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Nuclear Science and Technology Division

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1. INTRODUCTION

1.1 Background

Nuclear material safeguards in the United States Department of Energy (DOE) is defined as "An integrated system of physical protection, material accounting, and material control measures designed to deter, prevent, detect, and respond to unauthorized possession, use, or sabotage of nuclear materials." From the international perspective, the International Atomic Energy Agency (IAEA) executes safeguards agreements with member states based on a number of criteria; however, the predominate type of safeguards agreement is a "Comprehensive Safeguards Agreement" pursuant to the Nonproliferation Treaty. "For comprehensive safeguards agreements, the technical objectives of safeguards are the timely detection of the diversion of significant quantities of nuclear material from peaceful uses to the manufacture of nuclear weapons or other nuclear explosive devices or for purposes unknown; and the deterrence of such diversion by the risk of early detection." Internationally the term "safeguards" does not include the physical protection aspect; however, the IAEA does have guidelines for the "Physical Protection of Nuclear Materials and Nuclear Facilities" (INFCIRC/225/Rev. 4). An important consideration in the physical protection of nuclear material both domestically and internationally is the radiation level. This leads to the use of a graded approach. In general, this approach places more stringent measures on materials that are deemed to be attractive for weapons use (i.e., easy to prepare). One attractive physical protection feature is a characteristic called self-protection. Both DOE and IAEA use 1 Gy/h (100 rad/h) measured at 1 m to be the level that provides a measure of self- protection. Self-protection is the focus of this study.

Current guidance considers "highly radioactive special nuclear materials" (highly radioactive SNM) to be those materials that "unshielded, emit a radiation dose [rate] measured at 1 meter that exceeds 100 rem/hour."[1] Explanatory notes provide a basis for this threshold: A 350-rem absorbed dose, the midpoint of the 250- to 450-rem range, was generally accepted, at the time the DOE graded safeguards table (to be referred to as "graded physical protection" henceforth) was generated, as the dose at which 50% of exposed people are expected to die and was considered the "50% lethal dose." Based on this guidance, highly radioactive SNM are considered to be those materials that will deliver a 350-rem dose within 3 h,[1] which was rounded to a dose rate of 100 rem/h.

Although a 350-rem dose is considered lethal (for 50% of its recipients), the immediate health effects are minimal [vomiting (emesis)] with onset sometime between 0.5 and 16 h after exposure.[2] The delay to onset of emesis (especially when added to a three-h exposure period) allows a substantial amount of time in which exposed persons can function (albeit at reduced effectiveness) to complete a task. In light of worldwide terrorist events that graphically demonstrate the resolve of the perpetrators and their disregard for self-preservation, it seems reasonable and prudent to consider that terrorists will be willing to expose themselves to extreme (definitively lethal) levels of radiation. Their demonstrated willingness to sacrifice their lives (and, hence, to receive an immediately debilitating and speedily lethal exposure) is the impetus for reviewing the premise of a material's self-protection (or threshold radiation level) in graded physical protection.

1.2 Assumptions

Several assumptions have been made as part of this initial study of radiation levels that may provide self-protection:

- **Self-protection** for radioactive materials is the incapacitation inflicted upon a recipient from inherent radiation emissions in a time frame that prevents the recipient from completing an intended task. Such tasks are defined in terms of a set of actions and the time it takes to carry out these actions to facilitate malevolent use.

- **Gamma radiation** is the dominant ionizing radiation from spent nuclear fuel (SNF) presenting health effects to a recipient. Other forms of ionizing radiation (especially beta emissions and neutrons) are emitted from most highly radioactive materials, but they contribute only a small fraction of the total dose for contained (i.e., clad or canned) material in subcritical situations.

- **A normal distribution** is the assumed statistical model of incapacitation for a given dose at a specific time.

- The range of **characteristics for Research Reactor (RR) SNF** is essentially insensitive to the date in which the data are collected. This white paper used the 1998 International Atomic Energy Agency (IAEA) reactor database with its readily available information detailing reactor characteristics needed for this study. This database is assumed to be representative of current spent fuel inventories.

