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Prioritization methodology for the decommissioning of nuclear facilities: a study case on the Iraq former nuclear complex

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ABSTRACT

There are a number of sites in Iraq which have been used for nuclear activities and which contain potentially significant amounts of radioactive waste. The principal nuclear site being Al-Tuwaitha. Many of these sites suffered substantial physical damage during the Gulf Wars and have been subjected to subsequent looting. All require decommissioning in order to ensure both radiological and non-radiological safety. However, it is not possible to undertake the decommissioning of all sites and facilities at the same time. Therefore, a prioritization methodology has been developed in order to aid the decision-making process. The methodology comprises three principal stages of assessment: i) a quantitative surrogate risk assessment ii) a range of sensitivity analyses and iii) the inclusion of qualitative modifying factors. A group of Tuwaitha facilities presented the highest risk among the evaluated ones, followed by a middle ranking grouping of Tuwaitha facilities and some other sites, and a relatively large group of lower risk facilities and sites. The initial order of priority is changed when modifying factors are taken into account. It has to be considered the Iraq's isolation from the international nuclear community over the last two decades and the lack of experienced personnel. Therefore it is appropriate to initiate decommissioning operations on selected low risk facilities at Tuwaitha in order to build capacity and prepare for work to be carried out in more complex and potentially high hazard facilities. In addition it is appropriate to initiate some prudent precautionary actions relating to some of the higher risk facilities.

1. Introduction

The existing facilities that were seriously damaged during the Gulf wars in Iraq have the potential to cause radiological contamination of the environment and possible exposure of members of the public living in the neighbourhood of these nuclear sites. Many of these nuclear facilities have lost their containment and the radioactive materials now have an increased potential to be dispersed into the environment.

There are 10 nuclear sites in Iraq which have been identified as candidates for decommissioning and some sort of clean-up, the largest and most complex and eventually most radiologically significant of these being Al-Tuwaitha, located about 20 km from Baghdad. This site was established as Iraq's nuclear research centre for its legitimate nuclear activities from the 1960s onwards, although some of the facilities were subverted to a covert nuclear weapons programme in the period prior to the 1991 Gulf War. A total of 18 separate and distinct nuclear facilities and radwaste locations have been identified on this site. Of the other nine nuclear sites, two are located adjacent to Tuwaitha and are linked to its activities, and the other seven were part of a covert programme to procure, purify and enrich uranium.

Decommissioning shall be understood as a technical and administrative task taken to allow the removal of some or all of the regulatory controls from a facility, while remediation involves any measures carried out to reduce the radiation exposure through actions applied to the contamination itself (the source) or to the exposure pathways to humans (IAEA, 2007a). It is clear that the activities to be carried out at these sites will involve both decommissioning and remediation and must be carefully planned to take advantage of the synergies between them (IAEA, 2009).

Normally, it is expected that environmental impacts during the decommissioning of a facility or site will be lower if compared to those related to normal operations. In present case this assumption cannot be taken for granted and this situation stresses the need of an appropriate planning of operations. Guidance on decommissioning can be found in many documents published by

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the International Atomic Energy Agency (IAEA, 2005, 2006a,b, 2008a; Krieg et al., 2004).

Even if there is a clear need to decommission the former nuclear facilities as fast as possible, one has to recognize that under the prevailing social, political and economic situation of the country it would not be possible to undertake the decommissioning of all the nuclear sites and facilities at the same time. One important element to be considered in this work is the bombing of these installations: the safety and security of the installations differs a lot from those of well-preserved structures.

Consequently, a prioritization[3] strategy and methodology was developed. According to international experience and general scientific principles the prioritization should be based on both radiological and non-radiological risk considerations, such factors being amenable to appropriate quantitative objective analysis. It is evident however that many other subjective, but important, factors such as economics, skill development, social impact and politics must be considered as they would have a distinct influence in the overall decisions. As a result, the prioritization scheme applied to the Iraq nuclear sites/facilities took into account both objective and subjective issues. Also important was the lack of data. Williams (2007) made use of a Monte Carlo method to calculate uncertainty in the decision making on the decommissioning of nuclear power plants in the USA. Chidambariah et al. (1992) have also developed a risk-based approach for rapid prioritization of low-level liquid radioactive underground storage tanks for possible interim corrective measures and/or ultimate closure. Chidambariah et al. based their approach upon three major criteria: i) leaking characteristics of the tank, ii) location of the tanks, and iii) toxic potential of the tank contents. A more complex approach for the prioritization of groundwater remediation (Nasiri et al., 2007) made use of the concept of compatibility analysis that targets interactions between remediation technologies and site characteristics and fuzzy sets theory was used to deal with uncertainties.

The development of a complex prioritization system was out of the scope of our objective as the clear lack of information would not support any data demanding calculations. On the other hand a methodology that could be directly applied to address the problem of the prioritization of these facilities was not available in the literature. Therefore, the purpose of this paper is to present the scheme that was developed to prioritize the decommissioning and remediation of nuclear facilities in Iraq. It is believed that this methodology can be used for other situations, especially in those in which a consistent amount of data is not available.

2. Materials and methods

2.1. General description of the nuclear sites and facilities

The 10 nuclear sites are distributed across the country (Fig. 1) with Al-Tuwaitha, near Baghdad containing the greatest number of facilities and radioactive waste locations. Table 1 presents all the ten sites with a very brief description of the activities developed in each one of them.

