the filters was consistent with collection of very fine particles (0.1 to 0.5 µm) but probably few that would qualify as being in the ultrafine range (less than 0.1 µm).” Hence the reviewer speculates that the problem could not be solved within the time-scale of the test programme, and that possibly lack of evidence for a large ultrafine fraction in the results might have made it seem a less important issue than at the planning stage.

2.10.1.6 Sealing the vehicle
The aim was to have the vehicle closed, to obtain upper bounds on the aerosol concentration. Attachment 1 page 3.9 notes that the vehicle gun was not needed for the field tests and was not attached for the first Phase I shot. An inflated ball was placed in the gun breech to seal it, but was not effective. Subsequently a gun tube was in place, and a blank shell casing was sealed into the breech.

The hatches were closed and secured prior to all shots. After the fourth shot, the hatches were bolted but nevertheless sometimes opened.

2.10.1.7 Air sampling outside the vehicle
As noted (Attachment 1 page 3.31-3.32), for PI-1 and PI-2 the high volume air samplers (Hi-Vols) had to be operated manually (subsequently they were operated remotely), and also the filters overloaded (subsequently sampling times were reduced). Cascade impactors were not available until PI-5, and then became the primary sampling method. Although metal shields were installed to protect the tubing, electrical wires, and samplers during the impact events, damage to the hoses occurred, thus reducing the amount of usable data. Beginning with PI-6, the exterior CIs and the Hi-Vols were angled away from the impact point to reduce the opportunity for fragment damage.

The Superbox uses an armour ‘catch plate’ to stop and contain the penetrator exiting the target within the fragmentation chamber. The impact generates DU aerosol outside
the vehicle, increasing the concentration above that which would occur in an open battlefield. Attempts were made to mitigate this problem, using a ballistic polyethylene covering over the catch plate, and an aluminium plate in front of it to limit dispersion, but neither was effective.

2.10.1.8 Sample preservation
Attachment 1 Page 3.42 notes that from Phase II onwards, samples from the cyclone to be used for chemical analyses were placed under a nitrogen atmosphere to prevent further oxidation.

2.10.1.9 Radioactivity measurements
For expediency and cost, given the large number of samples, beta and gamma activities were used to assess uranium masses in samples. Beta counting also avoids the potential problem of self-absorption that would arise with alpha counting (Attachment 1, Page 5.6). However, beta counting relies on the assumption that the short lived decay products of U-238 and U-235 are in equilibrium. U-238 decays to Th-234 (24.1 d) and then to Pa-234m (1.2 minute), which decays to long-lived U-234. Attachment 1, Page 3.45, notes that it was found that this was not always the case.

The problem and steps taken to overcome it are discussed further in Attachment 2 (page A.10 onwards). The effect was greater on smaller aerodynamic diameter CI samples. Most samples were measured by beta counting at Aberdeen Test Centre (ATC) Health Physics Laboratory. There is extensive description of comparisons between ATC beta-measurements and USA CHPPM ICP-MS (absolute) to calibrate/validate, especially after the problem was recognised. Page A.17 further recognises that if some Th-234 separated during the impact process, at short times there could be Th-234 & Pa-234m activity that is not associated with the uranium in the sample, leading to an over-estimate of the DU present.

2.10.1.10 Ventilation rates
As described in Attachment 1, page 4.50, and Appendix G, after each shot was fired, the measured SF6 concentration increased steadily rather than decreased. This result was totally unexpected. It may have been caused by interference from combustion gases, but the real reason is not known. The concentration decreased about 2 hours later, when the Superbox ventilation system was turned on. Therefore, the ventilation rates after the shots were fired could not be estimated.

2.10.1.11 Mass balance
As noted in Attachment 1, page 4.50, a total DU mass balance analysis was not conducted because of the near impossibility of retrieving the portion of the DU penetrator imbedded in the catch plate, and because penetrator fragments were scattered over a wide area. The test team decided that attempts to recover the residual material would not provide sufficiently worthwhile information to justify the use of significant resources.

2.10.1.12 Pilot trials
These issues together suggest to the reviewer that if one or two pilot trials could have been carried out, and samples from them analysed, well in advance of the main programme, solutions might have been found.
Attachment 1 Page 3.3 notes that the twelve test shots were carried out over a period of about 4 months. Although not stated in the Capstone Report, it seems reasonable to speculate that there was a considerable overhead of effort in setting up the Capstone tests and clearing up afterwards, and hence an interval between a pilot and main study might have added substantially to the costs. Another possibility is that the Superbox facility was needed for other studies, which would have constrained the Capstone Program timetable.

However, Attachment 1 Page 4.4 notes that Shot PI-1 was initially viewed as a Superbox “shakedown” or pilot test, but because of its success, it was designated Shot 1. This seems to the reviewer reasonable, in order to make use of all available information, since relatively minor changes were made to the procedures following Shot 1.

2.10.2 Other issues

2.10.2.1 Transuranium elements

A single fragment from one penetrator was analysed by alpha spectrometry, with the stated aim of determining whether the concentrations of transuranium elements were consistent with those reported previously for US DU munitions. (Attachment 1, pages 3.50 and 5.64). However, no detectable amounts of Pu, Np or Am were measured. This suggests to the reviewer that either a larger sample or more sensitive technique was needed, but it is recognised that this was not a major objective of the study. The uranium isotopic composition of this fragment and that of the “DU oxide cone” (formed when a fragment oxidised) were analysed by thermal ionisation mass spectrometry (Attachment 1, page 5.62). The presence of U-236 suggested that a small amount of contamination from reprocessed fuel was present (AEPI, 1995).

2.10.2.2 Characterisation of aerosols

Attachment 1, page 5.59, notes that “Cost considerations limited the number of cyclone samples characterized to one from each phase.”

Attachment 1, page 7.9, notes that most of the detailed analyses were carried out on samples collected by the cyclone. As these ran for the entire sampling period, they do not provide information on how factors such as chemical composition might have changed over this time period.

In the opinion of this reviewer, it would have been useful (if resources had been available) to determine aerosol characteristics over at least a few broad time intervals. For example, the HHRA considers time intervals of potential exposure for those inside the struck vehicle of 1 or 5 minutes and 1 or 2 hours (Table 1). As outlined in Sections 2.7.1 and 2.7.5 above, there were large differences in DU air concentration and/or size distribution between the first few seconds, the next few minutes, and the next hour or so. It would therefore be useful to know if there were also significant differences in composition between these periods. However, whether this would have been technically feasible, e.g. whether there would have been space for additional cascade cyclones is not known.
2.10.2.3 Particle morphology
Attachment 1, page 3.51 notes that only cyclone samples and their backup filters were used. The particle morphology for selected samples was evaluated using an SEM equipped with an EDS system. A "touch grid" sampling of particles was collected by physically touching the SEM stubs to the aerosol sample, thus transferring a number of particles to the stubs. The stated particular advantage of this method was that it eliminated the need for aerosol sampling using point-to-plane electrostatic precipitators, additional extractive probes, high voltage power supplies, etc.

However, it is not self-evident that this method would transfer a representative sample of particles to the stub, and this is not discussed in the Capstone Report.

2.10.2.4 Cascade impactor and cyclone calibration
The effective cut-off diameters of the CI stages were based on the manufacturer’s calibration. In view of the central place of the particle size distributions in the study, and considering the high level of QA/QC applied elsewhere, the reviewer considers that it would have been useful if independent, confirmatory checks had been made on the collection characteristics of at least a sample of the instruments. It is noted in Appendix D, page D3 that less difference than expected was observed by SEM between particle sizes from different cyclone stages.

Presumably LRRI at least has facilities for calibration of such instruments. This might involve measuring the collection efficiency of a stage as a function of $d_{50}$. One approach is to use a real-time instrument that measures aerosol concentration as a function of $d_{50}$. A polydisperse aerosol is generated and the size distribution measured before and after the stage, and compared. However, in the subsequent analysis, the DU aerosols are represented by a combination of monodisperse aerosols. An alternative approach would be to sample suitably labelled monodisperse aerosols of similar sizes, and measure the amount deposited on each stage.

2.10.2.5 Particle dissolution
The dissolution rate of DU particles in the lungs has been identified previously (e.g. Royal Society, 2001) as an important factor in prospective health risk assessments. In the reviewer’s opinion it probably comes next after the intake: the mass (and so activity) of uranium inhaled, and the size distribution, which determines the fraction of the intake deposited in the lungs. For a given lung deposit, the early phase of dissolution determines the amount of uranium reaching the bloodstream, and hence the maximum concentration in the kidneys (and other) organs. The long-term dissolution rate determines the radiation dose to the lungs, which is the main factor in the radiological risk assessment. In addition, the dissolution rate in the lungs is a key factor relating the intake to the urinary excretion rate, and hence in the (retrospective) assessment of exposure and resulting consequences from measurements of uranium in urine.

The importance of the former is recognised in the Capstone Report. For example, the Data Quality Objectives include: “The following data requirements are needed to address DU exposures identified in DQO 1…, gastrointestinal tract solubility… and lung solubility and dissolution rates of respirable size DU particles.”

Although the term “solubility” is used, the reviewer notes that it is only used qualitatively. “Solubility” is normally defined quantitatively in terms of the concentration of a solute in
solution in equilibrium with the undissolved solid. That was not measured, and would be inappropriate here because the process is not reversible. There is no equilibrium, because if the solution were evaporated the precipitate would be different from the original material, which contained oxides that are stable at high temperatures. Similarly, the term “dissolution” is used broadly, since the process is not reversible as it would be for salt or sugar, but involves chemical reactions.

In vitro dissolution tests were carried out on 27 samples. The summary of the procedure used (Attachment 1, page 3.51) states: “The in vitro solubility of DU present in the aerosol samples was measured at LRRI using the static dissolution technique described by Kanapilly and Goh (1973) and Eidson and Griffith (1984). The aqueous solvent employed was synthetic ultrafiltrate (SUF; Eidson and Griffith 1984), with a composition based on Gamble’s solution, which is a laboratory surrogate for extracellular fluid (Gamble 1967). The basic in vitro test for solubility uses a simulated lung fluid as the sample matrix into which the sample is inserted for a period of at least 30 d and as long as 60 d.”

In this reviewer’s opinion, there is one major issue here and two minor related issues:

- Is the dissolution rate measured in vitro by this technique a reliable guide to the dissolution rate in the lungs?
- The dissolution rate was measured for 46 days. At this time most of the material (geometric mean 70%) remained undissolved. Its dissolution rate was estimated by extrapolation. The dissolution rates tend to decrease with time, and might well have decreased further at later times.
- No corresponding measurements were made of absorption of uranium from the particles in the gastro-intestinal (GI) tract, or even in a simulant for the GI tract environment.

Furthermore, there is no discussion, or apparent recognition of these as issues. Thus, there is no attempt made to justify the use of a “synthetic ultrafiltrate”, beyond the references above.

However, it is neither self-evident, nor universally accepted that dissolution measured in vitro will be a reliable guide to dissolution in the human lung (or GI tract). The Capstone Report itself recognises that the process is sensitive to conditions. Appendix E, Pages E4-E5 give some details. Flowing 5% CO₂ was used to maintain the pH at 7.4. In a closed container, the pH rises to 8.0 in 24 h, and to 9 in 48 h. For the uranyl ion this will shift equilibrium from soluble carbonate to insoluble phosphate. The reviewer notes, however, that the tests were run at room temperature, not body temperature. This would not necessarily have affected the results. For example Eidson and Griffith (1984) found that temperature (room temperature or 37ºC) had little effect on the dissolution rate in SUF of “yellowcake”, a mixture of U₃O₈ and ammonium diuranate. However, it would have been useful if this had been confirmed for the DU impact aerosols.

The issue of the applicability of in vitro dissolution tests to assessment of absorption from the respiratory tract has been addressed directly in some recent ICRP documents,
in the preparation of which this reviewer was involved. A brief summary follows. More information is given in Appendix A to this review.

ICRP Publication 66 (ICRP, 1994) which describes the Human Respiratory Tract Model (HRTM) considers that determination of the absorption rate of a material requires in vivo measurements of lung clearance of the material, and the study should be of sufficient quality to merit publication in a peer-reviewed journal. ICRP Publication 71 (ICRP, 1995b) which applies the HRTM to derive inhalation dose coefficients for members of the public, recommends that material-specific rates of absorption should be used in the HRTM for compounds for which reliable human or animal experimental data exist. For other compounds, default values of parameters are recommended, according to whether the absorption is considered to be fast (Type F), moderate (M) or slow (S). Neither of these ICRP documents supports the use of in vitro data beyond assigning a material to one of the default Types (F, M or S).

However, more recent ICRP (2002) guidance on application of the HRTM recognises that in vitro dissolution tests can provide information that enables better assessments to be made than reliance on general defaults, but with reservations. It notes that specific information should be used in preference to default values wherever appropriate, and that this applies particularly to values of absorption parameters since they depend on the physico-chemical form of the inhaled material. It notes that “These specific values are generally derived either from in vitro dissolution experiments or from in vivo data from animal experiments.” It also notes that, although not a specific assumption of the HRTM, it is assumed that rates of dissolution and absorption to blood are the same in different mammalian species, and if in vivo data are not available, that the dissolution rate in an appropriate in vitro system is the same as that in the human lung.

In this reviewer’s opinion, given the number of samples involved, the best approach would have been to validate the applicability of the in vitro measurement technique as a guide to dissolution in the lungs, by carrying out in vivo measurements on a selected sub-set of samples. Preferably this would have been done in more than one animal species to address the issue of possible interspecies differences. It would also have been useful to carry out similar measurements on samples of well-defined oxides (UO₂, U₃O₈, UO₃) for comparison (Section 2.13.3 below).

In this reviewer’s opinion, it would be reasonable to expect at least a discussion of the issue with justification based on any previous comparison of the technique with in vivo results, especially for uranium compounds.

For example, one of the studies considered by the RSWG (Scripsick et al, 1985a,b) did discuss the issue. Scripsick et al referred to an in vivo study (Damon, et al., 1984) which demonstrated agreement with in vitro tests previously conducted on samples of the same “yellowcake” uranium mill products (Eidson and Mewhinney, 1980). Eidson and Mewhinney reported that “yellowcake” is a mixture mainly of ammonium diuranate (ADU) and U₃O₈. They associated the rapid dissolution phase with the ADU, and the slow phase with U₃O₈. (Generally there was good agreement between the fraction of ADU determined by infra red (IR) analysis, and the fraction dissolved rapidly). As solvent, they used a “simulant of an ultrafiltrate of blood serum” (SUF) containing DTPA. DTPA was added, “to prevent the formation of insoluble phosphate precipitates, which
might result in an underestimate of yellowcake solubility”. Damon et al administered two of the four uranium mill products to rats by inhalation, and followed lung clearance up to 6 months. They expressed lung retention as a two-component exponential function with half-times of ~1 d and 180 d. For “Mill A” the fraction cleared rapidly from the lungs was 78%, compared with 86% rapid dissolution \textit{in vitro} and 82% ADU by IR. For “Mill D” the fraction cleared rapidly was 25%, compared with 26% rapid dissolution \textit{in vitro} and 25% ADU by IR. Damon et al. concluded that an \textit{in vitro} test could be used to determine the ADU:U$_3$O$_8$ ratio in yellowcake samples. Thus for yellowcake the \textit{in vitro} test was shown to provide guidance on the rapidly dissolved fraction. Similarly, Eidson and Griffith (1984) found that temperature (room temperature or 37ºC) had little effect on the dissolution rate in SUF of yellowcake.

Attachment 1, page 7.9, notes that the dissolution measurements were made only on uranium, and that it would be desirable to determine dissolution rates for other metals present. (Section 7 of Attachment 1 forms its ‘Conclusions’). However, in this reviewer’s opinion, if additional resources were available, validation of the dissolution tests carried out on the uranium should have higher priority, since it is the DU exposure itself that is of most concern.

2.10.2.6 Personal air samplers during recovery activities

Two recovery personnel each wore two personal air samplers: an IOM filter and a CI. To minimise the weight carried, the two samplers were connected to a single pump, which was operated at 4 Lpm to try to provide 2 Lpm to each. However, it is not known how evenly the flow was divided, adding an unknown uncertainty to the analysis. The CI data are tabulated (Appendix A Table A.41), but size distributions were not determined.

2.11 Analysis of results

2.11.1 General

It is noted (Attachment 1, Page x) that more data are in the report than the project team had time to evaluate, and this gives opportunities to others. It does not however elaborate on which data.

2.11.2 Generalised model for prospective assessments

The Capstone DU aerosol study provides remarkably comprehensive information about the DU aerosol concentration and size distribution as a function of time after impact, with valuable supplementary information, but for a limited number of test conditions. Most of the shots: the ten in Phases I-III which have the full data sets, were all expected to be towards the upper end of the range, in that there was no ventilation system operating, and hatches were closed. For the single Phase IV shot involving vehicle penetration by a DU round, with the vehicle ventilation system running, concentrations were much lower.

Ideally, models would be developed to predict the characteristics of the aerosol formed in other situations: at least for vehicles fitted out for operation and ventilated, but preferably extended to other vehicle types. Such models might range from a simple
physical model in an idealised geometry to a complex numerical model that took account of the detailed vehicle geometry etc.

However, in the HHRA a simple model is developed for the reduction in concentration with time taking account of ventilation and deposition onto surfaces (Attachment 3, pages 3.24-3.31). As a test of the model, the reduction in concentration with time was compared for shots PIII-1 and PIV-4. Both were for a DU round penetrating DU armour on an Abrams tank, but for PIII-1 there was no ventilation, whereas for PIV-4 the EC/NBC system was operating. The predicted reduction in concentration applied to the PIII-1 data was in reasonable agreement with the PIV-4 data. However, this model was not applied in the HHRA to dose and risk assessment, and so no assessment was made of what might be a “typical” exposure, corresponding to the RSWG “central” estimate, (other than those based on the single Phase IV test which involved DU armour).

Ideally, such models would be tested (validated) using the results of trials that were not used in the development of the model. If resources were available, this would mean further trials. Otherwise there may be existing data sets, perhaps from the studies of Fliszar et al (1989) or Chazel et al (2003).

2.11.3 Mechanisms of particle formation
Although a considerable amount of information was obtained on particle morphology and composition, there is relatively little discussion of how they might be related to the characteristics of the events. Such results are generally more valuable when used in conjunction with others: to help in explaining other more quantitative observations.

It is noted in Appendix D, page D1, that SEM analysis was limited to examination of relative sizes and particle elemental compositions. “Analysis of the mechanisms of particle formation was outside the scope of the study, although possible mechanisms are discussed in this report for certain cases.” Ideally, consideration would have been given to such mechanisms, and how they relate to the impact parameters. For prospective assessments, understanding of the mechanisms would be a major advantage in extrapolating to other situations.