2. IMPACT OF EXPOSURE ON CAPABILITY

To be considered an effective deterrent to theft, a self-protecting characteristic must demonstrate its effect within a relatively short period. Incapacitation is defined as an inability to function effectively. In the case of radiation sickness, incapacitation begins with emesis (vomiting), continues with gastro-intestinal (GI) damage, and finally results in damage to the central nervous system. In the progression toward incapacitation, emesis is considered to pose reduced function initially, with further performance decrement resulting from the onset of one or more other symptoms (reduced cognitive capability, reduced routine task skill, and depression in volitional performance). Temporary improvement in performance typically occurs during the next half hour, but the extent and duration of such recovery diminishes to very brief periods with increasing dose. This temporary recovery period gives rise to a descriptive term for the initial decrease in performance as Early Transient Incapacitation (ETI).

Early onset (within minutes) of emesis and incapacitation appears to occur in essentially all exposed individuals at levels of 25 gray (Gy)[*] and above, with initial delays (and ETI recovery periods) becoming

[*] A gray is a unit of absorbed dose where 1 gray = 100 rads. Doses expressed in units of both grays and rads are adjusted by weighting factors for differing radioactive emissions (i.e., photons, beta rays, neutrons, alpha particles) to characterize an Equivalent Dose in tissue – expressed in sievert or rem units, respectively. Absorbed dose (in grays) is recommended by the International Commission on Radiological Protection (ICRP) to describe deterministic effects (i.e., measurable tissue reactions causally determined by preceding exposures) as opposed to Equivalent Doses which are recommended for stochastic effects (i.e., such as cancer induction in which the effects are random but describable in terms of probabilities).

more abbreviated at higher exposures. Damage to bone marrow and other metabolic processes also occur as a result of these exposures causing incapacitation, but the actual effect of such exposure on an individual's ability to function within a defined time after exposure is not delineated in the literature. It should be noted that at even lower exposures (<25 Gy) capability is impaired in many individuals.

3. DEFINITION OF THE PROBLEM

In this study, the "task" refers to acquisition of an unshielded radioactive source and any subsequent events involving continuous exposure to radiation from this source at a nearly constant dose rate.

The source is considered to be self-protected at dose rate R if

$$T * E_R(T) < S , \qquad (1)$$

that is, if efficiency is reduced by continuous irradiation at dose rate R to the point that the effective work time during interval [0,T] is less than S, where

S = time required to acquire material and meet a malevolent objective (task) if fully efficient,
T = assumed time available before interruption of task ($T > S$, initial assumption), and
$E_R(T)$ = average work efficiency during the time interval [0,T] if exposed continuously at dose rate R from the source.

For given values of S and T, the problem is to estimate the minimum value of R at which a source is self-protected. This reduces to the problem of estimating the time-dependent reduction in efficiency, E_R, resulting from continuous exposure at any given R.

3.1 Information on Early Transient Incapacitation Due to a Brief Radiation Dose

Information about the early effects of a high-radiation dose comes from nuclear accidents, clinical irradiations, nuclear detonations over Hiroshima and Nagasaki, and studies on laboratory animals.[3–6] The monkey is considered to be the best laboratory model for man regarding behavioral effects resulting from acute irradiation. Early effects of radiation on monkeys have been studied extensively.[7–15]

Humans or monkeys receiving radiation doses of at least a few gray over a brief period may exhibit a period of performance decrement related to ETI. The timing and extent of recovery depends on the total dose and the dose rate. At extremely high doses and dose rates, recovery may be insignificant with regard to work efficiency.

For doses exceeding approximately 20 Gy (2000 rad), an exposed person may experience disorientation, confusion, prostration, hypotension, loss of balance, and seizures.[16] According to Nias,[17] "After a single dose of several thousand centigrays [several tens of grays or several thousand rads] to the whole body, particularly the head, the clinical onset is prompt and death may occur in minutes to hours. After more than 50 Gy [5000 rad], there are seizures ranging from generalized muscle tremor to epileptoid [seizure-related] convulsions similar to grand mal. This convulsive phase lasts a few hours and is followed by ataxia."

Performance decrement in monkeys has been evaluated for a variety of behavioral tasks after whole- or partial-body irradiation at different radiation qualities, total doses, and dose rates. When considered in the context of ETI, the following general conclusions have been reached on the basis of these studies.[5]

- The frequency of occurrence of ETI within a population increases with dose.
- For a given dose, the frequency of occurrence of ETI increases with the demands or stress of the task.
- ETI can be elicited by whole-body, trunk-only, or head-only irradiation.
- Neutrons are less effective than photons in producing ETI. The relative biological effectiveness for neutrons has been estimated as 0.23–0.62.