2.2. Availability and quality of data

Due to the military actions that led to the present conditions and the prevailing instability in the country, there is not a consistent set of data available to be used in the prioritization work. Key information would include the concentrations and amounts of the different radionuclides in the wastes and buildings at the sites/facilities to be decommissioned (or remediated), together with information on possible leakages in the structures containing liquid and solid wastes. Such data, which would make the prioritization

Fig. 1. Location map of the nuclear sites in Iraq.

Table 1
Description of the sites and facilities in Iraq.

Site/facility	Description
Al-Tuwaitha	This is the main and the oldest nuclear site in Iraq. Al-Tuwaitha contains the following 18 facilities (IRT 5000 Research Reactor, Tammuz 2 Research Reactor, Radiochemistry Laboratory, Radioisotope No. 1, Radioisotope No. 2, LAMA Hot Laboratory, Radioactive Waste Treatment Station (RWTS), Solid Waste Storage Silo, Waste Store, Contaminated ground area surrounding RWTS, Russian Silo, Uranium Metal Production Facility, Fuel Fabrication and Italian complex, Technology Hall, Po 210 Production, Out-1 Burial, Scrapyards & Burial sites)
Location C	This location is used to store both nuclear material (which is called *inventory*) and some waste materials.
Al-Qaim	This is a phosphate production site which includes the Unit 340 which was used to extract Uranium from H_3PO_4 to produce yellowcake
Al Jesira	This facility received yellowcake from Al-Qaim to produce UO_2, UCl_4 and UF_6
Adaya	This site contains miscellaneous solid wastes trucked from Al Jesira
Tarmiya	This site was the home of EMIS enrichment program. The site received UCl_4 and did isotopic separation
Geo survey pilot plant	This is the site of a small plant which used an ion-exchange resin to extract uranium from ores to produce yellowcake
Al Atheer	This facility involved melting and casting of uranium metals
Rashdiya	Rashdiya was a centrifuge development facility for radioisotope separation
Location B	This is a farming area that was used for temporary storage of spent fuel transferred from Al-Tuwaitha site.

[3] Prioritization is understood in the context of this work as a process whereby an individual or group places a number of items in rank order based on their perceived or measured importance or significance concerning the objective of the analysis that is being made.

work even more reliable, are relatively scarce. In order to overcome this problem, use of best-estimate information based on the operational histories of the facilities and the type and form of existing waste had to be used in the development of the prioritization approach. This information is supplemented with some preliminary characterisation data, but such authoritative and substantive data is limited in scope. As a result of the above, the scoring systems used in the quantitative prioritization process were designed to minimise the impact of this uncertainty, allowing quantitative scores to be allocated based on semi-quantitative inputs and best judgement.

Lack of data for prioritization efforts is a well-known constraint in this type of work and in other types of decision-making processes. As for example, Alonzo and Laborde (2005) reported that at present more than 50% of commonly used chemicals do not have the minimum data requirements for risk assessment, even though production and release volumes are well-established prioritization criteria.

2.3. Examples of prioritization techniques

Prioritization is generally needed when one faces the challenge of deciding the best way to distribute the available resources among the competing candidate activities. This section is not intended to provide an extensive review of prioritization techniques but to point out some relevant issues that relate to this work.

Cost–benefit analysis and risk assessment are elements to be combined to support the decision making. In addition to those, a compatibility analysis that targets interactions between remediation technologies and site characteristics is needed. Such an approach is presented by Nasiri et al. (2007) who introduced a decision aid tool based on their estimated compatibility index as mentioned before in the text. As the model receives data in the form of linguistic judgement and expert's opinion, fuzzy sets theory was used to deal with uncertainties. If several sites are candidates to clean-up it could be pointed out that a typical top-priority candidate would be the one to show the highest health risk with the lower clean-up associated costs.

Nagesha and Balachandra (2006) presented a different type of prioritization methodology. They tried to identify the relevant barriers to energy efficiency and their dimensions on small scale industry clusters and then prioritize the barriers based on the perceptions and experiences of entrepreneurs, the main stakeholders, by means of the use of the analytic hierarchy process (AHP). They concluded that financial and economic barriers and behavioural and personal barriers were the two top impediments to energy efficiency improvements.

A prioritization scheme that is very useful to the situation in Iraq was developed by CAPCOA (1990). Its purpose was to provide air pollution control districts in California with procedures for prioritizing facilities into high, intermediate and low priority categories as required by the Air Toxics "Hot Spots" Information and Assessment Act (1987). The prioritization scheme primarily relied on three parameters to prioritize facilities: emissions; potency or toxicity and the proximity of potential receptors. The calculation is expressed by the following equation:

$$\mathrm{TS} = \left[\sum^{c}(E_c)(P_c)\right](\mathrm{RP})\left(1.7\times10^{3}\right)$$

where TS is the total facility score, the sum of scores for all substances with carcinogenic effects; C is the specific carcinogenic substance; E_c is the emission of c (lbs/year); P_c is the unit risk of c; RP is the receptor proximity adjustment factors; 1.7×10^3 is the normalisation factor.