2.12 Report

2.12.1 Choice of test site and facilities.
Attachment 1, Page 2.3 notes: “After evaluating possible test sites, the study team selected ATC’s Superbox facility located on the Ford’s Farm range at APG to carry out the testing program.” It would be interesting to know what the other possible test sites were, and what their advantages and disadvantages were. The reviewer’s understanding is that the Superbox was designed to contain the DU produced in impacts and prevent environmental contamination. On that basis, there would need to be strong reasons for using a facility without such containment.
2.12.2 Real-time aerosol measurements
Attachment 1, Page 3.12 notes that real-time instruments were considered but not used because 1) they might not survive the hostile test environment, and 2) they could not be operated at very high aerosol concentrations. Hence the moving filter device was chosen to obtain the time-sequence aerosol profile, especially during the initial sampling period, because its simple design stood a better chance of surviving, and because particles collected on its substrate could be analysed.

Since consideration was given, it would have been helpful to describe possible techniques, with their advantages and disadvantages for the benefit of anyone planning future similar studies. Presumably advantages might include greater temporal resolution, and perhaps information about variation in concentration within the vehicle.

2.12.3 Aspiration efficiency of the air samplers
Aspiration efficiency is not discussed directly, but is relevant, especially when comparing results from different instruments, because initially, at least, large particles were present, and might well have accounted for a large fraction of the mass concentration.

The IOM filter has only a short, wide inlet, and so might be expected to have a high aspiration efficiency for large particles.

There is no clear view or diagram of the inlet to the Marple CI. It is noted (Attachment 1 p 3.19) that “The CI inlets were modified to change the standard right-angle inlet to a straight-through configuration to allow the arrays to be installed more efficiently at the crew sampling stations. The nominal cutoff diameter for the first stage of the Marple CI is 21 µm…” This suggests the presence of an inlet that would reduce the aspiration efficiency for large particles, but it could not be too low, since the cut-off diameter for the first stage is quite large.

The cyclone and moving filter sampler were mounted inside a stainless steel box with their inlets outside. No information is given on their aspiration efficiencies. It is noted (Attachment 1 p 3.19) that: “Because the IOMs and MVF have no pre-cutter to remove large particles, they collect suspended particles of all sizes and represent the total concentration of suspended particulate matter during the active time period sampled.” However, the efficiency with which larger particles are collected depends on the inlet geometry, flow rate etc., and this is not addressed.

The issue arises specifically in the HHRA. A decision is made to use air concentrations measured by the CI results rather than the IOM filter results, because the latter samples large particle more efficiently, and therefore the size distributions measured by the CI did not represent the mass concentrations measured by the IOM filters. Similarly the MVF is used to fill the 5-second gap in measurements before the CI and IOM samplers started. Comparison of the MVF results with others should take account of differences in aspiration efficiency. The approach taken seems reasonable to this reviewer, but it would have been useful if the issues had been addressed and explained more directly.
2.12.4 Uranium oxide composition
Attachment 1 page 3.50 notes that “The oxidation sequence of typical uranium products in order from metal to phases of progressively greater oxidization is the following: U > UO₂ > U₄O₉ > U₃O₈ > UO₃ > UO₃•2H₂O (known as schoepite).” However, U₄O₉, unlike the other forms, is not well known. For example it is not listed in older editions of the well-known CRC Handbook (eg CRC, 1984). It is in more recent editions (eg CRC, 2001), but with no information on melting point, boiling point or solubility. It would therefore be helpful if it was described, along with its properties, and how they compare with the more familiar forms: UO₂, U₃O₈ and UO₃. It seems reasonable to assume that it has properties intermediate between those of UO₂ and U₃O₈, but it would be helpful to give information, since it was identified as a major crystalline component.

2.13 Comparison with other results
Ideally the Capstone Report would have included a comparison with previous studies. (It is a common feature of the “Discussion” section of a research report, following the results.) The authors were well placed to do this, especially as some were involved in the previous studies. It was however a specific objective of this review (Section 1.4).

The scale of the Capstone Study provides perspective on the variability in the values of a range of parameters. The other studies available involved small numbers of samples and are therefore much less likely to provide representative values. This generally limits comparisons largely to whether or not the results are consistent.

The following is based on Annexes C and G (Bailey et al, 2001; Bailey, 2001) to Appendix 1 of Royal Society (2001), with some additions. Tables are reproduced here by kind permission of the Royal Society.

2.13.1 Air concentration and fraction of penetrator aerosolised
The studies reviewed by the RSWG and summarised in Annexe G involved impacts of penetrators against armour plate. They provide two types of information relating to the source term: measurements of the air concentration and estimates of the fraction of the penetrator aerosolised (Table 7).

One report (Hanson et al., 1974) relates to small-calibre munitions, the others to large-calibre munitions. In one case (Hanson et al., 1974) the impact was largely contained by enclosures, but their combined volume (~0.5 m³) was much smaller than that of a vehicle, which would tend to overestimate the initial concentration. The others seem to have been conducted outdoors, or in enclosures considerably larger than a vehicle, and so might tend to underestimate the initial concentration in a confined space.

Given the wide variability in air concentrations in space and time, it is easier to base comparisons on the fraction of penetrator aerosolised. In the Capstone Study, it was estimated to range between a maximum of 1% for the lighter armoured BFV to a maximum of 7% inside the heavily armoured Abrams tank (Attachment 3, Page 3.3). This is consistent with the more recent results (eg Chambers et al, 1982, Fliszar et al, 1989), and makes the earlier estimates above 10% seem less likely.
## Table 7. Summary of air concentrations and fraction “aerosolised” from DU penetrator impacts (partly based on Royal Society 2001, Table C1)

<table>
<thead>
<tr>
<th>Report</th>
<th>Mass concentration (mg m⁻³)</th>
<th>Fraction of penetrator “aerosolised” (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reports obtained</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hanson et al., 1974</td>
<td>Exit chamber: 500–1700</td>
<td>0.25*</td>
</tr>
<tr>
<td></td>
<td>Entrance chamber: 70–600</td>
<td></td>
</tr>
<tr>
<td>Glissmeyer and Mishima, 1979</td>
<td>8–35</td>
<td>70</td>
</tr>
<tr>
<td>Chambers et al., 1982</td>
<td>130 (average)</td>
<td>3 (1.5–5)</td>
</tr>
<tr>
<td>Brown, 2000</td>
<td>Inside enclosure, at 3 m: 13–60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Outside enclosure, at 7 m: 7–17</td>
<td></td>
</tr>
<tr>
<td>Chazel et al, 2003</td>
<td>(Outside tank, 1–4 m away) 8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(inside tank) 10</td>
<td></td>
</tr>
<tr>
<td>Capstone: Parkhurst et al 2004b†</td>
<td>BFV First 1 minute: 2200 – 3000</td>
<td>~1</td>
</tr>
<tr>
<td></td>
<td>BFV 30 – 60 mins: 50 – 130</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Abrams First 1 minute: 5700 – 16000</td>
<td>~7</td>
</tr>
<tr>
<td></td>
<td>Abrams 30 – 60 mins: 20 – 150</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Abrams DU armour: First 1 minute: 4200 – 10000</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gilchrist et al., 1979</td>
<td>Near target, &gt;0.3 for 5 min and &gt;15 min (dry surface); but &lt;15 min (wet surface)</td>
<td>17–28</td>
</tr>
<tr>
<td>Fliszar et al., 1989</td>
<td>Initial, inside tank: 44400</td>
<td>8.5</td>
</tr>
<tr>
<td>Jette et al., 1990</td>
<td></td>
<td>&lt;10 (0.02 – 0.5)</td>
</tr>
<tr>
<td>Parkhurst et al., 1990</td>
<td></td>
<td>&lt;10</td>
</tr>
<tr>
<td>*Not assessed by authors. Calculated from concentration and volume of enclosures (see Bailey, 2001)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>†Summarised from Attachment 1, Table S.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 2.13.2 Aerosol size distributions

In several studies the aerodynamic size distributions of activity or mass were measured directly. In all cases cascade impactors (CI) were used, and results were expressed as mass (or activity) median aerodynamic diameter, MMAD or AMAD and geometric standard deviation, GSD. Hanson et al (1974), Glissmeyer and Mishima (1979), and Chambers et al (1982) used cumulative logarithmic-probability graph paper to determine MMAD and GSD. Results are summarised in Table 8. Thus the RSWG concluded that for initial exposure near a target it is reasonable to take MMAD ~2 μm, with a large GSD (~10), but, at later times or further away to take lower values, ie, MMAD 1 μm, with GSD ~2.5, the HRTM defaults for environmental exposure. The AMADs measured by Chazel et al (2003) are consistent with that, although the GSDs are smaller close to the impact. The more comprehensive Capstone results are also broadly consistent, but provide more information about the change in size distribution with time, and about variability. They confirm the most important overall
observation, namely that most of the aerosol, at least after the first minute or so, is readily respirable, with an AMAD of about 1 µm.

Table 8 Aerosol size distributions from DU penetrator impacts (partly based on Royal Society 2001, Table G2)

<table>
<thead>
<tr>
<th>Report</th>
<th>MMAD, µm</th>
<th>GSD</th>
<th>&quot;Respirable fraction&quot; (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reports obtained</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hanson et al., 1974</td>
<td>2.1 – 3.3 (Entrance chamber)</td>
<td>1.8 – 3.3</td>
<td>42 – 64</td>
</tr>
<tr>
<td></td>
<td>2.4 – 4.2 (Exit chamber)</td>
<td>1.8 – 3.1</td>
<td></td>
</tr>
<tr>
<td>Glissmeyer and Mishima, 1979</td>
<td>0.8 – 3.1</td>
<td>1.6 – 18</td>
<td>51 – 70</td>
</tr>
<tr>
<td>Patrick and Cornette, 1978</td>
<td>†</td>
<td>†</td>
<td></td>
</tr>
<tr>
<td>Chambers et al., 1982</td>
<td>1.6 (1.4 – 2.0)</td>
<td>13 (12 – 17)</td>
<td>~70</td>
</tr>
<tr>
<td>Brown, 2000</td>
<td>3.7 (1.1 – 7.5) inside</td>
<td>3.5 (2.8 – 4.2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.8 (1.3 – 2.7) outside</td>
<td>4.1 (3.9 – 4.5)</td>
<td></td>
</tr>
<tr>
<td>Chazel et al, 2003</td>
<td>1.05 (glacis shot) outside</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 (turret shot) outside</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Capstone: Parkhurst et al 2004b†</td>
<td>BFV First 10 sec: 0.6 – 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BFV After 10 sec: 0.4 – 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Abrams First 10 sec: 0.2 – 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Abrams After 10 sec: 0.3 – 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Abrams DU armour</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>First 10 sec: 0.8 – 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>After 10 sec: 0.1 – 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reports not obtained (OSAGWI 2000, Tab L)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gilchrist et al., 1979</td>
<td>2.1 (High volume, preferred)</td>
<td>5.8 (Low volume)</td>
<td></td>
</tr>
</tbody>
</table>

* Here the term "respirable fraction" is used to mean the fraction of the airborne material that is small enough to be readily resuspended and inhaled, i.e., less than about 10 µm dae, and not, as usually defined for occupational health purposes, to mean the fraction of the aerosol that if inhaled could reach the alveolar region, i.e., the deep lungs. However, different definitions are used in different reports.

† Size distribution not measured, but a qualitative statement is made that a very wide range size was observed: from fragments >50 µm to submicron.

‡ No concise summary was found in the Capstone Report. These ranges are based on Attachment 1, Table 6.40, which gives results individually for each type of shot and time.

2.13.3 Dissolution characteristics

Except for the recent study by Mitchell and Sunder (2004) in which material was administered to rats, all other measurements of DU penetrator impact aerosols were made in vitro, and used broadly similar procedures to those used in the Capstone Study.

There were however some differences. In particular, Glissmeyer and Mishima (1979) and Scripsick et al (1985a,b) carried out tests at 37°C rather than at room temperature. Scripsick et al also used a dynamic system in which the solvent flowed past one side of the filter sandwich. This is considered by some to be more representative of the situation in the lungs, where the medium immediately around the particle can exchange with body fluids, including the circulating blood. They also compared dissolution rates
(and UO₂ content) of the material taken from the bunker with laboratory materials formed under a range of conditions. In addition, they measured the specific surface area of the respirable fractions of two of the laboratory samples by ⁸⁵Kr adsorption, and reported that after dissolution they were 65% and 39% lower than before. Thus in some ways this study went further than the Capstone Study in attempting to relate dissolution behaviour to mechanisms.

For use with the HRTM, it is necessary to estimate values of three parameters:

- the fraction that dissolves rapidly, fᵣ
- the dissolution rate of the rapid fraction, sᵣ d⁻¹
- the dissolution rate of the slow fraction, sₛ d⁻¹

These are easily obtained from in vitro tests where the undissolved fraction is expressed as a two-component exponential function. Results are summarised in Table 9. For the study by Mitchell and Sunder (2004), only rough estimates of fᵣ and sₛ could be made by the reviewer. Although it has the merit of being the only in vivo study, in the reviewer’s opinion it is not useful for risk assessment, even for validation of the in vitro results, because of factors including lack of information about the material, its large particle size, and the short duration of measurements.

In the Capstone Study using the two-component fits, (Table 6) values of the rapid fraction, fᵣ, ranged from 1% to 28%, broadly similar, but somewhat lower in range than in the previous studies (4% to 57%, Table 9). Values of the slow dissolution rate, sₛ, ranged from 0.0004 to 0.0095 d⁻¹, again broadly similar, but somewhat higher in range than the previous studies (0.0002 to 0.004 d⁻¹, Table 9).

<table>
<thead>
<tr>
<th>Report</th>
<th>Fraction dissolved rapidly (%)</th>
<th>Dissolution rate of the rapid fraction, d⁻¹</th>
<th>Dissolution rate of the slow fraction, d⁻¹</th>
<th>Duration of measurements, d</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reports obtained</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glissmeyer and Mishima, 1979</td>
<td>43 (34 – 49) respirable</td>
<td>--</td>
<td>&lt;0.01</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>15 (11 – 18) total</td>
<td></td>
<td>&lt;0.01</td>
<td></td>
</tr>
<tr>
<td>Scripsick et al., 1985a,b</td>
<td>25 (air filter) respirable</td>
<td>1.7</td>
<td>0.0014</td>
<td>~30</td>
</tr>
<tr>
<td></td>
<td>4 (core sample) respirable</td>
<td>4.7</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>Chazel et al, 2003</td>
<td>47 (glacis)</td>
<td>0.06</td>
<td>0.00018</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>57 (turret)</td>
<td>0.07</td>
<td>0.00034</td>
<td></td>
</tr>
<tr>
<td>Mitchell and Sunder, 2004</td>
<td>~5</td>
<td>~1</td>
<td>--</td>
<td>7</td>
</tr>
<tr>
<td>Capstone: Parkhurst et al 2004b</td>
<td>1 – 28</td>
<td>0.1 – 30</td>
<td>0.0004 – 0.0095</td>
<td>46</td>
</tr>
<tr>
<td><strong>Reports not obtained (OSAGWI 2000, Tab L)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jette et al., 1990</td>
<td>24 – 43 “Class D”</td>
<td>--</td>
<td>--</td>
<td>?</td>
</tr>
<tr>
<td>Parkhurst et al., 1990</td>
<td>17 “soluble”</td>
<td>--</td>
<td>--</td>
<td>?</td>
</tr>
</tbody>
</table>

Table 9. Dissolution characteristics of material formed from DU penetrator impacts (partly based on Royal Society 2001, Table G3)
2.13.4 Chemical composition

X-ray analysis was used in several studies to identify the oxides present and to attempt to quantify the proportions. Results generally indicate that most of the crystalline uranium oxide is present as UO$_2$ or U$_3$O$_8$ or intermediates (U$_3$O$_7$ and U$_4$O$_9$). However, there is variation in the oxides chosen (Table 10), perhaps reflecting the difficulty in distinguishing between some as noted in the Capstone Report. Chaz et al, like the Capstone Study, report U$_4$O$_9$ to be an important constituent.

<table>
<thead>
<tr>
<th>Report</th>
<th>Amorphous (%)</th>
<th>UO$_2$ (%)</th>
<th>U$_3$O$_8$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glissmeyer and Mishima, 1979</td>
<td>25</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>Patrick and Cornette, 1978</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Scripsick et al, 1985(a,b)</td>
<td>20</td>
<td>18</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>–</td>
<td>97</td>
<td>3</td>
</tr>
<tr>
<td>Chaz et al, 2003</td>
<td>30-40[^†]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mitchell and Sunder, 2004</td>
<td>9</td>
<td>44[^‡]</td>
<td></td>
</tr>
</tbody>
</table>

* Qualitative: Air samples mainly U, Fe. Soil also Si, Al and W.
† also 25-40% U$_4$O$_9$ and 20% UO$_3$
‡ also 47% U$_3$O$_7$

Glissmeyer and Mishima (1979) noted that the proportion of U$_3$O$_8$ may increase with decreasing size. This is consistent with the Capstone report observation that the proportion of U$_3$O$_8$/UO$_3$ (which could not be distinguished) increased with decreasing size.

2.13.5 Particle morphology

Particle morphology was examined by SEM in several studies, but is difficult to summarise, because of the heterogeneity observed.

The study of Patrick and Cornette (1978) was specifically concerned with particle morphology. They examined airborne particles collected on “double-stick” (double-sided?) cellophane tape at three locations, all 2 m above ground, and 1.5 – 4 m away. Segments were placed on stubs, and gold coated, for SEM. They also examined soil samples collected from directly beneath and behind target plates. However, these samples contained material accumulated over many months of testing. The material was sieved, suspended in thallium formate/ malonate solution (density 4.3 g cm$^{-3}$), and centrifuged to select denser material; collected on a membrane filter; washed, dried, and gold coated. Thus the sample collection procedures were quite different from those used in the Capstone Study. For the airborne particles a very wide range size was observed: from fragments > 50 µm to submicron. Most were spherical or ellipsoidal but with highly convoluted surfaces, suggesting that they had been molten. Some were extensively fractured: suggesting that they were fragile (mainly alloyed U and Fe resulting from the impact). An unexpected finding was the presence of many ultrafine particles (<0.1 µm),...
usually on surface of larger particles, but also as agglomerates. Soil particles were described as “rugose”, hollow and perforated. Again there was evidence of fragility.

Glissmeyer and Mishima (1979) noted that the SEM indicated that particles were composed of many small particles 0.03–0.1 µm diameter.

Chazel et al (2003) noted that SEM observations showed:

- Fine particles (0.5–2 µm) mainly composed of a mixture of uranium and aluminium (a component of the penetrator).
- Larger fragments (40–170 µm) containing Al, U, Si, Fe, Zn, P, Cu and Ni.
- Many large molten particles (>50 µm) of nickel covered by a porous surface of U and Al.
- Large particles (diameter > 30 µm) made only of uranium.

### 3 HUMAN HEALTH RISK ASSESSMENT (HHRA) OF CAPSTONE DEPLETED URANIUM AEROSOLS

#### 3.1 Scope

#### 3.1.1 Objectives

As noted in Section 1.1, the overall objectives of the HHRA were to give guidance on whether the health risks to Level 1 personnel are high enough to warrant changes in medical policy or in personal protective measures.

Specific objectives for the HHRA as related to these questions are as follows (Attachment 3 page 1.3):

- Use the Capstone data to estimate DU intakes for credible military scenarios and provide a measure of uncertainty.
- Use current models recognised by the national and international community to estimate organ concentrations and doses.
- Use organ concentrations and radiological doses to assess the chemical and radiological risk using appropriate risk models. Information from published literature was used to establish the relationships between doses and health effects.
- Use risk management techniques to determine if changes in policy or procedures are required.
- Use good risk communication to provide the estimated risks of DU exposure so that appropriate decisions can be made and actions can be taken.