Results of one study of radiation-induced ETI in monkeys are summarized in Fig. 1. In this case the animals received a brief dose of 25 Gy from mixed neutron-gamma radiation (neutron:gamma = 0.4). The photon-equivalent dose for ETI (defined as the dose from photons required to produce the same behavioral response) would be roughly 20 Gy (range of 19–22 Gy). Behavioral effects were almost immediate. The performance decrement depended to some extent on the task being performed, with largest and most frequent (100%) decreases occurring for a physically demanding task. A modest recovery in efficiency was evident, starting about 5 min after irradiation and ending at different times for different tasks. For a task requiring physical activity, balance, and visual discrimination, these data indicate an average efficiency on the order of 0.4–0.6 over any time period of 10 min or greater during the first 2 h after exposure.

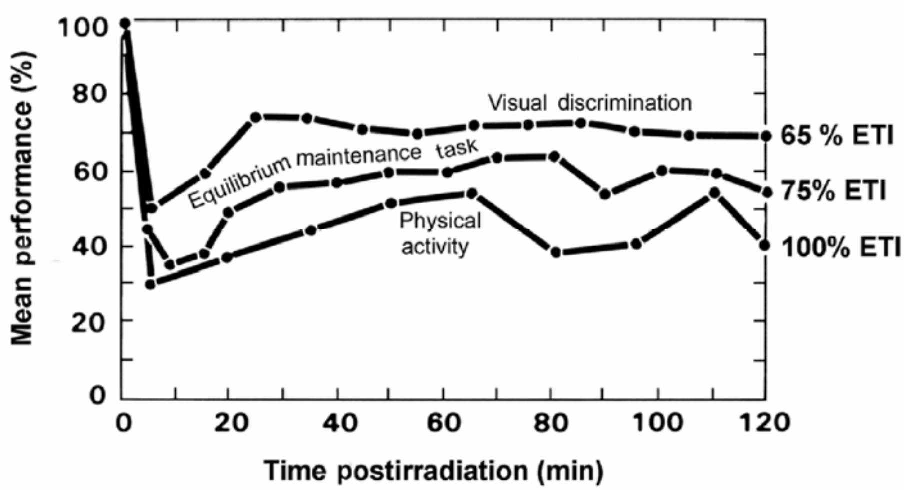

Fig. 1. Comparison of monkey behavioral responses after a pulse of 25-Gy (2500-rad) gamma-neutron radiation. Source: AFRRI, *Textbook of Military Medicine: Medical Consequences of Nuclear Warfare*, 1989.

To predict radiation-induced performance deficits in soldiers, the U.S. military has developed models based on data for humans and monkeys, together with subjective projections by soldiers concerning their expected changes in performance while experiencing early symptoms of radiation sickness.[4] These models provide a useful starting place for the present project but are difficult to translate into estimates of efficiency for the relatively short time periods of interest here. Derivation of an efficiency function, $E_R(T)$, for a comprehensive set of dose rates, R, and maximum available times, T, will require reassessment of the database in light of the specific problem addressed here.

3.2 Preliminary Approach for Estimating E_R

This section provides a preliminary approach using step changes for estimating average efficiency, E_R, based on assessments made to this point. Using this step-change approach, the assumption is made that efficiency remains at 1.0 as long as the cumulative dose is less than 25 Gy. This is a conservative assumption because data on humans and laboratory animals indicate that there could be some decrease in efficiency, possibly after a delay of several minutes, with much lower cumulative doses.

Once a cumulative dose of 25 Gy has been received, efficiency is assumed to fall immediately to 0.6 and remain at that level for at least 2 h. Furthermore, efficiency is assumed to decline by 0.1 with every increment of 5 Gy in the cumulative dose through 50 Gy. Efficiency of 0.1 is assumed for cumulative doses in the range 50–100 Gy and total incapacitation is assumed once 100 Gy is reached (Table 1).

Table 1. Assumed stepwise decline in efficiency with increasing cumulative dose

Dose (Gy)	Efficiency
<25	1.0
25–29	0.6
30–34	0.5
35–39	0.4
40–44	0.3
44–49	0.2
50–100	0.1
>100	0.0

The assumption that a low level of work can still be accomplished after receiving doses as high as 50–100 Gy is based on observations that some persons exposed to estimated doses in this range as a result of criticality accidents have been able to leave the accident site. The dose estimates for these accidents are uncertain, however, and represent mixed neutron-gamma doses rather than pure gamma doses.