Other prioritization methods exist and are described in CDC (2010). These include:

- The Simplex Method makes use of questionnaires. The answers to the questionnaires are scored and ranked and the issues with the highest scores are given the highest priority.
- Nominal Group Planning was developed for situations where individual judgement must be tapped and combined to arrive at decisions which cannot be determined by one person. This strategy is best used for problem exploration, knowledge exploration, priority development, program development, and program evaluation. It involves little mathematics and is based more on group discussion and information exchange. Group members generate a list of ideas or concerns surrounding the topic being discussed. This list becomes decision-making criteria and the prioritization is the ultimate result of consensus and a vote to rank order the criteria.
- The Criteria Weighting Method is a mathematical process whereby participants establish a relevant set of criteria and assign a priority ranking to issues based on how they measure against the criteria. The calculated values do not necessarily dictate the final policy decision, but offer a means by which choices can be ordered. The approach developed in our work makes use of this same concept when modifying factors were introduced to complement the ranking of installations and sites derived by the mathematical calculations.
- The Quick and Colourful Approach is a technique that uses a means whereby individual group members vote to prioritize each problem. A secret ballot method or an open method can be used. This is obviously a less sophisticated approach that may not involve the assessment of objective and technical issues and will depend very much on the perception of those involved in the process. However, it can be a valid approach to capture the perception of the involved community/people and compare or combined their perception with the results obtained by more technical calculation.

2.4. Methodology of prioritization

2.4.1. Overview of the prioritization scheme

It is broadly accepted that decommissioning projects should be prioritized based on worker and public health and safety, protection of the environment, compliance with environmental laws and regulations, cost-effectiveness and future site plans (USDOE, 1998), and hence a prioritization scheme should involve these factors (NDA, 2007). Because of the above, the prioritization scheme should be risk-informed, mainly driven by radiological and toxicological factors and the potential people getting exposed to the contaminants. However, political, social and economical factors will also play a role in the decision making.

2.4.2. Risk-informed quantitative analysis

In a similar way to the methodology proposed by CAPCOA (1990) and Chidambariah et al. (1992), three factors were used to build up the score that will ultimately lead to the prioritization rank, i.e. inventory, containment and environmental dispersion, as shown below. The first and the third factors were subdivided into 5 and 4 sub-factors respectively. The detailed scoring system used with each parameter is given in Table 2.

2.4.2.1. Risk assessment factors: inventory (I). Activity concentration (I_1). It is well established that the radiological risk is a dependent function of the dose and the dose correlates with the activity concentration of the radionuclide in the material that is being ingested/inhaled or to which the individual is being exposed. In the

Table 2
Parameter scoring system.

Parameter	Description	Score
I_1 – Activity concentration	0.1 Bq/g	1
	1	2
	10	4
	100	8
	$\gg$100	10
I_2 – Radiological risk factor	NORM	1
	Uranium	3
	^{60}Co	5
	^{137}Cs + fission products	7
	Pu + actinides	10
I_3 – Physical form of the material	Activated steel or concrete	1
	Encapsulated solid (concrete)	3
	Encapsulated solid (bitumen) Fixed contamination	4
	Contamination soil	5
	Sludges, powders, loose contamination	8
	Liquid	10
I_4 – Non-radiological hazard	Not significant	1
	Comparable with or greater than the radiological hazard	2
I_5 – Activity quantity	Tonne U Bq 0.01×10^8	1
	0.1×10^9	2
	1×10^{10}	3
	10×10^{11}	4
	50×5.10^{11}	6
	100×10^{12}	8
	$>100 \times 10^{12}$	10
C – Containment	At least two good barriers	1
	One good barrier	3
	Material covered in weatherproof shed	7
	Open to atmosphere or leaking to ground	10
E_1 – distance to population	>5 km	1
	3 km	3
	1 km	7
	<1 km	10
E_2 – distance to surface water	>5 km	1
	3 km	3
	1 km	7
	<1 km	10
E_3 – depth of Groundwater	>500 m	1
	200 m	3
	30 m	7
	<30 m	10
E_4 – surrounding land use	No use	1
	Industrial	3
	Urban	7
	Agriculture	10

case of gamma emitters external exposure to ionizing radiation will be relevant. Radionuclide concentrations are expressed in Bq/kg.

Radiological risk factor (I_2). The radiological risk factor is directly associated with the Dose Conversion Factor (DCF) which is the dose equivalent per unit intake of radionuclide and accounts for the relative biological effectiveness (RBE) of the radiation in question. As higher the value of the DCF is, higher the associated risk originated by the exposure will be.

Physical form of the material (I_3). The knowledge of the total activity concentration in the source will not be enough to infer the potential risk associated to a particular radionuclide. If the radionuclide is attached to a solid material it can be proposed that the potential for intake (ingestion and/or inhalation) and consequent exposure will be less than if the chemical species is dissolved in a liquid medium or attached to aerosols. As a result, it was decided to take into account the physical form in which a radionuclide exists. Therefore, the higher the potential mobility of the radionuclide, the higher the risk will be. Conversely, if the radionuclide is tightly attached to a material into a massive solid matrix such as activated concrete and steel, the potential risk will be lower.

Non-radiological hazard (I_4). Some of the sources of contamination may also contain other hazardous materials than the radionuclides, as for example heavy metals and organic substances. They will also constitute hazards that must be taken into account in the calculations.

Total quantity of hazardous material (I_5). Finally, the last subfactor has to do with the total activity contained in the source. That is to say, one may have a high activity concentration of a particular radionuclide in a particular source but the total amount may not be that important. Conversely, the activity concentration may not be that high but in total the contained amount may be relevant, especially if the radionuclides are found in a relatively loosely bound form.

2.4.2.2. Risk assessment factors: containment (C). The containment factor gives information on how the source is confined in the facility or site. As for example, a liquid source in a buried tank that is leaking will have a high a score in this factor in an opposite way to a source that is relatively safely contained in a concrete structure. Ultimately this parameter reflects the extent to which there is confidence that hazardous material within the site or facility is, and will remain to be, physically contained. In the methodology developed by Chidambariah et al. (1992) this factor was also consider and was termed as leaking characteristics of the tank emphasising the importance to take into account the conditions of the containment structure into account.