The HHRA process included:

- Developing exposure scenarios for the Level I exposure group (Chapter 2).
Developing intake parameters such as source-term and physiological data for use in modelling. The Capstone aerosol database was the basis for the source-term calculations (Chapter 3).

Selecting appropriate chemical and radiological dose models for the respiratory tract, ingestion, and uranium biokinetic behaviour (Chapter 4).

Calculating committed effective doses and committed equivalent organ doses (Chapter 5).

Evaluating known chemical and radiological levels that cause clinical effects (Chapter 6).

Characterising the nature and magnitude of human health risks from DU aerosol intake (Chapter 7).

Summarising the data and making recommendations about its use (Chapter 8).

As for the Capstone Aerosol Study, the project team involved a combination of independent and military experts, and was overseen by military steering committees and a peer review panel of independent experts. In this case, "Independent subject matter experts in the fields of aerosol science, toxicology, health physics, radiological dose assessment, and risk assessment were recruited from various laboratories and research institutes, including Los Alamos National Laboratory (LANL), Pacific Northwest National Laboratory (PNNL) operated by Battelle (Richland, Washington), Lovelace Respiratory Research Institute (LRRI), Battelle (San Antonio, Texas), and Battelle Eastern Science and Technology (Best) Center (Aberdeen, Maryland) to assist health physicists and toxicologists from USACHPPM with this study."

3.1.2 Scenarios
The HHRA addresses personnel in the vehicle at the time of vehicle perforation and individuals entering shortly afterwards to assist in the recovery of personnel and equipment.

Exclusions:

- Potential DU exposures and intakes to personnel on or near the vehicles was beyond the scope (Attachment 3 Page 2.3). Potential DU exposures and intakes to personnel outside the vehicle were considered lower because DU aerosol concentration is lower outside the vehicle, and the aerosol would diffuse faster in the open environment.

3.1.3 Exposure pathways
Only the inhalation of DU is considered.

Exclusions:

- Ingestion by hand-to-mouth transfer, which is addressed in Attachment 4 for Level II and III exposures.
• Evaluation of the health risks from embedded fragments and wound contamination was beyond the scope of the report (Attachment 3, Page 2.2)

• Chemical effects other than those associated with uranium. Attachment 3, page 1.3 notes that the interaction of the DU penetrator with the armour that it perforates creates DU oxides and aggregates with iron, aluminium, or other armour components (most of which would be trace amounts). The Report is focused on assessing potential health effects for soldiers who inhale DU oxides from armour perforations. The contributing effect, if any, of inhaling the non-DU particles is outside the scope.

3.1.4 Comparison of scope with that of other studies

There are similarities in scope and approach to the assessment carried out by the RSWG (Royal Society, 2001, 2002). Both assessments set up a set of exposure scenarios; estimated intakes and exposure parameter values based on available experimental data; used the same current international models to calculate tissue concentrations of uranium and radiation doses; reviewed the literature to assess radiation and chemical risks associated with DU intakes; assessed risks to exposed personnel; and made recommendations for further action and research. The HHRA was narrower in scope in that the Royal Society assessment considered Level I, II and III exposures. The Royal Society assessment considered all routes of intake, external exposure, etc. It also addressed, in Part II, the longer term environmental impact resulting from the dispersal of DU from both penetrator impacts and penetrators that missed their targets. The HHRA, however, went “deeper”, in having the comprehensive Aerosol Study database to draw on, and assessed doses and risks for each scenario, shot, and sampling position. It was thus able to build up distributions of intakes, doses and risks, based on the distributions of original data.

USACHPPM (2000)
The USACHPPM Assessment considers Level I, II and III exposures, including specifically the fire at Camp Doha, Kuwait in July 1991, using a similar procedure to the HHRA and RSWG assessments. It was able to refer to a wider range of previous studies than the RSWG study, in particular the work reported by Fliszar et al (1989). It also made recommendations for further studies, which appear to have contributed to initiating the Capstone Study.

3.2 Achievements of the Capstone Human Health Risk Assessment

The various aspects are described in the following sections (3.3-3.10). As for the Aerosol Study, as indicated by the title, these sections summarise aspects of the study considered “positive” by the reviewer. Thus, to avoid repetition, it can be assumed that throughout these Sections (3.2 – 3.11) the reviewer considers the approach taken to be reasonable, unless comment is made. As indicated in the objectives (Section 3.1.1), the HHRA used current models recognised by the national and international community to
estimate organ concentrations and doses, and with them used the Capstone data to provide appropriate parameter values and, in some cases, ranges. The current models (Section 3.5.1) are those adopted by the ICRP, and which are used almost universally around the world for both radiological protection and risk assessment purposes. The two most important models, the HRTM and the uranium systemic model (ICRP 1994, 1995a), are fairly recent and close to the state of the art. (The reviewer is a member of the ICRP Task Group on Internal Dosimetry, which is responsible for reviewing and updating the biokinetic models, and was a member of the ICRP Task Group that developed the HRTM.) Essentially the same models (but with some different parameter values) were used by the RSWG, of which the reviewer was a member.

### 3.3 Scenarios

Five scenarios, designated Scenarios A through E, were developed to evaluate the doses, but differ only in exposure duration (Table 2, Section 1.3). Scenarios A to D relate to personnel who were in the vehicle when it was perforated. Scenario E specifically relates to first responders who enter the vehicle shortly after impact.

The estimates of stay times were based on experiences from ODS (although little information was available) and an earlier study of the time needed to evacuate tank crew. Scenarios A and B were considered most likely (stay times of 1 and 5 minutes). The stay-times of 1 and 2 hours represented by Scenarios C and D were considered to represent upper bounds.

### 3.4 Exposures

Breathing rates were assigned to each scenario (Table 2) using appropriate ICRP default values.

DU intakes, peak kidney concentrations, and doses were calculated for each shot (Table 1, Section 1.2) and sampling position, and these individual values are listed in Appendix A.

The predictions assume that one LC-DU round perforates the crew compartment and that no ventilation systems are operating during or after perforation, except where indicated (Shot PIV-4).

The quantity of DU aerosol available for exposure is directly related to the amount of penetrator erosion caused by perforation of the armour etc. The uranium concentrations calculated from the Capstone CIs were used in the HHRA, and not those measured by the IOM samplers. Further details are given on pages 3.10-3.12. The IOM was considered to have a higher aspiration efficiency (Section 2.3.5) for very large particles, and so combining the IOM concentration measurement with the CI size distribution would lead to overestimates of intake. This seems reasonable to the reviewer, and furthermore, support for this view came from observation that the discrepancy only arose in first 10 minutes after impact, when a significant fraction of the DU was associated with large particles.
In the Capstone DU Aerosol Study “Field blank” samples were taken: no suction flow was applied, so they measure material deposited through the initial blast, air movement etc. In the Aerosol Study these data were subtracted from subsequent measurements. In the HHRA a different approach was taken to adjust for non-flow-related deposition in the samplers. In Phases I - III, the first set of samplers that began operating within a few seconds after the blast were not blank corrected because it was reasoned that an individual in the vehicle would be subjected to the initial blast, which could have driven an amount of DU particles into the respiratory tract and contributed to their overall intake. The approaches taken in both studies seem reasonable to the reviewer in their different circumstances.


In the reviewer’s opinion, these considerations all show commendable attention to detail and the benefits of the comprehensive data collection.

The Capstone CI data provided DU aerosol concentrations (for aerodynamic size fractions) versus time for calculating intake during the selected duration of exposure.

The alternative approach, as used for example by the RSWG, would be to estimate the source term in terms of the mass of DU aerosolised and to calculate from it the initial concentration. That was not appropriate here, since concentration measurements were directly available. Furthermore, it was noted that the total quantity of DU aerosol actually generated from impact with armour could not be measured directly because of losses. In the Capstone tests, the intact portion of each penetrator was captured in the armour catch plate behind the target vehicle, from which it could not be recovered and weighed. Additionally, most DU fragments landing outside the vehicle were not weighed. However, based on Capstone aerosol data, it was estimated that a maximum of 7% of the LC-DU penetrator was aerosolised inside the heavily armoured Abrams tank and a maximum of 1% in the lighter armoured Bradley vehicle (Attachment 3 page 3.2). (These estimates seem reasonable to the reviewer: they are consistent with the simple calculations carried out by the RSWG, Section 3.11.2.)

Composite results by phase and scenario make up the majority of this assessment’s discussions. These results were evaluated using arithmetic averages, medians, and 10th and 90th percentiles (Appendix A, Tables A2 – A5).

Attachment 3, Table S.3, summarises the assessed median intakes of DU (mass, mg) by scenario. Values, rounded for clarity, are given in Table 11. The striking features are that:

- For the unventilated vehicles the predicted intakes are large: of order hundreds of milligrams.
- For the unventilated vehicles there are relatively small differences in predicted intakes between vehicles and between scenarios.
- For the ventilated tank the predicted intakes are much lower, especially for the short stay times.
These data were used as inputs to the models for calculating DU organ concentrations and radiation doses.

### Table 11 Summary of median intakes by scenario (based on Attachment 3 Table S.3, but rounded)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>DU mass intakes (mg)</th>
<th>Abrams tank</th>
<th>BFV Conventional armoured, no ventilation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conventional armour, no ventilation</td>
<td>DU armour, no ventilation</td>
<td>DU armour, EC/NBC ventilation</td>
</tr>
<tr>
<td>Most likely scenario</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A – Exit in 1 min</td>
<td>300</td>
<td>300</td>
<td>10</td>
</tr>
<tr>
<td>B – Exit in 5 min</td>
<td>600</td>
<td>700</td>
<td>40</td>
</tr>
<tr>
<td>Upper bound scenario</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C – Exit in 1 hour</td>
<td>800</td>
<td>1000</td>
<td>90</td>
</tr>
<tr>
<td>D – Exit in 2 hour</td>
<td>800</td>
<td>1000</td>
<td>110</td>
</tr>
<tr>
<td>First Responders</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E – Entry 5 min post shot, exit 10 min later</td>
<td>160</td>
<td>200</td>
<td>30</td>
</tr>
</tbody>
</table>

### 3.5 Assessment of doses and uranium concentrations from exposures

#### 3.5.1 Biokinetic and dosimetric models
The biokinetic and dosimetric models selected for the radiological dose assessment included the following three respiratory tract, ingestion, and systemic models, which are the most contemporary published by the International Commission on Radiological Protection (ICRP):

- the inhalation/respiratory tract model (HRTM) described in ICRP Publication 66 (1994)
- the ingestion/gastrointestinal (GI) tract model described in ICRP Publication 30 (1979)
- the uranium systemic biokinetic model in ICRP Publication 69 (1995a).

However, specific parameter values derived from the Capstone Aerosol Study were applied in the HRTM.

The outputs derived from running these models included organ-specific DU mass concentrations and activities as a function of time, and time-integrated exposures for each of the scenarios. These results were used to calculate committed effective doses, $E(50)$; committed equivalent doses, $H_T(50)$; and selected dose versus time profiles. The calculated output was benchmarked against ICRP reports and commercially available internal dosimetry codes. Bayesian statistics and the Markov chain Monte Carlo method were employed to calculate probabilistic expansion of means, median, and confidence limits.
3.5.2 Respiratory tract deposition
The HRTM provides values of the fraction of inhaled material deposited in each region of the respiratory tract, for log-normally distributed aerosols, as functions of the AMAD and GSD of the distribution. This includes values for monodisperse (uniform sized) aerosols (for which GSD = 1.0). The values tabulated in ICRP Publication 66 for GSD values other than 1.0 were derived (by the authors of Publication 66) by convoluting values for monodisperse aerosols over lognormal distributions with the appropriate GSD. In the Capstone Aerosol study it was generally found that the aerosols produced inside the vehicles were not well fit by either unimodal or bimodal lognormal particle size distributions. To avoid losing information and data quality by approximating the measured distribution by a poorly fitting function, actual uranium masses from each of the eight size-specific CI stages were used. (Attachment 3, pages vi, and 3.15). As noted by the reviewer in Section 2.7.1 above, this is a commendable approach, which might well be applied elsewhere. Thus the aerosol was represented by nine monodisperse aerosols, corresponding to the eight CI stages and back up filter. The diameter of each component aerosol was calculated from the geometric mean of the effective cut-off diameter of the stage and that of the preceding stage (Attachment 3, page 3.23). To implement this, nine parallel dose calculations were performed, one for each monodisperse aerosol.

Other factors used in the deposition calculations (Attachment 3, page 4.7) included an average DU aerosol density of 9.0 gm/cm³ and a shape factor of 1.5 (USACHPPM 2000). The latter is not uncommon for irregularly shaped particles is the HRTM default value (ICRP 1994) and an appropriate choice for particles that are not of extreme shape (e.g. fibres).

3.5.3 Respiratory tract clearance by absorption to blood
Specific in vitro dissolution data were used to define the rates of DU absorption to blood in a size- and material-specific manner (Attachment 3, pages 3.24 and 4.13). The Aerosol Study CI data provided DU intakes as functions of time after impact for nine monodisperse component aerosols.

To evaluate aerosol dissolution as a function of particle size, the Capstone Aerosol study measured the in vitro dissolution of 15 cyclone samples and four backup filters, which sampled aerosols over the entire 2-h sampling period. Additionally, five IOM samples were analysed to evaluate dissolution as a function of time. The HHRA used these results to estimate specific dissolution rates corresponding to the CI data. One issue identified in the Capstone Report was that data were needed over a sequence of times, but the cyclone material was collected over the entire period. However, the IOM data were within the range of the cyclone data and did not show uniform time dependent changes in dissolution rate. Another was that there are only six cyclone stages (including the back-up filter), and so the dissolution rate for the first stage was applied to the three largest monodisperse aerosols, and the back-up filter rate was applied to the two smallest (Table 4.6). The dissolution results were grouped to produce averaged particle-size-specific dissolution patterns for the shots where they were not measured directly. These approaches seem, to the reviewer, to make good use of the available data to estimate dissolution rates as functions of time and aerosol size.
The following five paragraphs (except where noted) describe the treatment of respiratory tract clearance by absorption to blood in the HRTM (ICRP, 1994).

The HRTM recognises that absorption from the respiratory tract to blood is a two-stage process: dissociation of the particles into material that can be absorbed into blood (dissolution); and absorption into blood of soluble material and of material dissociated from particles (uptake). Both stages can be time-dependent. The simplest representation of time-dependent dissolution is to assume that a fraction \( f_r \) dissolves relatively rapidly, at a rate \( s_r \), and the remaining fraction \( 1 - f_r \) dissolves more slowly, at a rate \( s_s \) (Figure 4a). Provision is made in the HRTM for two fractions, to avoid undue complexity, and because it was considered that there would not normally be sufficient information to justify more. (However, the Capstone dissolution data were usually represented by three components, see Section 2.7.4, and below.)

A limitation of the system shown in Figure 4a, however, is that it can only readily represent an overall fractional dissolution rate that decreases with time. (This is the usual situation, and was found for all the Capstone samples measured). To enable dissolution rates that increase with time to be represented, the HRTM uses an equivalent system with the same number of variables, but which gives greater flexibility, shown in Figure 4b. In this, the material deposited in the respiratory tract is assigned to compartments labelled “Particles in initial state” in which it dissolves at a constant rate \( s_p \). Material is simultaneously transferred (at a constant rate \( s_{pt} \)) to a corresponding compartment labelled “Particles in transformed state” in which it has a different dissolution rate, \( s_t \). With this system, the initial dissolution rate is approximately \( s_p \) and the final dissolution rate is approximately \( s_t \). Thus with suitable choice of parameters, including \( s_t > s_p \), an increasing dissolution rate can be represented. The ratio of \( s_p \) to \( s_{pt} \) approximates to the fraction that dissolves rapidly.

If the dissolution rate decreases with time, as is usually the case, either system could be used, and would give the same results, with the following values:

\[
\begin{align*}
    s_p &= s_s + f_r (s_t - s_s) \\
    s_{pt} &= (1 - f_r) (s_t - s_s) \\
    s_t &= s_s
\end{align*}
\]

In many circumstances the system in Figure 4a has advantages. In particular, it is generally more straightforward to estimate from experimental data the values of the parameters in Figure 4a than those of Figure 4b. Thus, if the results of in vitro dissolution tests, such as those carried out in the Capstone Aerosol Study are expressed as:

\[
R(t) = A_1 \exp(-B_1t) + (1-A_1) \exp(-B_2t)
\]

where \( R(t) \) it the fraction of the original DU remaining undissolved at time \( t \), then \( A_1 \), \( B_1 \) and \( B_2 \) correspond directly to \( f_r \), \( s_t \) and \( s_s \).
Fig. 4. Alternative compartment models representing time-dependent dissolution, followed by instantaneous uptake to body fluids (ICRP 2002). In the model shown in Fig. 4(a), a fraction $f_r$ of the deposit is initially assigned to the compartment labelled “Rapid dissolution”, and the rest $(1 - f_r)$ of the deposit is initially assigned to the compartment labelled “Slow dissolution”. In the model shown in Fig. 4(b), all the deposit is initially assigned to the compartment labelled “Particles in initial state”. For definition of symbols, see text.

The system shown in Figure 4b is that “formally” used in the HRTM, rather than that of Figure 4a, only in that the default absorption parameter values are specified in terms of $s_p$, $s_{pt}$ and $s_t$, rather than $f_r$, $s_r$ and $s_s$.

Uptake to body fluids of dissociated material can usually be treated as instantaneous, but in some situations a significant fraction of the dissociated material is absorbed slowly into body fluids as a result of binding to respiratory tract components. To represent time-dependent uptake, it is assumed that a fraction $(f_b)$ of the dissolved material is retained in a ‘bound’ state, from which it goes into body fluids at a rate $s_b$, while the remaining fraction $(1 - f_b)$ goes to body fluids instantaneously. To enable this to be taken into account, the HRTM includes compartments in which activity is retained in each region in a ‘bound’ state. However, the bound state is not used in the ICRP default parameter values for Types F, M and S, and there is evidence that it can be neglected for uranium (ICRP 2002, Bailey and Phipps, 2001): soluble forms of uranium deposited in the lungs are rapidly and completely absorbed into the blood.

In the Capstone Aerosol Study, however, the fraction of undissolved DU was expressed as a three-component exponential function, with a rapid component, a slow component, and a very slow component. The rates and fractions of each component are denoted in the HHRA (Attachment 3 page 4.14) by $s_r$, $s_s$, $s_{vs}$, $f_s$, and $f_{vs}$, where $f_s$ is the slow fraction
and \( f_{vs} \) is the very slow fraction. The rapid fraction is given by \( f_r = 1 - f_s - f_{vs} \). To retain this information, the HHRA adapted the HRTM dissolution model (in Figure 4b) by employing the “bound state” compartment to represent the third component, which is termed the “vsd” (very slow dissolution) compartment.