For example, suppose the dose rate is 100 Gy/h (1.667 Gy/min or 166.7 rad/min). Efficiency is assumed to remain at 1.0 until the cumulative dose is 25 Gy, which occurs 15 min after the start of exposure. The next decline in efficiency occurs 3 min later when the cumulative dose is 30 Gy, which is 18 min after the start of exposure. Further declines in efficiency occur at 35-Gy (at 21 min), 40 Gy (at 24 min), 45 Gy (at 27 min), 50 Gy (at 30 min), and 100 Gy (at 1 h). Table 2 shows the cumulative effective work time (T_{eff}) at different times after the start of exposure. For example, the effective work time from 15–18 min is 3 min × 0.6 (efficiency) = 1.8 min so that the cumulative effective work time over 0–18 min is 15 min + 1.8 min = 16.8 min.

Table 2. Preliminary estimates of effective work times over different time periods while continuously exposed at a dose rate of 100 Gy/h (166.7 rad/min)

Time period (min)	Efficiency	Effective time this period (min)	Cumulative effective time, T_{eff} (min)
0–15	1.0	15	15
15–18	0.6	1.8	16.8
18–21	0.5	1.5	18.3
21–24	0.4	1.2	19.5
24–27	0.3	0.9	20.4
27–30	0.2	0.6	21
30–60	0.1	3.0	24
>60	0.0	0.0	24

The estimates of effective work times shown in Table 2 were used to project whether a dose rate of 100 Gy/h is self-protecting for different combinations of S and T (Table 3).

Table 3. Conclusions concerning self-protection based on a dose rate of 100 Gy/h (167 rad/min) for selected values of S and T

Case	Maximum time available, T (min)	Cumulative Effective time available, T_{eff} (min)	Minimum time S to complete task if fully efficient (min)		
			5	15	30
1	10	10	No	Yes	Yes
2	20	18	No	No	Yes
3	30	21	No	No	Yes
4	60	24	No	No	Yes

[a]A **Yes** conclusion indicates that the item is self-protecting using the criterion $T_{\mathrm{eff}} < S$. If, however, $T_{\mathrm{eff}} > S$, then the item is not self-protecting (indicated by **No**).

If the minimum time S required to complete the task is 5 min, then the task can be completed in all four cases (T = 10, 20, 30, or 60 min) because efficiency is not decreased during the 5 min required to complete the task at the assumed dose rate (100 Gy/h); hence, the item *is not self-protecting*.

If the minimum time S required to complete the task is 15 min, then the task cannot be completed in Case 1 regardless of the dose rate because the available time T is less than 15 min — and the item *is self-protecting*. However, the task can be completed in Case 2 because the effective work time available during the available 20 min is about 18 min, which is greater than the 15 min needed (i.e., the item is *not* *self-protecting*). Similarly, the task can be completed in Cases 3 and 4 because the effective work times are 21 min and 24 min — both of which are greater than the 15 min needed.

If the minimum required time is 30 min, the task cannot be completed under any of the cases either due to the available time being less than the required time ($T < S$ for cases 1 and 2) or to the effective work time being less than the required time to complete the malevolent task (i.e., the effective work time will never be greater than 24 min).

3.3 Alternate Approach for Estimating Effectiveness (or Incapacitation)

Another methodology for determining if an item is self-protecting is to measure how much time it takes to achieve complete incapacitation, defined as *lacking the strength or ability to physically function*. Data that exactly correlate to this point of incapacitation do not exist; therefore, emesis data in post-accident occurrences is assumed to have distributions (means and standard deviations) representative of incapacitation data. The mean and standard deviation for emesis at each dose level were determined from the graph in Fig. 2 and are tabulated in Table 4, Exposure Effects on Capability.

Since the most complete data[2] relate to the onset of emesis, it forms the foundation of onset time in Table 5. Table 5 was developed using the data from Table 4 (mean and range) for the different exposure levels. The range of data was assumed to define the 95% confidence interval and include two standard deviations above and below the mean. The distribution of cumulative probabilities was determined by using the Excel NORMDIST (normal distribution) function at time *t* with a 0.1-h increment from a nominal 0 (0.001) to 20 h. The result of the NORMDIST was multiplied by the probability of emesis and the probability of incapacitation (using the Index of Incapacitation in Table 4). This probability distribution can be seen graphically in Fig. 3.