2.4.2.3. Risk assessment factors: environmental dispersion (E). A full environmental risk assessment would, in addition to the appropriate description of the source term, need to be performed to aid in the decision making about the objects to be dealt with in first place. Risk assessments require the definition of the exposure pathways and involve the calculations of the exposures that in turn will take into consideration different types of information related to the site surroundings, social economical habits, hydrology, meteorology, etc. An extensive risk assessment for each site/facility is not feasible to undertake at the moment due to the prevailing situation in the country. However, for the purpose of prioritization one can assume that the existence of nearby population groups and the eventual existence of agricultural activities close to the sources would represent a potential problem as well as the proximity of these sources to groundwater and superficial water bodies. As a result four sub-factors were considered:

E_1 – Distance to nearest population centre (village etc.)
E_2 – Distance to nearest surface water
E_3 – Depth of local groundwater
E_4 – Surrounding land use

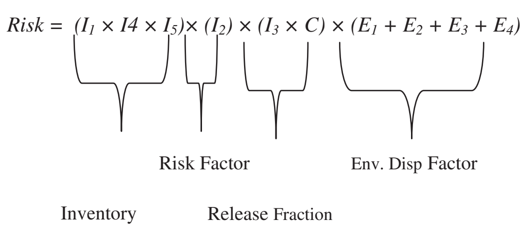
This type of information is very straightforward to obtain and taking them into consideration in the overall calculations will allow for taking into account the potential risks that the sources may pose to members of the public.

2.4.3. Surrogate risk calculation methodology

As mentioned before, because of the lack of adequate knowledge for most of the parameter values that would be part of a formal risk assessment, it would not be possible to undertake a full calculation. As a result the methodology described below was designed to make the best possible use of the available data and whenever data were not available best judgement was used. Consequently a surrogate risk assessment could be made. This approach was considered to give a reasonable representation of the relative order of risk posed by each site and facility, leading to the prioritization of the installations and facilities to be decommissioned.

The formulation of the prioritization scheme proposed in this paper as shown below:

Using the parameters discussed above this equates to:



Reformulating:

$$\text{Risk} = (I_1 \times I_2 \times I_3 \times I_4 \times I_5) \times C \times (E_1 + E_2 + E_3 + E_4)$$

The scores allocated to each parameter for each site and each facility are given in Table 3. Where several different nuclides were present, and/or several different types of physical forms of the waste existed, then educated judgements were made to assign parameter scores which were considered to be representative of the overall contribution to the risk from that site/facility. Table 3 gives also the best judgement score, together with upper and lower bounds. The best judgement score was used in deterministic calculation, and the upper and lower bounds were used in the probabilistic calculations to be discussed later.

The base risk assessment methodology allocates equal scoring ranges (1–10) to each of the parameters, with the exception of the non-radiological risk parameter which has a more limited range (1–2). These ranges indicate the differences between the highest and lowest scoring sites/facilities for any given parameter.

2.4.4. Prioritization ranking base on risk calculations

The results of the calculations are presented in Table 4. The risk scores were normalised on the basis of the highest score facility (IRT 5000) to which a value of 1000 was assigned. The assessed risk scores ranged over four orders of magnitude. If only risk considerations were taken into account the Tuwaitha site would be by far the top priority. In that site the IRT 5000 would be the facility to be decommissioned first, followed by the Radiochemistry Lab and Tammuz. The facilities at Tuwaitha were assigned as top priority due to, mainly, the greatest inventories of radionuclides. On the other hand, sites and facilities which have only uranium contamination, and especially where this was believed to be in low concentrations and/or low quantities, scored relatively low.

2.5. Sensitivity analysis

2.5.1. Probabilistic calculations

The equation used to produce the final result consists of a multiplicative chain. Despite the simplicity of the calculations, the issue of the uncertainty involved in each parameter estimate is of concern. The choice of the values for each parameter was based on available evidence but also, and to a large extent, on some degree of subjectivity. The concern here is to come up with a prioritization list that would not represent the real situation, i.e. attributing

Table 3
Iraq nuclear facilities prioritization.