Although this approach is mathematically correct, a problem with it is that (in contrast with the situation above) the formulae required to derive the model parameter values from those of the retention function fit to the data are complex. The Capstone Report noted that three of them are “nonlinear, and were solved by iteration”. A further potential problem with this approach is that in the HRTM material in the “bound state” compartments in the bronchial tree (bronchial, BB, and bronchiolar, bb, regions) is taken to be distributed through the epithelium. It is therefore very close to the target cells, and gives a higher dose per nuclear transformation than it would in the other compartments. This was recognised in the HHRA, and dose calculations were performed that used the appropriate radiation transport parameter values. However this required the development of specific software. The HHRA also recognised (Attachment 3 page 4.15) that “An alternative to the introduction of the vsd compartment, in order to represent three dissolution components, is to have two intake components. The first component can be used to represent two of the dissolution components, and the second intake component can be used to represent the third.” This much simpler, but perhaps less elegant, approach was used for the calculations of Level II and III exposures, performed outside the HHRA (Attachment 4), using existing, standard software. However, the use of both approaches had the advantage of enabling QA checks to be performed.

### 3.5.4 Implementation of models

The differential equations describing the ICRP models were solved using the code BK, developed at Los Alamos National Laboratory. The doses in target tissues were calculated using the specific effective energy (SEE, i.e., energy deposited per unit mass in the target organ from one transformation in the source organ) matrices calculated using the SEECAL code developed at Oak Ridge National Laboratory.

Data entry reviews and code validations and verifications (V&V) were carried out as part of the software quality assurance. A comprehensive comparison between the BK code and a completely independent code, AIDE (Bertelli et al, 2002) was performed for uranium isotopes \(^{234}\text{U}\) and \(^{238}\text{U}\), using Type S and Type M, standard 5-µm AMAD aerosol, and ICRP default breathing assumptions. Further comparisons were made with dose coefficients given in ICRP Publication 78 for selected radionuclides, and with output from the program IMBA (Birchall et al, 1998, 2003).

### 3.5.5 Uncertainty analysis

A sophisticated approach was used to calculate means, medians, and confidence limits of results. The analysis of each CI provided the concentrations of each of nine monodisperse aerosols, which together represent the DU aerosol at the time of measurement. A Bayesian approach was taken to estimate the radiation doses to individuals exposed to these aerosols. The HHRA authors considered this to have two advantages over other possible methods:
(i) It calculates a distribution of doses, thus allowing the means and standard deviations of the doses received to be determined rather than just a single estimate of dose.

(ii) It allows the use of a predefined set of reasonable air concentrations (the Bayesian prior). For the doses reported by the HHRA, the Bayesian prior was that only positive aerosol concentrations were reasonable.

Doses depend not only on the air concentration but also on additional parameters (e.g., breathing rate, nose/mouth breathing characteristics, and dissolution of the DU aerosol in the lungs). The dose and its uncertainty were calculated using Bayes’ Theorem, which requires probability distributions for the various parameters. However, since the distributions of additional parameters were not well known, the posterior distribution (the answer that results from a Bayesian statistical analysis) was calculated assuming that the parameters have single values rather than distributions. The effect of various discrete choices of parameter values was then investigated. The evaluation of the posterior distribution was done using the Markov Chain Monte Carlo (MCMC) method.

Depleted uranium intakes, chemical concentrations, and radiation doses to selected organs were calculated for each phase, shot, and sampling position for each scenario. Although the quantity of aerosol collected differed from shot to shot among the sampler arrays, no single sampling location was consistently high or low. As a result, each sampling location was considered to provide an estimate of the dose to the hypothetical occupants of the vehicle. Each shot within each phase was treated as a sampling of the universe of shot lines that result in the perforation of the vehicle. Hence all the shots within a test phase, representing a specific vehicle and configuration, were combined to provide statistical estimates of DU intakes and associated doses and peak kidney uranium concentrations. (The reviewer notes, however, that the number of shots in each Phase was small, and that several of the shots were chosen to maximise aerosol formation. They probably do not therefore provide a truly representative sample of all shot lines that would perforate the vehicle, but are biased towards those which result in high aerosol formation.)

The dose distributions could not be readily quantified as either normal, lognormal, or any other standard distribution. The median based on Bayesian Monte Carlo statistics is used to describe the radiological dose and the chemical concentration. Variation of the data about the median is shown by using the 10th and 90th percentiles and by reporting the minimum and maximum radiological doses and chemical concentrations. In most cases the mean and standard deviations are also presented for comparison. The data for each shot and sampling position on which these statistics are calculated are tabulated in Attachment 3, Appendix A and summarised in Attachment 3, Chapter 5.

These uncertainty calculations took into account measurement uncertainties such as counting statistics, uncertainty in determination of DU mass from activity, CI stage-specific collection efficiencies (Attachment 3, Page 5.12).

Model uncertainties were discussed but generally were not included in the uncertainty analysis (Attachment 3, pages 5.13-5.17). It was noted that the models used, particularly the HRTM and the ICRP uranium systemic biokinetic model are complex mathematical systems, which are not amenable to simple uncertainty estimation. For example, 69 parameters are associated with the HRTM. Although recent work by eg
Bolch et al (2001, 2003) and Huston et al (2003) provide comprehensive investigations of model uncertainties using classical statistics, ways to incorporate these new approaches into comprehensive uncertainty analyses, particularly in a Bayesian context, have not been developed. Therefore, the results of Bolch and his co-workers were recognised but were not incorporated into the uncertainty analysis.

However, according to Attachment 3, Page 5.14, some modelling uncertainty was incorporated at least for respiratory tract deposition. The particle-size-specific deposition fractions for the regions of the HRTM derived by Bolch et al were used to interpolate deposition fractions (geometric means and standard deviations) for particle sizes specific to the nine stages of the Marple CI used throughout the Capstone study.

The reviewer considers this to be a commendable effort in addressing issues of variability and uncertainty in the assessed intakes, doses and risks. However, as discussed in Section 3.15, ideally a full uncertainty analysis would have been performed, given the overall scale of the Capstone Program.

### 3.6 Results of dose calculation and risk assessment

The treatment of chemical and radiation risks are described in Sections 3.7 and 3.8 respectively.

#### 3.7 Chemical effects

**3.7.1 Chemical toxicity from uranium intakes – human data**

The Capstone Report notes (Attachment 3, page ix) that the chemical toxicity of uranium has been studied for many years in animals and uranium process workers. There have been several recent reviews, including that of the Royal Society (2002). These studies identified the kidney as the target organ for uranium toxicity. (Appendix B provides a review of animal studies, see below). Therefore peak kidney uranium concentrations were assessed. Reference is made to the *de facto* occupational guideline of 3 µg U/g kidney, based on early (1959) radiation dose considerations and experimental animal studies.

Detailed consideration was given to data relating to the chemical health effects of uranium (Attachment 3, Chapter 6 and Appendix B). The analysis focussed “on using available human data to define chemical doses that result in clinical endpoints that will either affect an individual’s ability to function, result in permanent injury, or require treatment”. Animal data were used to support and fill data gaps.

The Capstone Report notes that the current uranium safety standards are the subject of debate, but that this debate is centred on the levels at which there are measurable changes in human kidney biomarkers or renal damage in animal models, and not on the levels required to cause overt clinical or performance effects.

The HHRA developed further the approach taken by the RSWG, to correlate observed renal effects in humans occurring after acute exposures (from published reports) with
the calculated peak kidney uranium concentrations in each case (Royal Society, 2002, page 7, Table 1.2). An independent evaluation was conducted of the cases drawn from the Royal Society report, and of some additional cases that were described by Fisher et al (1990 a, b). For the latter, only one (out of 27) showed transient signs of renal dysfunction. Twelve others were included, selected on the basis of having better data and higher exposures.

The data on 27 acute human exposure cases (14 from the RSWG report and a further 13 from Fisher et al) were used to develop a set of “Renal Effects Groups (REGs)” correlating uranium (U) concentrations in the kidneys with renal effects (Attachment 3, page 6.12).

- REG 0 consists of kidney concentrations \( \leq 2.2 \, \mu g \, U/g \) kidney in which the predicted outcome is no kidney dysfunction.
- REG 1 consists of concentrations between 2.2 and 6.4 \( \mu g \, U/g \) kidney and, at worst, may cause transient renal dysfunction.
- REG 2 applies to concentrations in the range of >6.4 to 18 \( \mu g \, U/g \) kidney and may cause protracted (but not permanent) kidney dysfunction.
- REG 3 applies to concentrations >18 \( \mu g \, U/g \) kidney which may cause severe clinical symptoms

The REG were used to predict the potential effects of the modelled exposure concentrations.

Renal effects in humans from chronic uranium exposures are also discussed, developing the presentation in the RSWG report. The Capstone Report notes that the reported observations suggest that effects may increase with exposure time.

Possible effects on organs other than the kidney are reviewed and discussed (lungs, and the central nervous, reproductive, and immune systems). While possible effects in other tissues are not excluded, only the peak kidney concentration is considered as an end-point for chemical effects in the assessments.

Overall the reviewer considers this approach reasonable but notes (Section 3.16) that the review of the literature for human cases of exposure leading to toxic effects does not seem to have been exhaustive, and the precision of the REG levels seems high given the sparse data on which they are based. Although, as noted above, the HHRA appears to be mainly concerned with estimating uranium kidney concentrations high enough to cause “overt clinical or performance effects”, it does also consider levels that cause effects that would only be detected by means of tests on urine samples. The significance of biochemical indications of kidney dysfunction seems uncertain (and outside the expertise of the reviewer). For example, the RSWG report (Royal Society, 2002, page ix) concludes that whether uranium kidney concentrations that lead to short term kidney dysfunction “would lead to any long-term adverse effects is unclear as adequate studies of the long-term effects on the kidneys of acute exposures to elevated levels are not available.”
3.7.2 Appendix B Uranium Toxicity—Animal Studies

Appendix B provides a summary of animal studies giving information on the effects of uranium on kidneys with increased uranium concentration, and duration of exposure. It also covers effects on lungs, but does not address other tissues (e.g. brain), which have been discussed recently and which are considered in Attachment 3, Chapter 6.

Appendix B provides an overview of the animal studies related to various forms of uranium. The focus is twofold:

- studies in which animals were exposed to oxides of uranium, the principal forms likely to be produced when a target is struck by a DU munition,
- studies in which animals were acutely exposed to uranium, as the scenarios evaluated in HHRA are for acute exposures only.

The Capstone Report (Appendix B) notes, from the published observations, that acute inhalation exposure to uranium oxides have in animals led to:

- "Overt" effects including weight loss and a diminished frequency of urination.
- Biochemical changes including glucosuria, polyuria, and proteinuria, increased blood non-protein nitrogen (NPN) and retention of phenolsulfophthalein (PSP).

3.7.3 Assessed uranium kidney concentrations for Level I exposures

Peak kidney uranium concentrations were calculated for each shot and sampling position and are listed in Attachment 3, Appendix A (see Section 3.8.1). Attachment 3, pages 6.19-6.24 discusses results for each Phase (vehicle type).

Attachment 3, Table S.4, summarises the assessed median peak kidney uranium concentration (micrograms uranium per gram kidney, µg U/g kidney) by scenario. Values, rounded for clarity, are given in Table 12. The striking features, reflecting the predicted intakes (Table 11), are that:

- For the unventilated vehicles the predicted uranium concentration in kidneys are not trivial: of order 1-10 µg U/g kidney.
- For the unventilated vehicles there are relatively small differences in predicted concentrations between vehicles and between scenarios.
- For the ventilated tank the predicted concentrations are much lower, especially for the short stay times.
The Capstone Report concluded that for the mostly likely exposures, the predicted concentrations are unlikely to cause any adverse health effects. The highest predicted kidney concentrations were for the unventilated Abrams Tank with conventional armour, even though the highest intakes were for the unventilated Abrams Tank with DU armour (Table 11), reflecting the somewhat higher dissolution rate of the aerosols in the former case. The results show a possibility of transient or protracted indicators of kidney dysfunction for exposures of about 5 min or more in an unventilated Abrams tank perforated through non-DU armour (6-8 µg U/gk, Table 12).

3.8 Radiation doses and effects

3.8.1 Radiation toxicity of uranium

Attachment 3, section 6.5 discusses the direct evidence for cancer induction from exposure to uranium, which is sparse. Epidemiological studies have been carried out on uranium process workers, and these have been reviewed recently (e.g., Royal Society, 2001). The RSWG analysed 14 such studies, 11 from the US and 3 from the UK. There was no excess in deaths from any cause, or from all cancers combined, or in individual types of cancer, or urogenital disease, including chronic urinary dysfunction. Indeed, the central estimate of deaths for each cause-of-death category was less than the general population presumably as a result of the “healthy-worker” effect.

Another review cited by the Capstone Report (Fulco et al, 2000) identified two studies in which lung doses were estimated, and where there was a possible association between high lung doses, and excess lung cancer, but insufficient information to provide a quantitative risk per unit exposure.

According to documents cited in the Capstone Report, there is no direct evidence that natural uranium will cause bone cancers in humans, although enriched uranium has induced bone sarcomas in rats and mice, and the risk from uranium in humans has
been inferred from the risk for another long-lived, bone-volume-seeking radionuclide, $^{226}$Ra.

3.8.2 Radiation risks from inhaled DU

Ionising radiation is a known carcinogen, and the approach used to determine the radiation risks was to multiply the radiation doses for individual organs by the risk coefficients for fatal cancers. Two sets of risk coefficients were used. The first was the ICRP and the Interagency Steering Committee on Radiation Standards (ISCORS) methodology using the committed effective whole body dose and risk coefficient to estimate the whole body cancer risk. The second approach used organ-specific risk coefficients developed by ICRP and the US Environmental Protection Agency (EPA) to estimate cancer risks for various organs of the body. Both of these approaches assume a linear, no-threshold dose response for cancer.

Particular consideration was given to the risk of lung cancer, because calculated lung doses were higher than those to other organs. Sources of information were reviewed, including humans chronically exposed to alpha emitting radionuclides (radon decay products, plutonium). All gave broadly similar risk coefficients. The ICRP risk coefficient for workers was used in the assessment ($0.68 \times 10^{-2} \text{ Sv}^{-1}$) as it was by the RSWG.

Radiation-induced cancer risks were also calculated for liver, bone surface and red marrow, using ICRP risk coefficients. ICRP does not give risk coefficients for kidney and extrathoracic (ET) airways, and the HHRA used other sources of information: USEPA risk coefficient for the kidney, and for the ET airways one based on the risk coefficient for skin.

The HHRA did not calculate risks for lymph nodes. It noted (Attachment 3, Page ix) that some models calculate higher doses to the lymph nodes than lungs. However, it was considered that they do not have a high susceptibility to radiation induced cancer: studies in dogs have demonstrated that the lymph nodes are not target organs for cancer (Hahn et al, 1999b). (The reviewer notes that the RSWG “central estimate” assessment gave similar doses to lungs and thoracic lymph nodes. The RSWG “worst case (radiation)” assessment gave a higher dose to lymph nodes than lungs, because of the low dissolution rate assumed.)

In the reviewer’s opinion the approach used was appropriate. Internationally (and nationally) accepted risk coefficients were used where available (as they were by the RSWG). Very strong justification would have been needed to use any other values. Since doses calculated to the lung were higher than those to other tissues, information relating to its risk coefficient was reviewed. Consideration was also given to risks to tissues for which doses were not small compared to those tissues for which ICRP risk coefficients are available: kidneys, ET and thoracic lymph nodes. ICRP recommends risk coefficients for those tissues for which it considers that there is sufficient information from epidemiological studies to calculate a risk coefficient. The absence of an ICRP risk coefficient therefore implies that the tissue has a low sensitivity to radiation-induced cancer, otherwise a significant excess would have been expected in at least one study. Since tissues, notably lung, which have ICRP risk coefficients received significant doses, it could reasonably have been argued that there was no need to consider risks to
tissues such as kidney with low sensitivity, because this would not affect the overall assessed risk significantly. Nevertheless reasonable efforts were made to assess their risks.

3.8.3 Assessed radiation doses for Level I exposures

Capstone data specifically used in the HHRA included the aerosol concentration from 13 shots as a function of time, the aerosol particle size distribution as a function of time, and the dissolution in vitro of the aerosols as a function of particle size.

For the first 12 shots, at least three and usually four sampling arrays (each consisting of nine pairs of filter cassettes and eight-stage CIs) collected aerosols according to a predetermined time sequence. Shot 13 (PIV-4) used two sampling sites with smaller sampling arrays consisting only of CIs.

The seven tables in Appendix A provide modelling input data listings of DU concentrations by particle size and modelling output.

- Table A.1 (pp. A.5-A.10) lists information about the sampler arrays used for each scenario modelled.
- Table A.2 (pp. A.11-A.13) summarises the calculated intakes, doses, and concentrations for all phases and scenarios in which Bayesian statistics were used. They are the means of the individual results (Table A.3) except where identified as medians or as 10th or 90th percentile values.
- Table A.3 (pp. A.14-A.21) lists the individual intakes, doses, and concentrations by phase, shot, crew position (sampling array position), and scenario, calculated using Bayesian statistics.
- Table A.4 (pp. A.22-A.24) summarises the calculated intakes, doses, and concentrations for all phases and scenarios using conventional statistics. They are the means of the individual results (Table A.5) except where identified as medians or as 10th or 90th percentile values.
- Table A.5 (pp. A.25-A.32) lists the individual intakes, doses, and concentrations by phase, shot, crew position (sampling array position), and scenario, calculated using conventional statistics.
- Table A.6 (p. A.33) provides the output of the software assurance analysis conducted with six sampler scenarios. The results using the System for Internal Dosimetry (SID) code correspond to the Biokinetic (BK) model results presented in Table A.5 (Attachment 3, Sections 4.5 and 4.6).
- Table A.7 (pp. A34 –A.102) provides input data including the time midpoint of each sampling interval, the calculated median diameter of particles collected on each CI stage, and the DU concentration collected on each stage. The concentrations presented are adjusted for CI wall loss (Attachment 3, Section 3.2.3.3). This table also lists sample identifications for cross-referencing with the data reported in Appendix A of the Capstone Study final report.
Attachment 3, Table S.5, summarises the assessed committed effective doses by scenario. Values, rounded for clarity, and converted from rems to mSv, are given in Table 13. The striking features, reflecting the predicted intakes (Table 11), are that:

- For the unventilated vehicles the predicted committed effective doses are of order tens of millisieverts: not trivial, but similar to routine occupational dose limits and intervention levels. The HHRA compares them to the US Nuclear Regulatory Commission (USNRC) annual occupational limit for radiation exposure of 5 rem (50 mSv) which few exceed. (The reviewer notes that in the UK context they should be compared with an annual occupational dose limit of 20 mSv, which a high proportion exceed.)

- For the unventilated vehicles there are relatively small differences in predicted doses between vehicles and between scenarios.

- For the ventilated tank the predicted doses are much lower, especially for the short stay times.