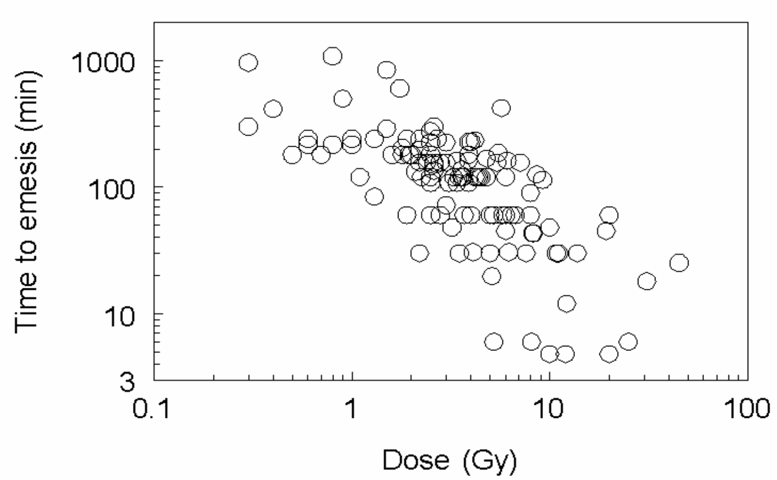

Fig. 2. Time to emesis post-accident as a function of dose (personal communication from R. E. Goans, Tulane University School of Public Health and Tropical Medicine).

From the assumed distribution in Table 4, the cumulative probability of emesis at a given dose rate and at a given time can then be calculated as follows:

$$P_e = \int_0^{\infty} \frac{1}{\sigma\sqrt{2x}} e^{-\left(\frac{(x-\mu)^2}{2\sigma^2}\right)}, \tag{2}$$

where

P_e = the cumulative probability of emesis,
x = time in hours,
μ = the mean time to emesis,
σ = the standard deviation, and
e = the base of the natural logarithm.

The Excel NORMDIST (x , μ , σ ,*True*) function yields the cumulative probability (a *False* last argument would return the probability mass value). These values can be used to estimate the onset of incapacitation by multiplying P_e by the Index of Incapacitation (I_i) determined and listed in Table 4, yielding the following for the Probability of Incapacitation (P_i):

$$P_i = P_e * I_i \tag{3}$$

The numerical data are provided in Table 5.

Table 4. Exposure effects on capability[2, 4, 11, 13, 18–26]

Dose (Gy)[a]	Probability of nausea	Time to emesis[b] (h)		Potentially lethal effects[c]	Chance of survival[d]	Time to death (d)	Index of incapacitation[c,e]
		Mean	Range				
0.5	15%	5	3–18	None	~100%	Unlikely	0.02 – Possible nausea or vomiting
1	30%	4	1.5–15	None	~100%	Unlikely	0.05 – Increased incidence and severity of nausea, vomiting
2	50%	3	0.8–12	Increased marrow damage	>90%	35–49	0.1 – Nausea, vomiting, reduced cognitive and routine task skills
3	70%	2	0.5–10	Extensive marrow damage	50%	28–42	0.15 – Same as above but more likely to occur and more intense
4	90%	1.5	0.3–8	Severe marrow damage	<40%	21–35	0.2 – Same as above but more likely to occur and more intense
6	~100%	1	0.1–6	Severe marrow damage; some GI and lung damage	Very low	14–21	0.25 – Depressed cognitive skills, task performance; animal studies show immediate depression in volitional performance
10	~100%	0.5	0.08–3	Combined GI, lung, and marrow damage	Very low	7–14	0.3 – Same as above but more likely to occur and more intense
15	~100%	0.4	0.08–2	GI damage	None	5–12	0.4 – Greater CNS involvement; ETI in many cases (animal data)
25	~100%	0.3	0.08–1.5	GI damage	None	2–5	0.7 - Substantial incapacitation for physical activity within 5 min in virtually all exposed persons (based on data for monkeys)
40	~100%	0.25	0.08–1	GI and CNS damage	None	2–3	1.0 - Increased frequency and intensity of incapacitation (humans and monkeys). Greatly reduced blood pressure in 5 min (monkeys)
100	~100%	Minutes	--	CNS damage	None	~2	1.0 – Incapacitation in minutes in most persons (humans, animals)
200	~100%	Minutes	--	CNS damage	None	~1	1.0 – Incapacitation within minutes expected (animal data)
1000	Rapid death	Rapid death	--	Inactivation of substances needed for basic metabolic processes	None	Perhaps minutes	1.0 – Rapid loss of consciousness; quick death (projected)