Priority score chart

Facility	I_1			I_2			I_3			I_4			I_5			C			E_1			E_2			E_3			E_4		
	L	**S**	H	L	**S**	H	L	**S**	H	L	**S**	H	L	**S**	H	L	**S**	H	L	**S**	H	L	**S**	H	L	**S**	H	L	**S**	H
Radiochem Lab	4	**8**	10	7	**8**	9	5	**8**	10	1.5	**2**	2	4	**7**	10	3	**5**	8	3	**6**	9	3	**6**	9	7	**10**	10	7	**10**	10
IRT5000	6	**10**	10	4	**6**	8	3	**7**	10	1	**1.5**	2	7	**10**	10	7	**10**	10	3	**6**	9	3	**6**	9	7	**10**	10	7	**10**	10
Italian isotope	1	**3**	5	2	**4**	6	2	**4**	6	1	**1**	1.5	2	**4**	6	2	**4**	6	3	**6**	9	3	**6**	9	7	**10**	10	7	**10**	10
Russian isotope	3	**6**	7	2	**4**	6	3	**6**	8	1	**1**	1.5	4	**6**	8	1	**3**	6	3	**6**	9	3	**6**	9	7	**10**	10	7	**10**	10
LAMA	1	**1**	3	1	**3**	5	2	**4**	6	1	**1.5**	2	2	**3**	6	2	**5**	8	3	**6**	9	3	**6**	9	7	**10**	10	7	**10**	10
Tannuz2	6	**7**	10	4	**6**	8	5	**8**	10	1	**1.5**	2	4	**7**	10	7	**10**	10	3	**6**	9	3	**6**	9	7	**10**	10	7	**10**	10
RWTS	5	**8**	10	7	**8**	9	6	**8**	10	1	**1.5**	2	4	**7**	10	2	**4**	7	3	**6**	9	3	**6**	9	7	**10**	10	7	**10**	10
French Silo	2	**4**	10	2	**3**	8	5	**7**	10	1	**1**	1.5	2	**4**	6	1	**2**	4	3	**6**	9	3	**6**	9	7	**10**	10	7	**10**	10
Warehouse	2	**3**	5	2	**4**	6	4	**7**	9	1	**1.5**	2	7	**10**	10	4	**6**	9	3	**6**	9	3	**6**	9	7	**10**	10	7	**10**	10
Contam Ground	2	**3**	4	2	**4**	6	3	**5**	8	1	**1**	1.5	8	**9**	10	7	**8**	10	3	**6**	9	3	**6**	9	7	**10**	10	7	**10**	10
Russian Silo	7	**9**	10	4	**6**	8	5	**8**	10	1	**1**	1.5	9	**10**	10	2	**4**	6	3	**6**	9	3	**6**	9	7	**10**	10	7	**10**	10
U metal	1	**2**	3	2	**3**	4	3	**5**	7	1	**1**	1.5	1	**1**	4	4	**6**	8	3	**6**	9	3	**6**	9	7	**10**	10	7	**10**	10
B73B	2	**4**	5	2	**3**	4	4	**7**	9	1	**1.5**	2	3	**5**	7	5	**7**	9	3	**6**	9	3	**6**	9	7	**10**	10	7	**10**	10
B73D	1	**1**	2	2	**3**	4	3	**5**	7	1	**1**	1.5	1	**2**	4	4	**6**	8	3	**6**	9	3	**6**	9	7	**10**	10	7	**10**	10
Technol Hall	1	**2**	4	2	**3**	4	4	**6**	8	1	**1**	1.5	1	**2**	4	4	**6**	8	3	**6**	9	3	**6**	9	7	**10**	10	7	**10**	10
Po 210	1	**2**	4	2	**4**	6	2	**4**	7	1	**1**	1.5	1	**1**	4	1	**5**	10	3	**6**	9	3	**6**	9	7	**10**	10	7	**10**	10
1.17 OUT-1	1	**3**	5	2	**3**	4	5	**6**	8	1	**1**	1.5	1	**2**	4	6	**8**	10	3	**6**	9	3	**6**	9	7	**10**	10	7	**10**	10
1.18 Scrapyards	1	**2**	4	2	**3**	5	3	**5**	7	1	**1**	1.5	7	**8**	10	7	**9**	10	3	**6**	9	3	**6**	9	7	**10**	10	7	**10**	10
2 Location C	3	**6**	7	2	**3**	4	6	**8**	10	1	**1.5**	2	8	**10**	10	1	**2**	4	7	**10**	10	1	**2**	4	7	**10**	10	7	**10**	10
3 Al-Qaim	1	**2**	4	2	**3**	4	4	**6**	8	1	**1**	1.5	1	**2**	4	3	**5**	8	3	**6**	9	2	**4**	6	3	**6**	9	7	**10**	10
4 Al Jesira	2	**4**	6	2	**3**	4	5	**7**	9	1	**1**	1.5	1	**3**	4	5	**7**	9	6	**8**	10	2	**4**	6	3	**4**	7	7	**10**	10
5 Adaya	2	**4**	6	2	**3**	4	5	**7**	9	1	**1**	1.5	4	**6**	8	7	**9**	10	6	**8**	10	2	**4**	6	3	**4**	7	7	**10**	10
6 Tarmiya	1	**1**	3	2	**3**	4	4	**6**	8	1	**1**	1.5	1	**2**	4	1	**2**	4	3	**6**	9	2	**4**	6	3	**6**	9	7	**10**	10
7 Geo Pilot	2	**4**	6	2	**3**	4	4	**6**	8	1	**1**	1.5	1	**2**	4	1	**1**	3	7	**10**	10	3	**6**	9	7	**10**	10	5	**7**	9
8 Al Atheer	1	**1**	3	2	**3**	4	2	**4**	6	1	**1**	1.5	1	**1**	3	2	**4**	6	3	**6**	9	3	**6**	9	3	**4**	7	7	**10**	10
9 Rashdiya	1	**1**	3	2	**3**	4	2	**4**	6	1	**1**	1.5	1	**1**	3	1	**2**	4	2	**4**	6	6	**8**	10	5	**7**	9	7	**10**	10
10 Location B	1	**1**	3	4	**6**	8	3	**5**	7	1	**1**	1.5	1	**1**	3	6	**8**	10	3	**6**	9	1	**2**	4	3	**5**	7	7	**10**	10
1 Tuwaitha	8	**10**	10	7	**8**	9	6	**8**	10	1.5	**2**	2	9	**10**	10	8	**10**	10	3	**6**	9	3	**6**	9	7	**10**	10	7	**10**	10

S – allocated score; L – lower bound score; H – higher bound score.

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Table 4
Surrogate risk scores for Iraqi sites and facilities.