### Table 13 Summary of median 50-year committed effective doses by scenario (based on Attachment 3 Table S.5, but rounded and converted from rem to mSv)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Crewmembers</th>
<th>First Responders</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E(50) mSv</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Abrams tank</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Conventional armour, no ventilation</td>
<td>DU armour, no ventilation</td>
</tr>
<tr>
<td>Most likely scenario</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A – Exit in 1 min</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>B – Exit in 5 min</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Upper bound scenario</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C – Exit in 1 hour</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>D – Exit in 2 hour</td>
<td>50</td>
<td>90</td>
</tr>
<tr>
<td>E – Entry 5 min post shot, exit 10 min later</td>
<td>9</td>
<td>20</td>
</tr>
</tbody>
</table>

The highest predicted radiation doses came from the unventilated Abrams Tank with DU armour, reflecting the highest intakes (Table 11).

The Capstone Report notes that averaged 50-year committed equivalent doses, H_{T}(50), to organs were calculated for the lung, bone surface, kidney, red marrow, and liver. The doses to the lung were higher by at least a factor of 10 than the doses to the other organs.

Attachment 3, Table S.6, summarises the assessed lung doses by scenario. Values, rounded for clarity, and converted from rems to mSv, are given in Table 14. The pattern is very similar to that for committed effective doses, because the lung dose makes a large contribution to the effective dose. For the unventilated vehicles predicted committed lung doses are of order hundreds of millisieverts, again, not trivial, but below
a level likely to cause any immediate health effects, such as fibrosis. The HHRA compares them to the (USNRC) annual occupational limit for individual organs (other than the lens of the eye) of 50 rem (500 mSv). All are below that except for the case in which an Abrams tank was perforated through DU armour and the stay-time was an hour or more.

Table 14 Summary of median 50-year committed equivalent doses to lung by scenario (based on Attachment 3 Table S.6, but rounded and converted from rem to mSv)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>H_{lung}(50), mSv</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abrams tank</td>
<td></td>
</tr>
<tr>
<td>Conventional armour, no ventilation</td>
<td>140</td>
</tr>
<tr>
<td>DU armour, no ventilation</td>
<td>300</td>
</tr>
<tr>
<td>DU armour, EC/NBC ventilation</td>
<td>400</td>
</tr>
<tr>
<td>BFV Conventional armour, no ventilation</td>
<td>400</td>
</tr>
<tr>
<td>Crewmembers</td>
<td></td>
</tr>
<tr>
<td>Most likely scenario</td>
<td></td>
</tr>
<tr>
<td>A – Exit in 1 min</td>
<td>140</td>
</tr>
<tr>
<td>B – Exit in 5 min</td>
<td>300</td>
</tr>
<tr>
<td>Upper bound scenario</td>
<td></td>
</tr>
<tr>
<td>C – Exit in 1 hour</td>
<td>400</td>
</tr>
<tr>
<td>D – Exit in 2 hour</td>
<td>400</td>
</tr>
<tr>
<td>First Responders</td>
<td></td>
</tr>
<tr>
<td>E - Entry 5 min post shot, exit 10 min later</td>
<td>90</td>
</tr>
</tbody>
</table>

Attachment 3, Table S.7, summarises the lifetime risk increase of fatal cancer (mainly resulting from lung cancer) by scenario. Values, rounded for clarity, are given in Table 15. The striking features, reflecting the predicted doses (Tables 13 and 14), are that:

- For all scenarios the predicted risks are less than 1%
- For the unventilated vehicles the predicted risks are typically in the range 0.1-0.5%.
- For the unventilated vehicles there are relatively small differences in predicted risks between vehicles and between scenarios
- For the ventilated tank the predicted risks are much lower, especially for the short stay times.
### Table 15 Summary of median lifetime risk of fatal cancer by scenario (based on Attachment 3 Table S.7, but rounded)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Abrams tank</th>
<th>BFV Conventional tank</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conventional armour, no ventilation</td>
<td>Conventional armour, no ventilation</td>
</tr>
<tr>
<td></td>
<td>DU armour, no ventilation</td>
<td>EC/NBC ventilation</td>
</tr>
<tr>
<td>Most likely scenario</td>
<td>Crewmembers</td>
<td></td>
</tr>
<tr>
<td>A – Exit in 1 min</td>
<td>0.11</td>
<td>0.005</td>
</tr>
<tr>
<td>B – Exit in 5 min</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Upper bound scenario</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C – Exit in 1 hour</td>
<td>0.25</td>
<td>0.4</td>
</tr>
<tr>
<td>D – Exit in 2 hour</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>First Responders</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E – Entry 5 min post shot, exit 10 min later</td>
<td>0.05</td>
<td>0.1</td>
</tr>
</tbody>
</table>

### 3.9 Application to military risk management

The Capstone Report notes that the risks need to be put into an appropriate framework that applies to the various risks of combat, so that field commanders can include them in mission risk analysis and management. Radiation Exposure Status (RES) categories are used to track the total radiation dose received by a combat unit. A RES unit of zero refers to a combat unit receiving no radiation exposure. A RES-1 category indicates a unit has received some radiation exposure, but the dose is ≤75 rad (750 mGy). The primary health endpoint in this dose range is the potential for increased risk of fatal cancer. The RES-1 category is subdivided into five levels (A-E) based on external gamma exposures.

In the HHRA, the RES risk-based system was modified to make it applicable to internal DU deposition and its related dose. This modification was achieved by converting the RES category doses into levels of increased risk using ICRP/NCRP risk coefficients and then comparing the calculated risks of cancer from inhaled DU aerosols to risks represented by these categories. (This approach is reminiscent of the ICRP dose convention for exposure to radon decay products. An effective dose in mSv is assigned to a given radon exposure on the basis of equating estimated risks.)

A dose and dose-rate effectiveness factor of 2 was applied to all absorbed doses less than 20 rad (200 mGy) and to any absorbed dose delivered at dose rates less than 10 rad/h (100 mGy/h).

Because there is no similar system developed for chemical toxicity the REG chemical risk model (discussed above), which is based on the peak kidney uranium concentration, was used to perform a similar function.

RES and REG categories were determined for each scenario (Attachment 3, Table S.8).
3.10 Conclusions of the Capstone HHRA

A summary is given in Attachment 3, pages xv to xvii, with further details in Section 8, pages 8.1-8.13. The following summarises the conclusions from the Capstone Report.

3.10.1 Scientific

- The data from the Capstone study provide a sound basis for assessing Level I inhalation exposures.
- The data represent situations that maximised DU aerosol exposure: shot lines that maximised aerosol production, and minimal ventilation.
- Measurements of DU aerosols in a fully equipped, perforated vehicle with an operating ventilation system and additional mathematical modelling of increased air exchange provided information on the effectiveness of ventilation in reducing doses and risks.
- Direct use of the size-specific stage data from CIs has advantages over the traditional method of fitting a distribution function, and could be useful in other applications.
- Similarly, direct application of multi-component functions describing particle dissolution in the HRTM made best use of the original data.
- Implementation of the Markov Chain Monte Carlo method for uncertainty estimation made good use of the extensive aerosol measurement data and allowed propagation of uncertainties in a robust manner.
- The use of Bayesian statistics involving the Markov Chain Monte Carlo method was considered to improve the estimates of the “true values.”
- Data from the literature review of human health effects following exposure to uranium were used to develop a set of Renal Effects Groups to predict the potential kidney effects of peak uranium concentrations.

3.10.2 Implications for military authorities

- The most important factor for reducing exposure and dose discovered in this analysis was the use of onboard vehicle ventilation.
- The doses and risks to human health resulting from the inhalation of DU aerosols in a perforated vehicle are low compared with many other combat risks.
- In ventilated Abrams tanks, the levels of predicted chemical toxicity and radiological risks for the time periods modelled (up to 2 h) are below routine occupational limits. Personnel are not likely to develop adverse health effects as a result of exposure at these levels.
- In unventilated Abrams tanks, no adverse health effects are predicted for the shortest stay-time (1 minute) but the potential for temporary kidney effects, increases with stay-time.
• In unventilated Abrams tanks, most of the intake would occur within the first 5 to 10 minutes after perforation. This intake would be significantly reduced by activation of the ventilation systems. Dose and risk reductions would also be expected in a Bradley vehicle with an operating ventilation system.

• The absence of identified adverse toxicological effects related to the presence of DU in veterans with DU fragment wounds supports the conclusion of this report that no immediate or long-term adverse health effect, especially to the kidney, would be expected for the most likely exposures presented.

• No adverse health effects are expected from exposures in unventilated Bradley vehicles for any of the time periods modelled (up to 2 h).

• The data from the double-shot tests suggest that the radiation doses and uranium concentrations could be approximated by doubling the doses and kidney concentrations from a single shot.

• Because of differences in individual exposures for crew in a perforated vehicle, DU bioassays are needed to establish individual dose estimates. This report provides information that can be used for deciding when biomonitoring should be implemented.

• Although radiation risks from all scenarios evaluated are predicted to be low, counselling of affected personnel and their family members is suggested because of the perceived radiological risks associated with exposure to DU.

3.11 Comparison with other assessments

Comparisons are made between the results (doses and peak uranium kidney concentrations) of the HHRA, and assessments made by USACHPPM (2000) and the RSWG (Royal Society, 2001, 2002) in Section 3.6 of the Summary Report (Parkhurst et al, 2004a). The Capstone report notes that there is good agreement between median values for the USACHPPM (2000) and the HHRA (Scenario A with no ventilation) and the RSWG central estimates. It also notes that the RSWG “worst case” assessments are more than an order of magnitude higher than those derived from the Capstone data, but that this is not surprising, because of the RSWG use of worst case assumptions for more parameters.

To give a better understanding of the differences between the assessments, a brief comparison (made by the reviewer) between that of the RSWG for Level I exposures, and that of the HHRA, follows (Sections 3.11.1 – 3.11.5).

3.11.1 Central estimates and upper bounds

Comparison of the approaches is not entirely straightforward, because there are differences in what is meant by “central estimate” and “worst case” by the RSWG and the HHRA.
This probably reflects differences in intended use. For the RSWG the central estimate was intended to be a best estimate of the population average, so that multiplying it by the number exposed would give an assessment of the total health impact, and could be used, for example, to consider the feasibility of obtaining a useful result from an epidemiological study. The “worst cases” were intended to be values that it was unlikely that any individual would exceed. A major aim of the worst-case assessments was to try to prioritise further investigation. If even the worst-case assessment for a scenario leads to small exposures, then there is little need to investigate it more closely.

For the HHRA, however, the overall aim was to give guidance to the US Department of Defense (DoD) on whether the health risks to Level I personnel were high enough to warrant changes in their medical policy, treatment or monitoring, or in their personnel protective measures. A second aim was to give guidance for field commanders to put the risks in the context of other combat risks.

3.11.2 Intakes
In the absence of a suitable data set, the RSWG made simple calculations to estimate Level I exposures, whereas the HHRA drew on the Capstone Aerosol Study data.

Details of the RSWG approach are given in Annexe C to Part 1 (Bailey et al, 2001). For the central estimate it was assumed that 100 g DU was dispersed (2-3% of a 4-kg penetrator) based on information reported from trials of penetrator impacts (Table 7, Section 2.13.1). This is consistent with the Capstone range of 1-7%. For the worst case it was assumed that 2000 g DU was dispersed (20% of two 5-kg penetrators). The vehicle was assumed to be a box, 3x2x2 m, having a volume of 12 m³. Thus initial air concentrations were about 10 and 100 g m⁻³ respectively. For both cases it was assumed that 50% was “respirable”, giving effective concentrations of 5 and 50 g m⁻³, respectively. These are in the same broad range as those for Capstone Phase I-III for unventilated vehicles (3-16 g m⁻³, Table 5, Section 2.6.1), but much higher than for the ventilated tank (0.1 g m⁻³).

To assess intakes, the RSWG assumed “heavy exercise” (ICRP, 1994), giving a breathing rate of 3 m³ h⁻¹, as assumed by the HHRA for the short-stay exposures (Table 2, Section 1.3). However, the HHRA uses a lower rate for longer exposures which is probably more realistic. For the RSWG central estimate, a 1-minute exposure was assumed (as for the HHRA scenario A, Table 2, Section 1.3), giving an intake of 250 mg. For the RSWG worst-case the exposure time taken was 1 hour (as for the HHRA scenario C, Table 2). The RSWG used measurements reported in USACHPPM (2000) of the reduction in concentration with time, and assumed (for simplicity) a step change drop of an order of magnitude every 10 minutes. This led to an intake of 5000 mg, half of which was incurred in the first minute.

The RSWG central estimate of 250 mg is close to those for HHRA scenario A in an unventilated vehicle: 80 mg for the BFV and 300 mg for an Abrams Tank (Table 11, Section 3.4), but much higher than for the ventilated tank (10 mg).

However, the RSWG worst case (5000 mg) is considerably higher than any HHRA scenarios (up to 1000 mg, Table 11).
3.11.3 Modelling

The same current ICRP biokinetic and dosimetric models were used for both the RSWG and HHRA assessments.

Model parameter values

Breathing rates were noted above.

The RSWG selected three sets of parameter values, one for the central estimate, and two “worst-cases”, one for radiation effects, for which the lung dissolution rate was the lowest consistent with available information, to maximise the lung dose in particular, and one for chemical effects, for which the lung dissolution rate was the highest consistent with available information, to maximise the peak kidney concentration. Parameter values were generally based on information reported from trials of penetrator impacts (Tables 8–10, Section 2.13), and are given in the Royal Society (2001) report Part I, Table 14. Again the HHRA drew on the Capstone Aerosol Study data for distributions of values.

The parameter values relating to deposition are broadly similar for the two assessments. However, different approaches were taken to lung clearance. The HHRA relied entirely on the Capstone data, based on in vitro tests, to assess particle dissolution rates in the lungs.

The RSWG report took account of the results of in vitro dissolution tests that had been reported, but also took account of in vivo studies on uranium oxides. As described in Appendix 1 (Bailey and Marsh, 2001), with additional information in Annexe A (Bailey and Phipps, 2001), results of in vitro tests on material collected from DU impacts (and combustion) were used to define the fraction that dissolves rapidly. For aerosols formed from impacts, a typical value is 0.3 with a range of 0.1 – 0.5. (For the Capstone Aerosols the geometric mean is 0.13, with a range of 0.01 – 0.3, somewhat lower, but not dramatically.)

However, the RSWG used results of in vivo experiments on U₃O₈ and UO₂ (Annexe A, table A5) to assess the rapid dissolution rate (1 d⁻¹) and, more importantly, the central estimate of the slow dissolution rate (0.001 d⁻¹). The reported analyses had identified U₃O₈ and UO₂ as the major crystalline components, and for each, there were results available from in vivo studies carried out for the civil nuclear fuel industry in laboratories in the UK (Hodgson et al 2000) and France (Ansoborlo et al, 2002). For the Capstone Aerosols the geometric mean values based on two-component fits were 6 d⁻¹ and 0.0026 d⁻¹ respectively, qualitatively similar, but somewhat greater. It was recognised by the RSWG that the dissolution rate of these compounds is likely to depend on the process of formation, size distribution, presence of other metals etc. For the worst case estimate for radiation dose, the RSWG noted that very long term lung retention has occasionally been observed in follow-up studies of humans occupationally exposed to uranium compounds, and a slow dissolution rate of 0.0001 d⁻¹, as for default Type S was assumed.

With respect to the RSWG approach, the Capstone Aerosol Study provides much better information (from in vitro dissolution tests on nearly 30 samples) than was available to
the RSWG, to assess a central value and range for the fraction that dissolves rapidly. However, since no \textit{in vivo} experiments were conducted, and no evidence was provided to justify extrapolation of \textit{in vitro} dissolution rates of DU aerosols to their absorption in the human lungs, the reviewer sees no obvious reason to change the RSWG assessment of the rates of dissolution of the rapid and slowly dissolving fractions.

### 3.11.4 Results: Radiation doses

For the central estimate, the RSWG committed effective dose (20 mSv) is similar to those for HHRA scenario A in an unventilated vehicle: 6 mSv for the BFV and 20 mSv for an Abrams Tank (Table 13, Section 3.8), but much higher than for the ventilated tank (1 mSv).

However, the RSWG worst case (radiation) is considerably higher (1100 mSv) than any HHRA scenarios (up to 90 mSv, Table 13). This is partly due to the higher intake (5000 vs 1000 mg) and partly to the higher dose per unit intake, which mainly reflects the assumption of much slower dissolution in the lungs.

### 3.11.5 Results: Kidney concentrations

For the central estimate, the RSWG peak uranium concentration in kidneys (4 µg U/g kidney) is similar to those for HHRA scenario A in an unventilated vehicle: 1 µg U/g kidney for the BFV and 3 µg U/g kidney for an Abrams Tank (Table 12, Section 3.7), but much higher than for the ventilated tank (0.05 µg U/g kidney).

However, the RSWG worst case (chemical) is considerably higher (400 µg U/g kidney) than any HHRA scenarios (up to 8 µg U/g kidney, Table 12). This is partly due to the higher intake (5000 vs 1000 mg) and partly to the faster assumed dissolution in the lungs (rapid fraction of 0.5 vs about 0.1).

### 3.12 What might have been achieved with more time and resources

As noted in the Introduction (Section 1.1), in this review the Capstone Program's achievements and limitations are considered not in relation to the objectives of the Capstone Program itself, but in relation to the wider requirements of assessing exposures to DU resulting from its use in weapons, and from a UK perspective. Thus consideration is given to the extent to which the Capstone Program filled gaps in information identified by assessments such as that carried out by the RSWG. Several issues identified by the reviewer are described in the following sections (3.13-3.17).

### 3.13 Scope

#### 3.13.1 Exposures outside the vehicle

The obvious limitation of the HHRA is the restriction to Level I exposures inside the vehicle. Level II and III exposures inside (and to some extent outside) the vehicle by
inhalation of resuspended dust and hand-to-mouth contact are addressed in the Capstone Report, but in a separate assessment, described in Attachment 4 (Szrom et al, 2004). This is discussed below in Section 4 of this review.

The HHRA does not consider exposures outside the vehicle, even though the Capstone Aerosol Study includes some measurements of concentrations and size distributions outside the vehicle (but with reservations). It notes that exposures outside are likely to be much lower. This is probably true, and the HHRA is exclusively concerned with military personnel. However, UK public perception is that whereas in ODS most DU on armour impacts occurred in remote areas, in the 2003 Iraq conflict there were many engagements in urban areas. Hence the population exposed outside could well involve much larger numbers, include non-combatants, with wide ranges of ages and health status. The reviewer considers that there are both moral and political needs to consider their exposures (and similar potential future exposures). While the priority for commanders in the field is for their own personnel and their continued effectiveness, others need to consider the overall health impact of the use of a weapon system. In the case of DU munitions, concern is already widespread. There is therefore a remaining need to consider exposure as a function of distance from a struck vehicle. As noted elsewhere (Section 1.1), for those outside US military organisations, the ability to do so is limited by the restricted distribution of report on the key study (Fliszar et al, 1989). A recent French study (Section 2.13) is a useful addition. However, the only publication available is a four-page account in the proceedings of a conference (Chazel et al, 2003), and only two shots were involved, so the information available from it is limited. There is a need to review this issue taking all available information into account.

3.13.2 DU fragments and wounds
Evaluation of the health risks from embedded fragments and wound contamination was stated to be beyond the scope of the HHRA. However, these are potential exposure pathways for Level I personnel, and so for completeness they would have been addressed, at least by a comprehensive review of the current literature. There is some account of the follow-up study of US ODS veterans who sustained DU fragment wounds (McDiarmid et al 2004). Although Appendix B reviews animal studies on uranium toxicity, it does not cover direct effects of fragments, although there have been some animal experiments addressing possible affects (Hahn et al 1999a, 2000).