[a] Gamma and/or neutron irradiation. Gamma rays appear to be slightly more effective than neutrons in producing early effects.
[b] Exposed persons may experience severe nausea without vomiting.
[c] GI = gastrointestinal system; CNS = central nervous system; ETI = early transient incapacitation.
[d] Chance of survival is in the absence of intensive medical care.
[e] Index numbers are used to determine probability of incapacitation and are qualitative and preliminary at this point.

Table 5. Time to incapacitation

Dose in rad (Gy)	Probability of emesis	Index of incapacitation at 20 h	Hours to emesis					Probability of incapacitation at time t (h)					
			Mean	Low	High	Range	Sdev	0.01	0.1	0.5	1	10	20
50 (0.5)	0.20	0.02	5.00	3.00	18.00	15.00	3.75	0.00	0.00	0.00	0.00	0.00	0.00
100 (1)	0.40	0.05	4.00	1.00	15.00	14.00	3.50	0.00	0.00	0.00	0.00	0.02	0.02
200 (2)	0.60	0.10	3.00	0.50	12.00	11.50	2.88	0.01	0.01	0.01	0.01	0.06	0.06
300 (3)	0.70	0.15	2.00	0.40	10.00	9.60	2.40	0.02	0.02	0.03	0.04	0.10	0.10
400 (4)	0.90	0.20	1.50	0.30	8.00	7.70	1.93	0.04	0.04	0.05	0.07	0.18	0.18
600 (6)	1.00	0.25	1.00	0.08	6.00	5.92	1.48	0.06	0.07	0.09	0.13	0.25	0.25
1000 (10)	1.00	0.30	0.50	0.08	3.00	2.92	0.73	0.08	0.09	0.15	0.23	0.30	0.30
1500 (15)	1.00	0.40	0.40	0.08	2.00	1.92	0.48	0.08	0.11	0.23	0.36	0.40	0.40
2500 (25)	1.00	0.70	0.30	0.08	1.5	1.42	0.36	0.14	0.20	0.50	0.68	0.70	0.70
4000 (40)	1.00	1.00	0.25	0.08	1	0.92	0.23	0.15	0.26	0.86	1.00	1.00	1.00
10,000 (100)	1.00	1.00	0.07	0.00	0.5	0.50	0.12	0.32	0.61	1.00	1.00	1.00	1.00
20,000 (200)	1.00	1.00	0.03	0.00	0.25	0.25	0.06	0.35	0.86	1.00	1.00	1.00	1.00
100,000 (1000)	1.00	1.00	0.01	0.00	0.01	0.01	0.00	0.75	1.00	1.00	1.00	1.00	1.00