Tuwaitha facility	Score	Site
	2031	Tuwaitha
IRT 5000	1000	
Radiochemistry Lab	569	
Tammuz 2	560	
RWTS	341	
Russian Silo	274	
Warehouse	120	
A/B Fuel Lab	70	
	69	Location C
Contam Ground	68	
	59	Adaya
Russian Isotope	41	
Scrapyards/Burial sites	34	
	23	Al-Jesira
OUT-1	14	
Italian Isotope	12	
French Silo	11	
Technology Hall	7	
	5	Al-Qaim
LAMA	2.9	
U Metal	2.9	
C/D Italian complex	2.9	
	2.7	Location B
Po 210	2.5	
	2.4	Geopilot
	0.9	Tarmiya
	0.6	Al-Atheer
	0.3	Rashdiya

Table 5
Comparisons with probabilistic assessment scores.

Deterministic		Probabilistic		
Score	Site/facility	Site/facility	Mean	90% Percentile
2032	Tuwaitha	Tuwaitha	2260	1895
1000	IRT 5000	IRT 5000	1000	1000
569	Radiochem Lab	Tammuz 2	760	741
560	Tammuz 2	Radiochem Lab	702	714
341	RWTS	RWTS	512	529
274	Russian silo	Russian silo	412	408
120	Warehouse	Warehouse	174	184
70	B73A–B73B	Contam ground	127	130
69	Contam ground	Adaya	98	98
69	Location C	B73A–B73B	88	90
59	Adaya	Location C	105	82
41	Russian isotope	Russian isotope	65	74
34	Scrapyard	French silo	41	51
23	Al Jesira	Scrapyard	58	49
14	OUT-1	OUT-1	28	31
12	Italian isotope	Al Jesira	28	24
11	French silo	Italian isotope	20	24
6.9	Technol hall	Technol hall	16	18
4.7	Al-Qaim	Po 210	12	16
4.3	LAMA	LAMA	13	15
2.9	U Metal	Location B	13	15
2.9	B73D	U Metal	9.6	11
2.7	Location B	Geo Pilot	7.6	8.7
2.5	Po 210	B73C–B73D	7.5	8.2
2.4	Geo Pilot	Al-Qaim	7.2	5.6
0.93	Tarmiya	Tarmiya	3.7	4.4
0.62	Al Atheer	Al Atheer	3.0	3.6
0.35	Rashdiya	Rashdiya	2.0	2.3

inappropriate higher/lower priority to an object just because numerical values were inappropriately attributed to the parameters in the calculation in a deterministic way i.e. without considering the possible full range of variation of the parameter.

To account for the uncertainty in the final result, probabilistic sensitivity analysis (PSA) was used to consider the uncertainty in the prioritization calculations. One of the simplest ways to perform PSA involves running the model many times using randomly sampled values of the model inputs (a Monte Carlo approach). Statistical distributions are assigned to each specific parameter. If a database for a particular parameter in the calculation is available it is possible to check which type of function best describes the distribution of the parameter value and give this information as an input for further model calculations. In this work the Hyper-Latin Cubic method of sampling was used by the Crystal Ball® software to select parameter values from the distributions assigned to each parameter and calculations were repeated 1000 times for each site/facility.

Triangular distributions were assigned for each parameter with the best-estimate value (as used in the deterministic assessment) used in one of the vertices of the triangle – corresponding to the highest frequency value – and the lower and upper bounds of the probability range were used in the other vertices of the triangle. The triangle will be distorted (skewed) if the best-estimate value approaches one of the vertices, in other words, if the triangle is not symmetrical. Because of that, a larger area next to these values will lead to higher number of values being picked in this region.

The priority ranks are shown in Table 5 that also provide a comparison between the results arising from the probabilistic calculation with those from the deterministic calculation. For the 28 considered objects the priority ranking was kept the same for 13 of the objects, the others suffered a change in the position in the prioritization list obtained from the deterministic calculation. Twaitha appears as top-priority site in both calculation approaches. The IRT 5000 is the top-priority single installation in both ranks. However, in the deterministic calculation the second priority would be the Radiochemistry Lab as opposed to the results from the probabilistic calculation that would assign Tammuz 2 as the second top priority. From there both approaches converge in determining the RWTS, the Russian Silo and the Warehouse as the 3rd, 4th and 5th priority installations respectively. The approaches also converge in pointing out Tarmiya, Al Atheer and Rashidya as the lowest priority installations to be decommissioned.

It is also useful to look at the numerical differences between the calculations obtained for the deterministic calculation and for the probabilistic one. Differences below 20% were observed for the following installations/facilities: Twaitha, IR 5000, Al Jesira, Location C, Al-Qaim, Radiochem. Lab., B73A–B73B, and Tammuz 2. For the other installations the difference between the deterministic calculation and the 90% percentile value were above 20% being even greater than 80% for Location B, Al Atheer, Po 210 and Rashdiya. One can conclude that with the aid of probabilistic analysis the decision makers can gain confidence on the priority rank of the installations/sites to be dismantled and cleaned-up; as long as the priority is based only on the objective calculations, that is to say, without considering modifying factors. The calculated values can be used to show all the relevant stakeholders and interested parties that care was taken not to loose any important information from perspective and present them with the priority rank based on the surrogate risk assessment, i.e. the top-priority installations being those that present the highest potential risks of contamination of the environment and subsequent exposure of the members of the public to the undesirable effects of ionizing radiation, which can be very different from the perceived risk from the potentially affected individuals.

2.6. Practical impact of the 'modifying factors'

Calculations so far addressed objective issues on the prioritization process. However, other subjective factors – something that is being called in this text modifying factors – can change the order of

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the prioritization list. The modifying factors that were considered in this work are described below.