3.13.3 Scenarios and extrapolation to other situations
Attachment 3, Page 2.1 discusses the range of scenarios. It is stated that: “Because it was not possible to evaluate every conceivable scenario, operational conditions were selected for modelling that would reflect relatively long stay-times and the associated potential for resulting in the highest doses or kidney uranium concentrations.” As shown in Table 2, the “stay time”, or duration of exposure is the main parameter varied explicitly in the assessment, and both long and short stays were considered.

Attachment 3, Page 2.1 states that: “Certain conditions that would increase aerosol removal, such as operation of ventilation systems and opening of hatches, were not modelled but were qualitatively discussed. Additionally, evaluation of other confounders,
such as the operation of the fire-suppression system after perforation, were not addressed. The impact of shot lines other than those presented in the Capstone study was not considered. The Capstone study shot lines were based on either composites of actual events during ODS or shot lines that did not occur but would have increased aerosol concentrations.

As discussed in Section 2.11, the reviewer considers that a major limitation of the Capstone Aerosol Study is the lack of development and testing of a model to extrapolate the results to other scenarios. However, this is addressed to a limited extent in the HHRA. The Capstone Report notes (Attachment 3, page 2.4) that in actual operations, at least minimal ventilation would be expected, and any number of hatch positions would be possible. A simple model is developed on pages 3.24-3.31. The ventilation systems on the vehicles are described, and the values given in Attachment 1 Table 4.23 repeated (summarised here in Table 4, Section 2.5.3). A simple model is developed for the reduction in concentration with time taking account of ventilation and deposition onto surfaces. It is noted that the latter is particle size-dependent. As a test of the model, the reduction in concentration with time was compared for shots PIII-1 and PIV-4. Both were for a DU round penetrating DU armour on an Abrams tank, but for PIII-1 there was no ventilation, whereas for PIV-4 the EC/NBC system was operating. The predicted reduction in concentration applied to the PIII-1 data was in reasonable agreement with the PIV-4 data: an overall decrease by an order of magnitude every 3 minutes. For the BFV the predicted effect of ventilation system is less dramatic, partly because the air exchange rate without mechanical ventilation is higher, and partly because the ventilation system is less effective. The predicted overall reduction is an order of magnitude every 23 minutes.

However, this model was not applied in the HHRA to dose and risk assessment. It is not clear why to the reviewer. As noted in Section 2.1.3, The Data Quality Objective (DQO) 1 for the Aerosol Study (Attachment 5, Page 2) includes the following:

“Develop an experimental scenario that provides the data required for bounded (upper-bound, lower-bound and most probable) estimates of the inhalation and ingestion in the crew compartments of Bradley Fighting Vehicles (BFV) and Abrams tanks (with and without DU armour) at the time the vehicles are struck by DU munitions. The design must allow for reasonable extrapolations to less or more severe scenarios…”

(The status of the DQOs, the extent to which they were for guidance rather than mandatory, is not clear to the reviewer. They are, however, included in the Capstone Report package, and so it seems reasonable to refer to them.)

The impression is given that vehicle ventilation is a major factor in determining the exposure of the crew. A model such as this appears to have potential for extrapolating the results to more probable and/or less severe exposures. However, data were only available for one test (PI-4) in which the ventilation system was operating, and in that test there was much more limited sampling than in the others (no Capstone air sampling arrays). It is unfortunate that the Capstone Report does not state whether it was considered to form an adequate basis for extrapolation.

Thus these scenarios are not designed to give exposures that would correspond to the RSWG objectives of a “central estimate”. The RSWG “central estimate” was intended to
be representative of the Level I population average, and could be used to make an assessment of the overall impact (e.g., additional cancers) resulting from a given number of strikes. Some scenarios are closer to the RSWG “worst case” objective of an exposure such that it should be unlikely that any individual would exceed it (Section 2.1.3).

Attachment 3 page 2.3 states “The focus of this modelling effort is to provide upper bound estimates of potential DU aerosol exposures and intakes to personnel inside a perforated Abrams tank or a Bradley vehicle.” The HHRA generally applied parameter values and ranges as determined directly by the Capstone Aerosol Study.

Thus the modelling considers worst-case exposures and intakes, but the subsequent stages of the HHRA appear to be based on modelling using central estimates of parameter values.

This suggests to the reviewer that a UK-based reassessment might be worthwhile, combining military expertise on armour, ventilation rates, evacuation times etc relevant to UK vehicles, and independent expertise (aerosols, biokinetic modelling, risks).

### 3.14 Assessment of tissue doses and uranium concentrations

#### 3.14.1 Respiratory tract deposition

Rather than using either assumed or fitted unimodal or bimodal lognormal particle size distributions, actual uranium masses from each of the eight size-specific CI stages were used (Attachment 3, page vi). As noted by the reviewer in Sections 2.7.1 and 3.5.2 above, this is a commendable approach, which might well be applied elsewhere. However, the reviewer also considers that ideally an evaluation would have been provided of how much difference this made to the dose (and uranium concentration) assessment, compared to the standard and simpler approach of using the AMAD and GSD.

For example, the RSWG Report (Royal Society, 2001, Annexe G; Bailey, 2001) investigated the implications of a wide or multimodal size distribution on respiratory tract deposition and radiation doses, in relation to the very high values of GSD (>10) reported by Chambers et al (1982). It was shown that (for an aerosol of AMAD 1.6 µm, density, \(\rho\), 10 g cm\(^{-3}\) inhaled by an ICRP reference worker) increasing the GSD from its HRTM default value of ~2.5 to 13 had little effect on total deposition, but deposition in the extrathoracic (ET) airways decreased and lung deposition increased. There was some increase in dose for Types M and S, but it was not large. However, it was noted that the apparent large GSD probably represented a multi-modal distribution. The dose per unit intake (\(\mu\)Sv Bq\(^{-1}\)) was considered for \(^{238}\)U aerosols with GSD = 2.5, \(\rho = 10\) g cm\(^{-3}\) inhaled by a reference worker, consisting of four equal components with AMAD 0.01, 0.1, 1 and 10 µm. It was shown that for all three absorption Types (F, M, S), the dose was considerably higher for the components with AMADs of 0.01 and 0.1 µm than for those of 1 and 10 µm. For Type S, the average was about twice that for the very broad aerosol (GSD 13), which in turn was about twice that for an aerosol with default parameter values. A similar pattern was seen for Type M. Thus it is quite possible that the improvement is significant, but it would be useful to confirm it, particularly in relation...
to the issue of extrapolation to other scenarios (Section 3.13.3), where it would be simpler to use a distribution function than a matrix of values.

### 3.14.2 Particle composition and morphology

The HHRA did not use all the information collected in the Capstone aerosol study. In addition to the exposure pathways and scenarios, discussed in relation to the Scope of the HHRA, Attachment 3, Page 3.8 notes that the following were “either not assessed separately in this report or were outside the scope of the risk assessment”:

- Chemical forms by particle size over time
- Particle morphology by particle size over time
- Total elemental composition by particle size.

This seems related to a similar limitation in the Capstone Aerosol study (Section 2.11.3): “Analysis of the mechanisms of particle formation was outside the scope of the study, although possible mechanisms are discussed in this report for certain cases.” In the reviewer’s opinion, ideally, consideration would be given to such matters, in order to make best use of the information obtained, and especially to gain understanding of the processes involved in aerosol production and their consequences for risk assessment. Again, however, this is mainly in the context of providing a scientific basis for extrapolating to other situations (Sections 2.11.2 and 3.13.3).

### 3.15 Uncertainty analysis

The only factors included in the HHRA uncertainty analysis were those that could readily be quantified from the Capstone Aerosol Study: measurement uncertainties and variability in the measured data. The reviewer considers that the exclusion of other factors could possibly lead to underestimation of overall uncertainties and hence in the worst-case upper bound. Furthermore, a full uncertainty analysis is useful in identifying the contributions to overall uncertainty made by all the factors involved and hence provides guidance on options for reducing uncertainties if that is required.

In particular, modelling uncertainties were not included. The Capstone Report notes that the models used, particularly the HRTM and the ICRP uranium systemic biokinetic model are complex mathematical systems, which are not amenable to simple uncertainty estimation. It also notes that although recent work by e.g. Bolch et al. (2003) provides comprehensive investigations of model uncertainties using classical statistics, ways to incorporate these new approaches into comprehensive uncertainty analyses, particularly in a Bayesian context, have not been developed, and model uncertainties were not included.

The reviewer considers that ideally a full uncertainty analysis would be carried out, and would not rely only on the work of Bolch et al. as indicated in the HHRA Report, but would focus on model aspects specifically related to the DU intakes in question here.
Similarly it would go beyond variability in the measurements. Attachment 3, pages 5.16-5.17 discusses uncertainty in solubility. The variability in the measured in vitro samples was used to test the effect of solubility on committed dose. However, it does not address the issues of extrapolation (i) from in vitro measurements to the human lung and (ii) from measurements conducted over 46 days to complete dissolution, over months or years. For the first, (in the absence of experimental validation specific to these materials and in vitro test system) a first step would be to review the literature for available comparisons between in vitro and in vivo results, with emphasis on uranium oxides.

The reviewer recognises that to carry out a full uncertainty analysis would require a very large effort. However, in the context of the Capstone Program it does not seem to be an unreasonable expectation, given its large scale and the overall resources involved.

3.16 Radiation and chemical effects

The reviewer’s opinion is that although reviews were conducted of the literature relating to radiation and chemical effects, these were limited to reasonable complementary studies, consistent with their presumed role in support of the main effort, which was to apply the results of the Capstone Aerosol Study. They do not seem to have been exhaustive studies, as for example recommended by the RSWG with respect to the lymph nodes: “a thorough review of the effects of radiation from radioactive particles retained in lymph nodes, including any possible carcinogenic effects.” The lymph nodes are considered, but briefly, (Attachment 3 page 6.37): “Studies in dogs with high burdens of inhaled, highly radioactive plutonium have shown that lymph nodes that accumulate large burdens of plutonium are not target organs for cancer (Hahn et al. 1999).”

Similarly, although a review of the literature was carried out for human cases of acute exposure to uranium, leading to toxic effects, it does not seem to have been exhaustive. A relevant study that is not included, which came to this reviewer’s notice recently is that of Bassett et al (1948) in which people were injected with increasing uranium masses until effects on kidney function were detected.

Thus the reviewer considers that the need for a project in the MOD DU research programme on Health Effects remains.

The precision of the REG levels seems high (e.g. REG 1 goes from 2.2 to 6.4 µg U/g kidney) in view of the sparse data (Attachment 3, Table 6.3) on which they are based. Thus the original data include only two cases in REG 3, two in Reg 2, eight in REG 1, and 15 in REG 0.

3.17 Report

3.17.1 Risk communication

Attachment 3, Page 2.3 gives a list of the specific objectives for the HHRA, which includes: “Use good risk communication to provide the estimated risks of DU exposure so that appropriate decisions can be made and actions can be taken.”
In this reviewer's opinion, while overall this is done well, there is a tendency to downplay some of the assessed risks, especially in the Report Summary. This is unfortunate, as it detracts from the overall high standards and objectivity of the work, and unnecessary, because the assessed risks are generally small anyway. Examples follow here.

In the Executive Summary, in presenting the risks of radiation induced cancer assessed in the HHRA, it states "The calculations used the conservative Linear, No-Threshold theory of effect that may overestimate risks at the levels predicted in this study and are, therefore, thought to be conservatively protective of health" (Parkhurst et al, 2004a, Page xiii: a similar statement is made on Page 3.6). So far as the reviewer is aware, no evidence is presented in the HHRA to support the view that the Linear, No-Threshold theory overestimates risks at the levels predicted in the study. While the reviewer agrees that it "may" overestimate such risks, and that some scientists think that it is "conservatively protective of health", these are judgements which are not universally held.

For example, Preston (2003), in a specific review of the subject, concluded that at the time of writing: "The requirement for a dose-response model to be used for risk assessment purposes is that it fits the great majority of data derived from epidemiological and experimental tumour studies. Such is the case for the LNT model as opposed to other nonlinear models." Preston also recognised the need for additional data.

In a review of the data available for assessing risks of radiation-induced cancer for radiation protection purposes the UK National Radiological Protection Board (NRPB, 1995) stated that: "in consideration of a broad body of relevant cellular and molecular data, it is concluded that the weight of evidence in respect of the induction of the majority of human common tumours falls decisively in favour of the thesis that, at low doses and dose rates, tumorigenic risk rises as a simple function of dose without a low dose interval within which risk may be discounted." Thus NRPB did not consider that the assumption of no threshold to be "conservative".

The UK Committee Examining Radiation Risks of Internal Emitters (CERRIE) discussed the issue in its final report (CERRIE, 2004, page 18): "Having applied a DDREF of two, the ICRP assumes a linear relationship between dose and risk at low doses. It is the consensus among radiological protection scientists that this is the best approach on current evidence (Preston, 2003). However, Committee members differed in their acceptance of this assumption for radiological protection purposes. ...The assumption of a linear no-threshold response is certainly convenient and is not inconsistent with current observations, but as important consequences follow from the assumption it is important that this issue is addressed by further research."

The recent pooled analysis of the increased risk of lung cancer from radon in homes (Darby et al., 2005), gives support to the LNT theory, and is especially relevant because it relates to protracted alpha irradiation of the lungs at levels of exposure of similar magnitude to some within the scope of the HHRA. A key finding was that: "The dose-response relation seemed to be linear, with no evidence of a threshold dose, and there was a significant dose response relation even below currently recommended action levels."
Note that the LNT theory was actually used in the HHRA, and so the reviewer considers that reasonable risk estimates were made, based on the doses assessed, and not overestimates, as implied in the summary.

It is stated that (Attachment 3, Page ix) “The true annual dose is much less than the 50-yr committed dose, both for individual organs and for the effective dose.” A similar statement appears in the Overview Report (Parkhurst et al, 2004a, page 3.7). It would have been helpful to give details, because this is not consistent with the RSWG calculations (which admittedly made some different assumptions about parameter values). Royal Society (2001) tabulated tissue and effective doses to 1, 5, 10 and 50 years for Level II/III intakes by inhalation for its Central Estimate and Worst Case scenarios (Appendix 1, Table 21, page 47). For both, just over half the 50-year committed effective dose is received in the first year, as is most of the lung dose. However, doses to other tissues, notably lymph nodes and red bone marrow build up more slowly.

3.17.2 Restricted information

Another factor that detracts from the risk communication is that some of the important references cited are not on unrestricted distribution (see e.g. Table 3). (As a minimum, it would be helpful to the reader if documents that are not publicly available were identified as e.g. “Restricted circulation” in the reference lists where they are cited.)

Ideally, however, those documents that are considered to be essential references in support of the Capstone Report, and which are not obtainable through normal inter-library requests, would have been identified, and where possible de-restricted (removing any security sensitive material). Attachment 5, Page 12 states that: “the focus and the primary reasons for ensuring the quality of this DU Exposure Assessment and Health Risk Characterization, updated with the DU Capstone Test data, are:

a. Trust of the soldier and DOD/DA civilian, his/her family, military commanders, the military veteran, U.S. Allies (Coalition Forces), the media, the citizens of the United States, and the Congress.

b. Scientific credibility of the DU health risk assessment product.”

Although there is much within the Capstone Studies and Report that helps meet these aims, the continued inability to access some apparently key documents referenced in the report remains a barrier to the objective of achieving scientific credibility within the wider academic community. This aim can only be met by adopting “standard scientific practice” and making all the relevant information publicly available, unless of course, there are reasons of national security for withholding it.

The key document in that respect is the report of Fliszar et al (1989), which is often cited, and is regarded as the most valuable source of information on exposures downwind of a struck vehicle. For example, Attachment 3, page 1.1 states “Before the Capstone study, data from the most comprehensive test of aerosol generated in a test that involved firing DU and non-DU munitions at a DU-armoured Abrams tank was reported by Fliszar et al (1989). The primary objectives of that test were to measure the aerosol plume as a function of distance from the vehicle, estimate the level of soil
LEVEL II AND LEVEL III EXPOSURES

4.1 Introduction

A separate health risk assessment (Szrom et al., 2004, Attachment 4) was carried out to estimate potential DU inhalation and ingestion exposures for personnel who enter or work around perforated vehicles hours to days after the impact (Level II and III personnel). Its Preface states that it makes use of the information presented in Attachments 1, 2 and 3 to do so.

The main difference from Level I exposure scenarios (which are addressed in the HHRA) is that Level II and III personnel would not have been in, on, or near the vehicles at the time of perforation. Level II and III personnel are potentially exposed by inhalation of DU resuspended from surfaces as a result of their physical activities in and on struck vehicles or by ingestion (hand-to-mouth transfer) of DU residues transferred from surfaces to hands. Removable DU contamination could be on the surfaces of a vehicle damaged by DU munitions or on a vehicle that has damaged DU armour.

The primary exposure pathways are the same for Level II and III. However, the Capstone report notes that Level II personnel spend more time inside the vehicles, and the physical activities performed in and around the vehicles may also be different for Level II and III.

It also notes that some important data were available before the Capstone Program, e.g. relating to fires and to aerosols outside vehicles. USACHPPM (2000) gives a summary of the available data for assessing Level II and III exposures, with assessments of its quality, and identification of data gaps. These gaps included measurements of DU resuspended into the air inside vehicles and measurements of DU hand contamination, for which the Capstone DU Aerosol Study has provided data.

Important assumptions of the assessment by Szrom et al. were that:
The Capstone samples are representative of vehicle conditions that Level II and Level III personnel would encounter.

The physical activities performed by Capstone sample recovery personnel are surrogates for the types of physical activities performed by Level II and Level III personnel in and around DU contaminated vehicles.

4.2 What was achieved

4.2.1 Inhalation of resuspended DU

4.2.1.1 Capstone source data

Two Capstone study data sets were used to estimate DU inhalation intakes and subsequent doses and kidney uranium concentrations:

The 29 personal cascade impactors (P-CIs) worn as breathing zone monitors (BZMs) by sample recovery personnel. They worked inside the vehicle removing samples, reloading samplers and taking equipment in and out of the vehicle. Some of these duties were similar to Level II activities.

Phase I, II, and III personnel entered the vehicle at least 2 h after perforation. The BZM operated from the time that personnel crossed the “hot-line” to enter the testing facility until they returned across it. Most of this time was spent inside the vehicle.

During Phases I, II, and III, the P-CIs were paired with personal filter cassette (P-FS) samplers and were operated simultaneously from the same pump (the pump vacuum line was split with a “Y”) (results are given in Attachment 2, Table A.41). The pumps for Phases I, II and III were adjusted to a flow rate of 4 litres per minute (Lpm). The actual flow rate across each sampler was unknown, and an even split of the flow rate was assumed for the concentration calculations reported. The P-CI and P-FS sampling configuration was tested subsequently (as part of the assessment by Szrom et al) to determine actual flow rates for each sampler. The test indicated that 2.6 Lpm was across the P-CI, and this flow rate was used in the analysis of the results. Following the procedure used in the HHRA, only the P-CI data were used to determine aerosol concentrations. (It was reasonably considered that the PF-S collected large particles more efficiently than the P-CI, and therefore the total air concentration of DU measured by the P-FS was not consistent with the size distribution measured by the P-CI: see Section 3.4 or the original documents for further information.)