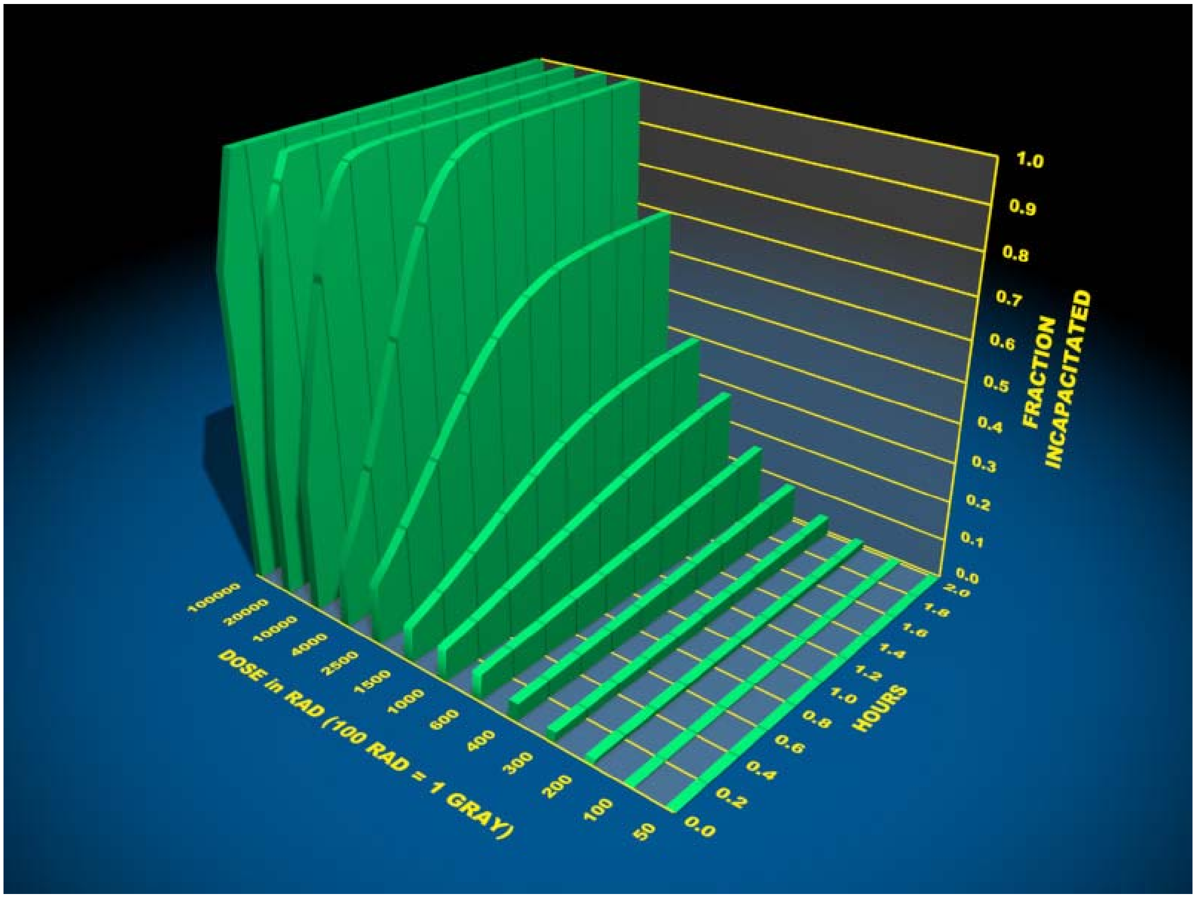

Fig. 3. Estimated time to incapacitation.

4. RESEARCH REACTOR MATERIAL AVAILABILITY AND CHARACTERISTICS

In order to estimate the dose consequences of burned research reactor fuels worldwide, it was necessary first to prepare a data file of the world's research reactors, populated with information about each facility, including fuel type, fuel form, enrichments, power levels, fissile material loadings, typical fuel burnup, etc. The basis for this data file was the Research Reactor Database, available as an IAEA publication.[27]

4.1 Material Availability

A summary of the data file is given in Table 6, (assumed reactor types are shown in Column 1) along with information on the number of facilities, average number of fuel elements per reactor core, and ^{235}U mass per element for each reactor type.

Table 6. Research reactor data summary

Reactor type [a]	Fuel form [b]	Enrichment (wt %)	Reactors	Elements per core	^{235}U g per element
MTR	UAl	20/90	61	50	241
TRIGA	UZrH	20/70	43	90	72
IRT	UAl	10/36/80	24	42	152
HWR	UO_2/UAl	3/20	12	86	463
Slowpoke	UAl	90	9	326	3
LWR	UO_2	LEU[c]	10	175	288
Tubes	UAl	20/60/90	5	68	225
Fast	UO_2/PuO_2	NA	9	84	1391
Misc	UAl	10	6	31	395
Graphite	Metal	Natural U	3	4	650
		Total	**182**		

[a] Materials test reactor (MTR); IRT is Russian fuel-tube design; heavy-water reactor (HWR); light-water reactor (LWR).

[b] UAl = uranium-aluminum alloy; UZrH = uranium-zirconium hydride; UO_2/UAl = uranium dioxide or uranium-aluminum alloy; UO_2 = uranium dioxide; UO_2/PuO_2 = uranium dioxide / plutonium dioxide; Metal = elemental uranium.

[c] Low enriched uranium (LEU) is less than 20% ^{235}U.

This information was used to characterize the range of research reactor fuels available around the world. The top three categories above were selected for further study since they formed the majority of facilities worldwide.