2.6.1. Developing human skills and expertise, and demonstrating progress through early success

There has been major social and political disruption in Iraq over the last decade or longer, one consequence of which has been the loss of much nuclear expertise and experience. Iraq has also been isolated from international developments in the nuclear field. Very little effective infrastructure exists on any of the nuclear sites, and the project management team is newly established, with no decommissioning experience. It is evident that addressing the higher risk facilities on the Tuwaitha site will involve higher work-related risks and higher environmental risks from potential incidents and accidents when compared to the lower risk facilities.

Recognizing the potential risks of the top-priority installations it may be advisable to start with the overall decommissioning programme on the basis of seeking to learn and develop experience on relatively low risk facilities in order to build up both expertise and confidence (IAEA, 2008b). Meanwhile, regarding the top-priority installations no such imminent threats have been identified, although some prudent precautionary actions can be implemented (as will be discussed in Section 3.3).

This approach is supported by the benefit that moving forward initially with a low risk project would build confidence within the team through gaining an 'early win'. It would also provide important external stakeholders (principally the Iraq Government, the US Government as an important funding provider for the work, and the wider international community supporting this work, including IAEA) with visible evidence of progress.

2.6.2. Developing regulatory competence and interfaces

This factor is closely related to the above consideration of human skills development. There is no significant history or experience of regulating nuclear sites or decommissioning activity in the country. In addition to this the nuclear complex operated by the Ministry of Science and Technology (MoST) has no history or tradition of being regulated by an independent regulatory body.

2.6.3. Availability of waste storage and disposal facilities

There are currently no facilities available in Iraq for the interim storage or disposal of radioactive waste arising from decommissioning activities. Plans are being developed which could allow dedicated areas at Tuwaitha to be used on a temporary basis for waste storage pending the design and construction of a proper interim waste store. The development of a facility for disposal of Low-Level Waste and very Low-Level Waste is a longer term activity, and Intermediate Level Waste disposal is likely to require even longer timescales (IAEA, 2007b).

On this basis it would be advantageous for the early decommissioning projects to be chosen such that relatively small volumes of radioactive waste would be generated, thereby allowing the necessary time for the provision of waste storage facilities.

2.6.4. Re-use of sites and facilities

International experience has demonstrated that pressure to secure the re-use of sites or facilities can be a significant driver for decommissioning existing facilities (IAEA, 2006b). In Iraq all the sites except one (Geo Pilot Plant) are owned by MoST, and for the MoST sites there are no strong pressures for the re-use of specific areas. However, the Geo Pilot Plant is located in central Baghdad within the Geological Survey Institute, where there is pressure on space and a strong desire to move forward with re-using the area currently occupied by the contaminated facility.

2.6.5. The security situation in Iraq

The ability to undertake work on the various sites in Iraq is very strongly influenced by the need to ensure the safety of the personnel involved. In the current security climate there are many areas of Iraq where the safety of workers cannot be guaranteed. In broad terms the security situation is more difficult in the more remote sites, and sites adjacent to Baghdad are the most amenable to work activity. Hence in practice it is possible to work on the highest risk site, Tuwaitha, and much less attractive to work on the more remote locations which actually have very low radiological risk. In this sense the security factor is re-enforcing the need to work on the prioritized high risk sites, and as such has not in practice been a significant modifying factor at this stage of the programme.

2.6.6. Social considerations

It is internationally recognized that stakeholder involvement can have a significant impact on decommissioning programmes, particularly in terms of the views of local communities (IAEA, 2008b). This is one topic where further interactions could occur as the Iraqi social and political structures hopefully move towards normalisation. At the current time there has been evidence of a desire by some communities adjacent to some remote sites to request that their sites be remediated in order to remove what is perceived as a significant hazard. It is noted that the quantitative risk prioritization in fact results in very low scores for these sites. As such the products from the prioritization work will be very relevant in assisting the discussion with the different stakeholders. However, as noted above, the security issue gives an over-riding prohibition against work on such sites at the current time. The remote sites will have a low priority for the near future.

2.6.7. Radiological conditions

Several of the high scoring facilities at Tuwaitha have local areas where the radiological conditions, particularly gamma radiation fields, are challenging. This is the case for the liquid waste storage tanks in the Radiochemistry Laboratory and RWTS and for areas in the IRT 5000 and Tammuz research reactors. High radiation fields also exist in the Russian silo. To date there has only been a very limited survey programme in these areas, and there is a need to carefully build both radiological protection expertise and the availability of protection and measurement equipment capability.

2.6.8. Unsafe structures

A large proportion of the buildings containing radioactive material have been very significantly damaged as a result of warfare. This applies particularly to the Tuwaitha site, but also to several of the remote sites. These conditions apply across the full range of sites and facilities as assessed in the quantitative analysis. There are many parts of buildings where access is not possible or is very dangerous due to unstable structures. This has impacted the ability to undertake characterisation survey work to date. However, whilst this safety issue requires positive management during any dismantling and decommissioning programme, it does not have a direct impact on the prioritization order because it is so widespread an issue that it must be taken into account in all projects.

2.6.9. Finance and funding issues

The decommissioning project is funded primarily through the normal budgetary processes of MoST, with supplementary external support from the US Government. At this stage of the programme there is no overall cost estimate available for the completion of the decommissioning programme. Whilst the MoST funding system ideally may require adaptation to secure a more efficient approach to decommissioning project management, there is no evidence

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that, in the short term, funding constraints will be a limiting feature for the programme. Indeed, it is likely that the ability of the programme to efficiently and effectively spend money will be a greater challenge.