In Phase IV, only the P-CIs were used and the flow rate was 2.0 Lpm. Entries began 40 min after the PIV-4 shot and continued over the next few days. Personnel conducted a variety of tasks including sample recovery, equipment removal, and vehicle decontamination.

After shots PI-6 and PI-7, the CIs from two Capstone sampling arrays collected aerosols inside the vehicle before, during, and after recovery activities were performed in it.

All the data were generated using actual flow rates and applying stage-specific wall-loss correction factors.
4.2.1.2 Analysis of CI data
As in the HHRA, each DU aerosol was represented by nine monodisperse aerosols. The nine components corresponded to the median aerodynamic diameters (AD) of the nine P-CI stages (the 9th is the backup filter) for the flow rate at which the P-CI was operated. Full details are given on how the CI data were analysed to achieve this. As noted in Sections 2.7.1 and 3.5.2 the reviewer agrees that while it is useful to fit a lognormal distribution and obtain an AMAD and GSD to give a broad description of the aerosol size distribution for comparison purposes etc, it is better to use the original CI stage data to calculate deposition in each part of the respiratory tract.

Inhalation intakes by component were calculated by multiplying the concentrations by the breathing rate (BR) and the time the P-CI was run. This included time the wearer spent in and around the vehicle performing sample recovery activities. The monodisperse ADs were then related to the corresponding cyclone stage and appropriate lung fluid dissolution rate-functions derived from the Capstone cyclone aerosol samples. (Again, this follows the HHRA procedure, as outlined in Section 3.5.3, and the reviewer agrees that it makes good use of the available information.)

4.2.1.3 Calculation of uranium concentrations and doses
Dissolution functions from the Capstone Aerosol Study (Attachment 2, Appendix E) were fit to three-compartment exponential functions with rapid, slow, and very slow fractions and dissolution rates (Sections 2.7.4 and 3.5.3). However, whereas the HHRA developed specific software for the subsequent calculations, Szrom et al (2004) used existing commercially available software (IMBA-URAN) to calculate peak kidney uranium concentrations and organ equivalent dose conversion factors (DCFs) for a unit (1-µg) inhalation intake. The software, which implements the HRTM, only provides for two components of dissolution, (fast and slow, Section 3.5.3). To take full account of the three components available from the Capstone Aerosol Study, Szrom et al took (in the reviewer’s opinion) a simple and ingenious approach. For each combination of AMAD and three-compartment dissolution function, the software was run twice and the results were summed. The first run (“a” fraction) calculated results for the rapid and slow fractions of the dissolution function. The second run (“b” fraction) calculated results for the very slow fraction. These were then summed. The reviewer considers that this approach is preferable to that used in the HHRA, being so much simpler (and easier to follow). The use of the two independent approaches does however have the merit of providing additional QA checks on both. A minor comment is that the reference given to the IMBA-URAN software is to the user manual supplied with it, which is not generally available. Descriptions of IMBA software (although not IMBA-URAN specifically) are in the open literature (Birchall et al 1998, 2003).

4.2.1.4 Assessments based on personal CI
Results from each of the twenty-nine P-CI were used to calculate committed (50-year) effective dose and lung dose and peak uranium kidney concentration. These were divided by the exposure time to calculate rates, i.e., the doses and concentrations resulting from 1-hour exposure (Attachment 4, Table 2.15, which also gives the recovery activities being performed when each sample was taken).
The highest dose rates were for PIV-4 personnel who carried out decontamination activities. They were several times higher than any others, and one to two orders of magnitude larger than the other P-CI results for PIV-4. The Capstone Report discusses possible explanations for the high values in the Abrams tank that had the lowest mean value of DU contamination. Possibilities include the large variability in the DU contamination inside the vehicle, and the type of work performed, in particular resuspension of small particles by the exhaust from the vacuum cleaner used.

On the assumption that each P-CI sample was representative of the values that may occur during Level II exposure in and around a DU-contaminated Abrams tank or BFV, all the P-CI values were given equal weight in estimating a mean value. This seems reasonable to the reviewer to provide an overview, for e.g. comparison purposes. However, given the very large variability noted, great caution would be needed in applying them to any specific situation. Table 16 summarises the results of the P-CI measurements.

Table 16 Summary of results based on P-CI measurements for 1-hour Level II inhalation exposure in and around vehicles (based on Attachment 4, Table 2.16, but rounded and rem converted to mSv).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DU intake, mg</th>
<th>E(50), mSv</th>
<th>H_{lung}(50), mSv</th>
<th>24-h kidney U concentration[^*]</th>
<th>µg U/g Kidney</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.5</td>
<td>0.02</td>
<td>0.12</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>0.4</td>
<td>0.02</td>
<td>0.16</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>0.08</td>
<td>0.0015</td>
<td>0.0003</td>
<td>0.0002</td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>1.5</td>
<td>0.11</td>
<td>0.8</td>
<td>0.01</td>
<td></td>
</tr>
</tbody>
</table>

[^*] The peak kidney uranium concentration occurs about 24 hours after intake: Attachment 4 Appendix A, page A5.

4.2.1.5 Assessments based on sampling arrays

The cascade impactors (CIs) from the sampling arrays at the loader’s position collected aerosols just before the start of sample recovery operations and while they were being performed in the vehicle after shots PI-6 and PI-7. They provide estimates of DU aerosol concentrations inside the vehicle before, during, and after recovery activities were performed in it. As for the P-CI, results from each were used to calculate doses and uranium kidney concentrations from a 1-hour exposure. Individual results are listed in Attachment 4, Table 2.17, with a note on the activity taking place at the time, and plotted as functions of time in Figs 2.1 and 2.2. For both sets the first sample provided a baseline level of residual airborne DU from the impact. Note that for the subsequent measurements, one out of eight from PI-6 and two out of three for PI-7 were below the baseline. As for the P-CI, average values were calculated and are summarised in Table 17.
Table 17. Summary of results based on sampling array measurements for 1-hour Level II inhalation exposure in vehicles (based on Attachment 4, Table 2.18, but rounded and rem converted to mSv).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DU intake, mg</th>
<th>$E(50)$, mSv</th>
<th>$H_{lung}(50)$, mSv</th>
<th>24-h kidney U concentration* $\mu g$ U/g Kidney</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>15</td>
<td>0.8</td>
<td>6</td>
<td>0.14</td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>11</td>
<td>0.7</td>
<td>5</td>
<td>0.12</td>
</tr>
<tr>
<td>Minimum</td>
<td>2</td>
<td>0.07</td>
<td>0.3</td>
<td>0.02</td>
</tr>
<tr>
<td>Maximum</td>
<td>40</td>
<td>2</td>
<td>20</td>
<td>0.4</td>
</tr>
</tbody>
</table>

* The peak kidney uranium concentration occurs about 24 hours after intake: Attachment 4 Appendix A, page A5.

Taking the two sets of results together, the most striking feature (to the reviewer) is that the mean intake rates are 30 times higher for the static arrays (also described as “area monitors”, AM) than for the P-CI (also described as “breathing zone monitors”, BZM). Mean doses and kidney concentrations are 40 and 50 times higher respectively, presumably because of differences in size distributions between the BZM and AM. To the reviewer, this is surprising: the traditional wisdom is that static samplers will tend to underestimate exposures in situations where the worker’s activity gives rise to the aerosol, because they are further from the aerosol source. There is some discussion of this (Attachment 4, page 2.17), where it is noted that there was a systematic difference in location. The P-CIs were worn inside and outside the vehicle, whereas the array was inside, near the loader’s hatch, which was used for entry and exit by the personnel. However, it is also stated (Attachment 4, page 2.1), that most of the time that the P-CI were operating was spent inside the vehicle. Hence it does not seem to the reviewer that this could account for such a large difference. The other main feature, noted in Attachment 4, is the high degree of variability between measurements. As discussed in Section 4.3.1 below, in the reviewer’s opinion, consideration should be given to further work on this issue.

4.2.1.6 Comparison with surface contamination

Attachment 4 Figures 2.5 and 2.6, respectively, compare for each Capstone Phase, the mean effective dose and peak kidney concentration from a 1-hour inhalation exposure, with the mean surface concentration based on wipe data (1, 5 and 9 mg DU per wipe for Phases II/IV, I and III respectively). There is some tendency (but not significant) for the dose to increase with surface deposit, but none for the kidney concentration. As the Capstone Report, Attachment 4 notes, the results suggest that the activity being performed by the person in the vehicle is just as important as the quantity and particle sizes of material deposited inside the vehicle.

4.2.2 Ingestion from hand contamination

Estimates of potential Level II and Level III DU ingestion from hand contamination were made using the cotton glove contamination data collected during the Capstone study (Attachment 1). Recovery team members wore cotton inspection gloves over personal protective equipment (PPE) work gloves. Data were available from 28 pairs worn by personnel performing Level II- and Level III-like activities during sample recovery
operations for Phases I, III, and IV. Details of each (shot number, duties, DU mass etc) are given in Tables 3.1 and 3.2.

Results were corrected for the estimated difference between DU-adherence to skin versus the cotton gloves to obtain an estimate of hand contamination. Estimates of hand-to-mouth transfer were calculated from the fraction of the hand contamination that potentially could be ingested. For both parameters probability distributions were estimated. Monte-Carlo calculations were performed to obtain distributions in the output parameter values from the dose modelling: committed doses, and the 24-h (peak) kidney uranium concentration from 1 hour exposure (Tables 3.4 and 3.5).

Because of the variability in the small data sets, data for the three Phases (I, III and IV) were combined to give ingestion intake and dose rate estimates for Level II and Level III personnel based on the glove contamination data.

This approach generally seems reasonable to the reviewer, and the estimation of probability distributions for some parameters is a useful step towards evaluating the uncertainty on the assessed doses. However, as noted in Section 4.3.2, although the transfer from surface to hand was based on extensive data, the estimated transfer from hand to mouth was based only on judgement.

4.2.2.1 Correlation of DU collected on wipes with that on gloves
Twelve data sets of gloves worn by recovery personnel inside the vehicle and corresponding interior wipe-test samples were available. For each pair, the glove/surface transfer factor and glove/surface transfer rate were calculated.

The six PIV-4 sets were used to estimate Level-II transfer rates. To validate their use to estimate surface-to-glove transfer, predicted values for Phases I and III were compared to measured values, and reasonable agreement was obtained.

As the Capstone Report, Attachment 4 notes, these results indicate, that it is reasonable to use wipe-test data for a DU-contaminated vehicle combined with Capstone Study glove contamination rates to predict hand contamination and subsequent ingestion intakes for individuals performing Level II or Level III activities in and around the contaminated vehicle.

4.2.3 Summary
The Capstone Report, Attachment 4 proposed general strategies for estimating potential doses from Level II and III activities. For inhalation (Level II and III) it is suggested that the results from the sampling arrays (termed “Area monitors”, AM) are used for time inside the vehicle and results from the personal CI (termed “Breathing zone monitors”, BZM), are used for time outside, although it is considered that the latter would be overestimates. For ingestion, the glove sample data enabled a distinction to be made between Level II and Level III activities.

Recommended rates for such estimates are given in Table 4.2, and summarised here in Table 18. The Capstone Report notes that these assume that no personal protection is
used. It is also noted that for protracted exposures the peak kidney concentration cannot be derived simply by multiplying by the exposure time, because clearance takes place.

This seems to the reviewer a reasonable strategy for estimating “potential” doses, for prospective, planning purposes, given the limitations of the available data, noted above, which are more apparent for inhalation than for ingestion, and provided that these limitations are recognised. Presumably these predicted exposure rates could be used with caution as guidance for the need for protective measures and/or personal monitoring to provide dose estimates in specific situations.

Table 18 Summary of estimated intakes, doses and kidney concentrations for 1-hour Level II or III exposure (based on Attachment 4, Table 4.2, which also gives standard deviations, but rounded and rem converted to mSv).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DU intake, mg</th>
<th>E(50), mSv</th>
<th>24-h (peak) kidney U concentration, µg U/g Kidney</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breathing zone monitors (Levels II &amp; III)</td>
<td>0.5</td>
<td>0.02</td>
<td>0.003</td>
</tr>
<tr>
<td>Area monitors</td>
<td>15</td>
<td>0.8</td>
<td>0.14</td>
</tr>
<tr>
<td>Ingestion</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level II</td>
<td>11</td>
<td>0.007</td>
<td>0.08</td>
</tr>
<tr>
<td>Level III</td>
<td>2</td>
<td>0.0012</td>
<td>0.013</td>
</tr>
</tbody>
</table>

4.3 What might have been achieved with more time and resources

For both exposure pathways results are very variable, and in the case of inhalation, very difficult to predict on the basis of surface contamination levels.

4.3.1 Inhalation of resuspended DU

The large difference between the measurements made by the personal CI, and those made by the static array means that there are large uncertainties in applying the results to risk assessments. In principle, with more resources, more extensive sampling could have been carried out after each shot. The sampling arrays used to measure the impact aerosol could have been reloaded, and recovery teams could have carried out actions that more closely resembled Level II activities. (Strictly this applies to the Capstone Aerosol Study rather than to the assessment.)

4.3.2 Ingestion from hand contamination

It is noted that glove contamination data were not collected during Phase II (BFV) because of an oversight.

For one key parameter in calculating doses from intakes, the fractional absorption from the GI tract to blood, the ICRP default value of 0.02 for relatively soluble compounds was used “as a conservative value”. Ideally (especially given the large scale of the Capstone study) measurements would have been made on selected samples, preferably in vivo, but at least in a suitable in vitro system, to obtain an appropriate value, and information on its variability. (Again, strictly this applies to the Capstone Aerosol Study rather than to the assessment.)
Another factor, the fraction of material on the hand that is ingested, appears to have been based simply on judgement. Ideally it would be based on the results of some sort of study.

### 4.4 Comparison with the RSWG assessment

In the absence of a suitable data set, the RSWG (Royal Society 2001) made simple calculations to estimate Level II and III exposure rates. No distinction was made between the two. Details are given in Annexe C to Part 1 (Bailey et al, 2001). For the central estimate it was assumed that 100 g DU was dispersed (2-3% of a 4-kg penetrator, which is consistent with the Capstone range of 1-7%). For the worst case it was assumed that 2000 g DU was dispersed (20% of two 5-kg penetrators). For both it was assumed that 50% was respirable. The vehicle was assumed to be a box, 3x2x2 m, having a volume of 12 m$^3$ and surface area of 32 m$^2$. Thus surface concentrations were 0.31 and 6.25 mg cm$^{-2}$ respectively. Capstone wipe data averaged 1, 5 and 9 mg DU per 100 cm$^2$ wipe for Phases II/IV, I and III respectively, giving values (0.01, 0.05 and 0.09 mg cm$^{-2}$) somewhat lower than the RSWG central estimate.

For inhalation, considerations of resuspension factors and dust loadings led to air concentrations which were rounded to 0.5 and 10 mg DU m$^{-3}$ for the RSWG central estimate and worst-case, respectively. Combining with breathing rates of 1 and 2 m$^3$ h$^{-1}$ gave hourly intakes of 0.5 and 20 mg respectively (Table 19). These are broadly consistent with the Capstone values based on the breathing zone and area monitors respectively.

For ingestion, two approaches by the RSWG led to the assumption that the contamination from 1 cm$^2$ was ingested per hour, giving estimates of 0.3 and 6 mg h$^{-1}$, respectively, which were rounded to 0.5 and 5 mg h$^{-1}$. These are similar to, but somewhat lower than the Capstone values. However, since they were based on surface concentrations higher than those measured, it suggests that the Capstone assessment makes more conservative assumptions, for example in hand-to-mouth transfer.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DU intake, mg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Capstone</td>
</tr>
<tr>
<td></td>
<td>Central estimate</td>
</tr>
<tr>
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5 CONCLUSIONS

The conclusions of this review essentially reflect the reviewer’s opinions of the achievements and the limitations of the Capstone Program as described above.

5.1 Capstone Aerosol Study

The Capstone Aerosol Study produced a wealth of information on the characteristics of aerosols produced inside an armoured vehicle when pierced by a DU penetrator. It is far more comprehensive than all other published studies put together. It thereby enables more reliable assessments to be made of the hazards to personnel exposed to such aerosols than was hitherto possible. Major achievements and findings included:

- Development of systems to characterise the aerosol produced inside an armoured vehicle when pierced by a DU penetrator, taking account of the hostile environment directly after the penetrator impact (blast, heat, fragments etc), the high initial air concentration and its rapid decrease.

- Successful collection of data on DU air concentration and size distribution as a function of time after impact and position within the vehicle, for several different shot lines within the same vehicle, and for a few different vehicle types. The comprehensive data collected from each shot, and the combination of results from different shots carried out within a co-ordinated programme enables inferences to be made about variability in concentration and size distribution that can arise.

- The initial DU air concentrations in the test vehicle configurations without ventilation were very high, of order grams per cubic metre, consistent with the results of previous, but more limited, impact tests.

- For the Abrams tank with its ventilation/air filtration system operating, the initial concentration was about two orders of magnitude lower than for an unventilated tank.

- The initial DU air concentration in the vehicle increased (as expected) with the hardness of the target, but over a relatively small range.

- The exposure from a ‘double shot’ (two hits which both penetrate the vehicle armour) can be assessed simply as twice that from a single shot.

- The fraction of the penetrator converted to DU aerosol was estimated to range between a maximum of 1% for the lighter armoured BFV to a maximum of 7% inside the heavily armoured Abrams tank, consistent with results of other more recent studies, and making the earlier estimates above 10% seem less likely to be realistic.

- For all the configurations there was not much difference between the average DU air concentrations at 10 seconds, 30 seconds and 1 minute after impact. The concentration at 30 minutes was much lower: by a factor between 10 and 300 times.

- The first measurements of aerosol size distribution, made within the first minute, showed most of the DU to be associated with particles of a few microns or a few
tens of microns diameter, which would be largely non-respirable. However, most
subsequent measurements showed most of the DU to be associated with particles
of about 1 micron diameter, which would be largely respirable. Again, this is
consistent with the results of previous, but more limited, impact tests.

- Extensive complementary measurements were made of particle structure and
  composition, and properties such as dissolution rate.

- Measurements of the dissolution of samples showed that a fraction (1-28%)
  dissolved rapidly (in about a day) and the rest with half times between 70 and 1700
days. Again, this is broadly consistent with the results of previous, but more limited,
  impact tests.

- Measurements were made of ventilation rates in vehicles, according to the extent of
  natural and forced ventilation. It was inferred that vehicle ventilation is probably a
  major factor in reducing the DU air concentration, and hence the exposure of
  personnel.

- Measurements were made of aerosols formed by resuspension of surface deposits,
  as a result of activities carried out by personnel a few hours after an impact. DU air
  concentrations resulting from recovery activities were found to be very variable, and
  related as much to the activities being carried out as to the level of surface
  contamination.

- Extensive measurements of surface contamination were made, and good correlation
  was found between the results of wipe tests and radiation survey instruments.

- Presentation of the study and its results in full detail, including description of
  problems (and occasional errors) with remarkable candour. This detailed reporting
  and openness increases confidence in the results, and provides valuable information
  for those carrying out assessments based on the results and for those who might be
  involved in conducting similar tests in future.

In considering what might be regarded as ‘limitations’ or ‘shortcomings’ of the Aerosol
Study, it should be recognised that resources and time-scale for completion and
reporting were finite. As noted above, the review does not judge the Capstone Program
against its own objectives, but against the wider requirements of assessing exposures to
DU resulting from its use in weapons, and from a UK perspective. Priority in the
Capstone Study was presumably given to what were regarded as the most important
data gaps relevant to US interests, which included situations that might lead to the
highest exposures in future. In the opinion of this reviewer, the main limitations of the
Capstone Aerosol Study relate to its scope:

- The Capstone Study tested only large calibre DU rounds, and no consideration is
  given in the report to the small calibre rounds such as those fired from aircraft.

- Most of the aerosol data were obtained in the “Ballistic Hull and Turret” (BHT,
  stripped shell) of a US Abrams Tank and a Bradley Fighting Vehicle (BFV).
  Extrapolation to operational vehicles in general, and to UK vehicles in particular
  remains an issue.
• The RSWG recommendation: “the development and validation of models to enable DU exposures to be predicted in a wide range of circumstances”, was only addressed to a limited extent. (It is more important in the UK context, because of the need to extrapolate to vehicles different from those used in the tests.) One test (PIV-4) made in an operational Abrams tank gave much lower DU concentrations than in the corresponding BHT, and this was attributed to operation of its ventilation/air filtration system. As noted above, measurements were made of ventilation rates in different vehicle configurations, although attempts to measure ventilation rates in vehicles after DU penetrator impacts were unsuccessful. To make best use of the results in assessing exposures in other situations requires a model of some sort, but none is presented as part of the Aerosol Study. A simple model to take account of vehicle ventilation is presented in the HHRA report. It appeared to work well when tested against the trial on a ventilated vehicle. However, it was not applied in the HHRA to produce estimates of exposure in ventilated vehicles.

• Ideally the Capstone Report would have included a comparison with previous studies of the characteristics of aerosols formed when a DU penetrator impacts on armour plate. (It is a common feature of the “Discussion” section of a research report.) The authors were well placed to do this, especially as some were involved in the previous studies.

In the opinion of this reviewer, the studies were well conducted, especially considering the constraints imposed by the experimental conditions. A number of problems were identified by the Capstone team, which led to changes in procedures during the course of the study. They are described in the Capstone Report (and summarised in Section 2.10.1 of this review). While the comment is made here that some of these might have been avoided (i.e., the revised procedures implemented from the outset) if it had been possible to conduct a pilot trial (or trials) in advance of the main programme, none would appear to have an important effect on the results or their application in risk assessments. Some other issues were identified by the reviewer and for completeness they are summarised in Section 2.10.2 of this review. Again, most are not expected to have an important effect on the results or their application. However, two issues are noted here as being of greater significance and so meriting further attention:

• Reliance placed on in vitro dissolution tests to quantify DU particle dissolution in the human lung. Although dissolution rates were measured for twenty-seven samples, which usefully covered a range of sizes and times after impact, the measurements were all made in “simulated lung fluid”, and over a relatively short period (46 days), at the end of which most (50-90%) of the sample remained undissolved. The issue of extrapolation to human lung clearance was not discussed. It was discussed in the RSWG Report, which recommended: “long-term in vivo studies of the dissolution of DU oxides formed from penetrator impacts and fires involving DU. These are needed to assess doses from inhalation prospectively, and, more importantly, to assess intakes and doses (especially lung and thoracic lymph node doses) from urine samples. Doses to thoracic lymph nodes are especially sensitive to the long-term dissolution rate of DU oxides in the lungs and lymph nodes”. This issue therefore remains open.
• Measurements of DU air concentrations produced by resuspension of surface contamination showed great variability, a lack of correlation between surface and air contamination levels, and in particular a large difference between measurements made with personal samplers worn by the recovery personnel, and those measured by static arrays. These measurements were much more comprehensive than any others previously available, but the main finding seems to be the extent of the variability, rather than reliable representative values for dose and risk assessment purposes.

5.2 The Capstone Human Health Risk Assessment (HHRA)

To avoid repetition, conclusions relating to the assessment of Level II and III exposures (Attachment 4) are included here. Generally, the risk assessments used standard, internationally recognised methods and relevant parameter values to assess radiation doses and associated risks, and peak uranium kidney concentrations. The reviewer considers this to be current best practice, as used for example by the RSWG in its assessments, and that any other approach would be difficult to justify at this time.

In some respects the Capstone assessments go beyond what might be regarded as minimum requirements for applying the ICRP methodology, but do so in a way consistent with the ICRP principles and guidance on applying the models to a specific situation. These are regarded by the reviewer as specific achievements, made feasible by the comprehensive data obtained in the aerosol study, and include the following:

• For convenience, the ICRP Human Respiratory Tract Model (HRTM) provides values of the fraction of inhaled material deposited in each region of the respiratory tract, for aerosols with log-normal size distributions (as functions of the characteristic parameters, the median and geometric standard deviation, GSD of the distribution). However, the aerosols produced in the Capstone Aerosol study were not well fit by lognormal particle size distributions. To calculate respiratory tract deposition with the HRTM, the masses of uranium collected on each size-specific stage of the cascade impactors were used directly. The aerosol was thus treated as a combination of nine aerosols: one for each stage. This required more calculations, but made best use of the available information, and the approach might well be applied elsewhere.

• The HRTM recognises that dissolution of material deposited in the lungs is time dependent, and represents this simply by assuming that a fraction dissolves relatively rapidly, at one constant rate, and the rest dissolves more slowly. Provision is made in the HRTM for two fractions, to avoid undue complexity, because it was considered that there would not normally be sufficient information to justify more. However, the Capstone dissolution data were usually represented by three components, and additional calculations were made to use that information.

• A sophisticated Bayesian approach was used to calculate distributions of doses to personnel, based on the results of the Capstone Aerosol Study. This included calculating doses for each shot and sampling position.

• The HHRA concluded that the most important factor for reducing exposure and dose discovered in the analysis was the use of onboard vehicle ventilation.
• The HHRA concluded that because of differences in individual exposures for crew in a perforated vehicle, DU bioassays are needed to establish individual dose estimates. The report provides information that can be used for deciding when biomonitoring should be implemented.

• Although the HHRA used internationally recognised (ICRP) risk factors where available for assessing radiation-induced cancer risks for each tissue considered important (in terms of radiation exposure or sensitivity), special consideration (by review of the current literature) was given to lung cancer risks, because risks to other tissues were calculated to be much lower. Risks of radiation-induced cancer were also assessed for kidney and the extrathoracic airways although ICRP has not provided specific risk factors for these tissues.

• The HHRA recognised that the risks needed to be put into an appropriate framework that applies to the various risks of combat, so that field commanders can include them in mission risk analysis and management. The existing Radiation Exposure Status (RES) categories used to track the total radiation dose received by a combat unit are based on external gamma exposures. The HHRA modified the RES approach to make it applicable to internal DU deposition and its related dose, by comparing the calculated risks of cancer from external gamma and internal alpha radiation from DU.

• To assess the chemical toxicity risks, the HHRA extended and developed the approach taken by the RSWG, which was to correlate observed renal effects in humans after acute exposures with the calculated peak kidney uranium concentrations. Some additional cases were added, and the results used to develop a set of “Renal Effects Groups (REGs)” correlating uranium concentration in the kidneys with renal effects. Because there is no system similar to the RES categories developed for chemical toxicity, the HHRA used the REG chemical risk model to perform a similar function.

As noted above, with regard to the Aerosol Study, in considering what might be regarded as ‘limitations’ or ‘shortcomings’ of the HHRA (Level I) and the Attachment 4 risk assessments (Level II & III), it should be recognised that resources and time-scale for completion and reporting were finite. Similarly, this review judges the assessments against the broad requirements of assessing exposures to DU resulting from its use in weapons from a UK perspective. In this reviewer’s opinion, as for the Aerosol Study, limitations of the HHRA relate more to the scope, than to the methods used:

• The assessment does not consider exposures and risks to personnel (or the public) outside the struck vehicle from the initial plume (dust cloud) produced by the impact, except to note that they would be lower than to those inside the vehicle. This is of greater importance since the 2003 Iraq war, because of the public perception, at least, that there was more use of DU weapons in urban areas than there was in ODS. From a UK perspective, the ability to make such assessments is limited by the restricted distribution of the report on the most relevant study.

• Evaluation of the health risks from embedded fragments and wound contamination was stated to be beyond the scope of the HHRA. However, these are potential
exposure pathways for Level I personnel, and so for completeness they would have been addressed, at least by a comprehensive review of the current literature.

- The assessments are restricted to the situations (shots, vehicles ventilation, sampling positions) actually investigated in the Capstone Aerosol Study. Most of these seemed to have been designed to maximise the DU air concentration within the vehicle by maximising aerosol production through hitting a particularly massive target, and minimising dilution through ventilation. Although a simple model is described to estimate the reduction in DU air concentration resulting from ventilation, it is not applied to assess the likely range of exposures that might occur in practice as a result.

- Thus the modelling considers worst-case exposures and intakes, but the subsequent stages of the HHRA (calculations of doses and risks from the intakes) appear to be based on modelling using central estimates of parameter values. Care is therefore needed to interpret what is meant by e.g. “Most likely scenario”, which is used to refer to a short stay time, but no ventilation.

- The only factors included in the HHRA uncertainty analysis were those that could readily be quantified from the Capstone Aerosol Study: measurement uncertainties and variability in the measured data. It did not for example include modelling uncertainties. A full uncertainty analysis would be needed to assess the overall distributions of potential doses and risks, and would also be useful in identifying the contributions to overall uncertainty made by all the factors involved and hence providing guidance on options for reducing uncertainties by further study.

- Although reviews were conducted of the literature relating to radiation and chemical effects, these were limited to reasonable complementary studies, consistent with their role in support of the main effort, which was to apply the results of the Capstone Aerosol Study. The reviewer’s opinion is that they are not exhaustive studies, as for example recommended by the RSWG with respect to the lymph nodes: a thorough review of the effects of radiation from radioactive particles retained in lymph nodes, including any possible carcinogenic effects. Thus the need for a project in the MOD DU research programme on Health Effects remains.

Although the HHRA concluded that because of differences in individual Level I exposures for crew in a perforated vehicle, DU bioassays are needed to establish individual dose estimates, no similar recommendation is made with regard to level II exposures. Nevertheless, the lack of correlation between surface contamination and airborne activity demonstrated the difficulty in assessing potential exposures from surface contamination measurements, and the potential intake from an hour’s exposure based on the area monitor measurements is of the order of 10 mg, leading to a committed effective dose of about 1 mSv.
6 RECOMMENDATIONS

One of the recommendations made by the RSWG in Part 1 of its report (Royal Society, 2001) was for: “An independent and fully resourced assessment of the risks, particularly from Level I and II exposures, ensuring that all of the data are available, including restricted material not available to us, and data from any new test firings.” Data from new test firings are now available, which is much more comprehensive than that available to the RSWG in 2001, and no more is expected in the foreseeable future. With regard to exposures within (but not outside) struck vehicles, it is probably more comprehensive than that in the restricted reports.

Consideration should be given to updating the assessments carried out by the RSWG (Royal Society, 2001) of exposures to DU resulting from the use of DU munitions, and the resulting radiological and toxicological risks. Such a re-assessment should take into account not only the results of the Capstone Program, but those of other studies carried out in the last few years, and in particular those from the MOD's own research programme on DU, which is due to be completed in March 2006. As noted above, the RSWG assessment made “central” estimates of exposure for each scenario, which might be used (in combination with an estimate of the number of people exposed) to assess the overall impact on health, and “worst case” estimates, which it was unlikely that any individual would exceed. Since the Capstone Program aimed to maximise aerosol production, re-assessment of “worst case” estimates should be relatively straightforward. Reassessment of the “central” estimate making best use of the available information, however, should include consideration of extrapolation of the results to UK vehicles, and issues such as ventilation rates in operational vehicles. Hence it seems to this reviewer that a multi-disciplinary team involving both independent expertise (on e.g. biokinetics) and military expertise (on e.g. armoured vehicle operation) might be most effective to conduct such a reassessment. Such a team could well consider the remaining data gaps, and the studies required to address them.

7 REFERENCES


REFERENCES


Hahn FF, Guilmette RA and Hoover MD (2000). Toxicity of depleted uranium fragments in Wistar rats. Health Phys 78 (6, Suppl), S129.


APPENDIX A

ICRP Guidance on estimation of material specific absorption from the respiratory tract

The issue of the application material specific rates of absorption from the respiratory tract to the blood (systemic circulation), and the use of in vitro dissolution tests, has been addressed directly in recent ICRP documents, in the preparation of which this reviewer was involved. The discussion below is therefore largely drawn from these documents and reproduced here by kind permission of the ICRP.

A1 PUBLICATION 66 (ICRP, 1994)

ICRP Publication 66 (ICRP, 1994), which describes the Human Respiratory Tract Model (HRTM), states (paragraph 266, page 75): “The absorption rate of a given compound may vary greatly, depending on its method of production, and history. Ideally the absorption rate of any important material should be determined from a study of the material itself. This requires in vivo measurements of lung clearance, and the study should be of sufficient quality to merit publication in a peer-reviewed journal. Appropriate methods of deriving absorption rates from experimental data are described in Section E.2.2.3.”.

A2 PUBLICATION 71 (ICRP, 1995)

ICRP Publication 71 (ICRP, 1995) which applies the HRTM to derive inhalation dose coefficients for members of the public, states (paragraph 48, page 17): “It is recommended that material-specific rates of absorption should be used in the model for compounds for which reliable human or animal experimental data exist. For other compounds, default values of parameters are recommended, according to whether the absorption is considered to be fast (Type F), moderate (M) or slow (S) (corresponding broadly to inhalation Classes D, W and Y in the ICRP Publication 30 system).”

Neither of these ICRP documents supports the use of in vitro data beyond assigning a material to one of the default Types (F, M or S).

A3 ICRP SUPPORTING GUIDANCE 3 (ICRP, 2002)

More recently, ICRP (2002) has produced guidance on practical application of the HRTM, which addresses these issues specifically. In the main text, Paragraph 147 states “ICRP Publication 66 strongly recommends that specific information should be used in preference to default values wherever appropriate, and the HRTM was designed to facilitate incorporation of such information. This applies particularly to values of
absorption parameters since they depend on the physico-chemical form of the specific inhaled material. These specific values are generally derived either from in vitro dissolution experiments or from in vivo data from animal experiments." Hence the most recent ICRP document on the subject is more sympathetic to the use of in vitro data.

ICRP (2002) Annex C, Clearance from the Respiratory Tract, describes and discusses both in vivo and in vitro methods for obtaining dissolution rates. Paragraph C58 states: "Compared to in vivo studies, such measurements are relatively inexpensive and simple to set up, and if the amount of material available is very small may be the only ones feasible. They are also the easiest to interpret quantitatively, because the system is simple compared to the situation in the respiratory tract in vivo. However, obtaining results that can be applied with reasonable confidence to human exposure is not straightforward (Section C6.3, ICRP Publication 66, Annex E, Paragraphs E38 and E39)."

Paragraph C139 states: Although not a specific assumption of the HRTM, it is assumed that rates of dissolution and absorption to blood are the same in different mammalian species (Section C6.4.1), and if in vivo data are not available, that the dissolution rate in an appropriate in vitro system is the same as that in the human lung (Section C6.3).


"(C91) Reviews of in vitro methods designed to estimate dissolution rates in the respiratory tract and discussions of factors affecting in vitro dissolution rates have been published by Kanapilly and Goh (1973), Kanapilly et al. (1973); Moss and Kanapilly (1980); Eidson et al. (1989); Eidson (1994); Cusbert et al. (1994). This description is based on a recent review and critical analysis by Ansoborlo et al. (1999).

(C92) In vitro dissolution measurements generally require less sophisticated and specialised facilities than in vivo studies, are less expensive to conduct and easier to analyse. However, obtaining results that can be applied with reasonable confidence to human exposure is not straightforward. As noted above (Section C6.1) the main problem is that dissolution rates, like chemical reaction rates in general, are potentially very sensitive to conditions: hence solubility in water may not be even a reliable qualitative guide. Conditions in the respiratory tract are complex, and two different sets of conditions occur. Initially after deposition, particles are likely to be immersed in the airway lining fluid, such as mucus or surfactant. Particles remaining after a few hours are, however, likely to have been taken up by macrophages. Conditions within the macrophages are quite different from those in lung fluids, and dissolved material has to cross cell membranes before it is available for uptake.

(C93) This sensitivity of dissolution rates to conditions and the complexity of conditions in the respiratory tract makes it difficult to simulate respiratory tract dissolution in vitro. The problem is well illustrated by recent studies on uranium tetrafluoride (Stradling et al., 1985; André et al., 1989; Ansoborlo et al., 1990). A wide range of dissolution rates had been reported previously, due partly to differences in in vitro technique and partly to differences in the method of production of the material. All three studies found that, following deposition in the lungs of rats, most of the material was absorbed into blood
with a half-time of several days. André et al. (1989) found a much lower dissolution rate \textit{in vitro}, using a serum simulant, but a rate similar to that \textit{in vivo} when oxygen was bubbled through the medium, or with cultured alveolar macrophages \textit{in vitro}. Ansoborlo et al. (1990) used eight different media and found dissolution half-times ranging from 285 d (serum simulant alone) to 2 d to 3 d (pyrogallol + bubbled oxygen), and confirmed the finding of André et al. (1989), that dissolution of uranium tetrafluoride in the lung is mediated by oxygen.

(C94) Nevertheless, there are practical requirements for relatively rapid and inexpensive techniques to estimate absorption rates of workplace materials, particularly where a large number of samples must be evaluated. Moreover, there are circumstances in which insufficient material is available, or the specific activity is too low to conduct an \textit{in vivo} study. \textit{In vitro} tests are often used as a screening method to classify materials according to their solubilities and the results are sometimes used in dosimetric models if \textit{in vivo} dissolution data are not available. If it is demonstrated that a particular \textit{in vitro} method provides results consistent with \textit{in vivo} dissolution for a particular material (ie, by comparing results \textit{in vivo} and \textit{in vitro}), it can be used to test further samples of that material. Another suitable application arises when a material consists of a mixture of compounds that have distinctly different \textit{in vivo} dissolution characteristics: an \textit{in vitro} test may be used to determine the fraction that is absorbed rapidly (Eidson and Griffith, 1984). Hence there are continuing efforts to develop reliable methods for appropriate circumstances (eg, Eidson and Griffith, 1984; Ansoborlo et al., 1990; Duport et al., 1991; Helfinstine et al., 1992; Metzger et al., 1997; Ansoborlo et al., 1998). The main techniques applied in published papers are described in the following paragraphs.

Thus there is a recognition that \textit{in vitro} dissolution tests can provide information that enables better assessments to be made than reliance on general defaults, but with strong reservations.

**A4 REFERENCES**