The ability to provide funding for the programme, and to arrange that the funding mechanisms are appropriate to the needs of the programme, will be aided by an early demonstration of success in achieving a relevant, visible goal. This will help build the confidence of the key funding stakeholders. Whilst funding is not seen currently as an issue directly impacting the prioritization of the programme, it is not yet possible to predict the extent to which it may have an influence in the medium to longer term.

3. Overall prioritization outcome

All of the factors identified above have contributed to the decision process on the determination of the order of priority for undertaking the decommissioning of the Iraq former nuclear complex. It is essential that the decision makers are informed of the relative safety and radiological risks of the sites and facilities, although this in itself cannot be the only input into the final decisions. From the above analysis it is evident that there are several factors which are crucial to the outcome, as follows:

- There are very clear and substantial reasons why it is not in the best interests of the programme to begin with the highest risk facilities. These present the highest risks in terms of ensuring the safety of the decommissioning work itself, both in terms of worker and environmental safety. It is important to learn and build competence and confidence, both within the operating organisation and in the regulatory body, through initiating the programme with lower risk activity.
- Given the lack of radioactive waste storage and disposal infrastructure, and the time needed to develop this capability, it is advantageous to begin the decommissioning programme on work which is expected to generate only very low quantities of radioactive waste.
- There is significant pressure to re-use one of the contaminated buildings which currently houses the Geo Pilot Plant.

The combination of these factors leads to the following conclusions on the order of priority for the future programme:

3.1. Lama facility

The LAMA building at Tuwaitha has been assessed as a low risk facility. Its operational history leads to the expectation that there is very little contamination remaining, and hence low volumes of active waste. It will allow the development of dismantling and decommissioning experience and expertise on a full scale building within a relatively safe environment, although with significant challenges relating to structural safety. Likewise, it will allow the development of the regulatory interface and processes, including the clearance[4] regime. It is anticipated that it will provide an opportunity for an early demonstration of success and the consequential building of confidence within the decommissioning team.

3.2. Geo pilot plant

The decommissioning of this relatively small scale facility located in central Baghdad will release the building for re-use by the owner. It represents a different type of challenge, being a well-defined and undamaged research-type rig with uranium contamination. Relatively small volumes of waste will result.

3.3. Oversight and contingency planning for liquid waste at Tuwaitha

On the basis of current best information it is considered that there are no imminent threats requiring immediate and urgent action relating to the highest risk facilities at Tuwaitha. In particular it is considered that the key liquid wastes stored in tanks in the Radiochemistry Laboratory and RWTS are adequately contained, as is the contaminated water in the IRT 5000 reactor pool. However, these liquid wastes (especially the tank liquors) represent the greatest potential hazard to the environment if the effectiveness of the containment deteriorates. On this basis it is appropriate to develop plans to identify and characterise the liquors, to monitor the integrity of the containment, and to determine and assess the options for stabilising and/or treating this waste so that appropriate action can be taken on the shortest timescale if there is evidence of containment failure.

3.4. Scrap metal and debris at Tuwaitha

There are very significant quantities of scrap metal and debris lying in many locations on the Tuwaitha site. It is not yet known what proportion is contaminated and how much could be cleared for recycle. Addressing this material is a precursor activity to the decommissioning of buildings (including LAMA) because of the widespread distribution of the scrap metal. The intention is to monitor, sort, and release material for recycle where appropriate, and provide appropriate interim storage for contaminated metal. This project will develop monitoring capability, bring good visual improvement to the site and underpin the decommissioning of other buildings.

3.5. Further development programme

The above programme will form the basis of the initial hands-on work on the decommissioning programme, and will provide a good platform for building experience and capability. During the period taken to complete this work the next phase of the programme will be developed, taking account of the factors identified and discussed in this paper.

4. Conclusions

A multi-faceted prioritization tool has been successfully developed and applied to support the development of the overall plan to decommission the Iraq former nuclear facilities. The approach is based on a quantitative risk-informed assessment of the sites and facilities, with the prioritization outcome modified in the light of other qualitative factors.

The quantitative assessment component has been developed to accommodate the limited detailed knowledge on the characterisation of the facilities, and the output from this assessment has been shown to be substantially robust against judgements made. However, this methodology can be applied to other situations and will benefit from more robust data sets. It is important that the decision makers who determine the order of priority for the decommissioning programme are aware of the intrinsic safety and environmental risks posed by the sites and facilities in their current state. However, it is evident from the discussion in the paper that risk alone is not the over-riding factor in determining priority. In particular in the context of Iraq, it has been

[4] Removal of radioactive material or radioactive objects within authorized practices from any further regulatory control by the regulatory body (IAEA, 2007b).

demonstrated that the need to build experience and confidence through commencing decommissioning activity on relatively safe, low risk facilities is of dominant importance at this stage of the programme.

This assessment has given a quantitative relative ranking of the sites and facilities which is considered to be appropriate and substantially robust for the current state of knowledge. On this basis there is a clear indication of the high, medium and low ranking sites and facilities. However, given the relative lack of hard data, there is a need to develop a modest program to gather quantitative data at all 10 sites in order to provide improved characterisation data and to confirm that there are no critical situations that need urgent remediation. Despite the absence of a robust data set and with the aid of the probabilistic calculations it is likely that this current quantitative review is adequate for its intended purpose.

The impact of the qualitative 'Modifying Factors' on the order of priority is quite significant. At this time it has been possible to conclude on the first five priority projects for the overall programme, and these will take some time to bring to completion. The next phase of the programme needs to be assessed during this period, taking account of the factors identified in this paper, together with the learning experiences from the work undertaken in the early part of the programme.

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