4.2 Research Reactor Fuel Burnup

Of additional interest is the degree of burning experienced by the various research reactor types described in Table 6. The data collected were used to survey the burnup characteristics of these research reactor fuels. It should be noted that the information in the data file is cursory in nature since it was contributed voluntarily. As such, not all entries are complete; the values quoted herein should only be used to estimate the general characteristics of these fuels worldwide. The results provided in Fig. 4 show the number of fuel elements in specific burnup bins: 0–10%, 11–20%, 21–30%, 31–40%, 51–60%, 61–70%, and 71–80% burned ^{235}U. These results show that there are a large number of assemblies with nearly zero burnup and with >70% burnup. These cases are not of specific interest in this study since they represent the extremes; small burnup assemblies are not expected to provide self-protecting characteristics of a fuel element, while extremely high burnups would overly bias the self-protecting characteristics if they formed the basis of the guidelines. Thus, the desired range of burnups to be used in the prediction of self-protection characteristics is the prevalent lower-middle range of burnups. From Fig. 4, the burnups of 30, 40, and 50 % ^{235}U are chosen for further study.

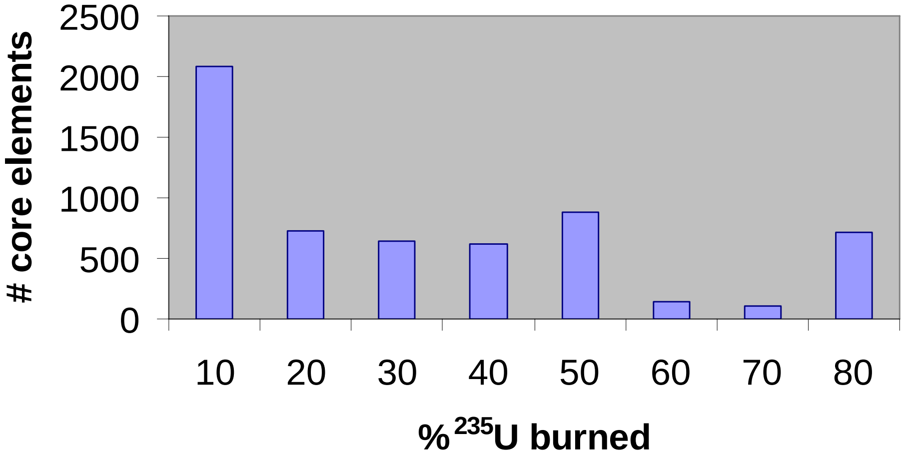

Fig. 4. Typical average fuel element burnup for research reactors. Data obtained from IAEA RRD Database.

The radioactive sources for the nine cases discussed above (30, 40, 50% burned fuel for TRIGA, MTR, and IRT designs) were generated using the ORIGEN-ARP code.[28] The ORIGEN-ARP code has been extensively validated for several power reactor-type fuels; however, very little validation data exists for research-type reactors. As a result, many of the libraries developed in-house at the Oak Ridge National Laboratory have not been released for public use. They have been compared with other depletion methods and are expected to give reliable results. The reactor libraries used in this study include a TRIGA-STD fuel assembly with a 20 wt % U-ZrH matrix, a 19-plate MTR design with 20 wt % fuel in a U_3Si_2 matrix, and an IRT 4-tube design with 36 wt % fuel in a U_3O_8-Al matrix. Sources were generated for each of the three burnups shown above and cooling times of 0.1, 0.3, 1, 3, 10, 30, 100, 300, 1000, 3000 h followed by 1, 2, 3, 5, and 10 years.

4.3 Research Reactor Spent Fuel Dose Rates

The sources generated using ORIGEN-ARP were input into shielding models for the QADS point kernel code. The explicit geometry of each fuel type (i.e., 19 plates for MTR, 4 tubes for IRT, and a single rod for the TRIGA designs) was modeled in the QADS code. The dose rates at 1 m from each assembly were predicted for each of the three burnup values at each of the 15 cooling times. For the MTR design, doses were computed opposite the open and closed faces of the fuels, with the maximum values selected.

The dose rates as measured in grays per hour are given in Figs. 5–7 for the MTR, TRIGA, and IRT fuel designs, respectively. Each of the dose curves has similar shapes with no discernable differences seen between the 30, 40, and 50% burnups for early cooling times due to the assumption of uniform specific powers (180 MW/MTU for MTR, 62 MW/MTU for TRIGA, and 500 MW/MTU for IRT). The selection of specific powers is arbitrary, but the values selected are felt to represent typical power levels for the selected designs. The later cooling times indicate expected differences in dose rates that approximately scale by the ratio of the burnups.

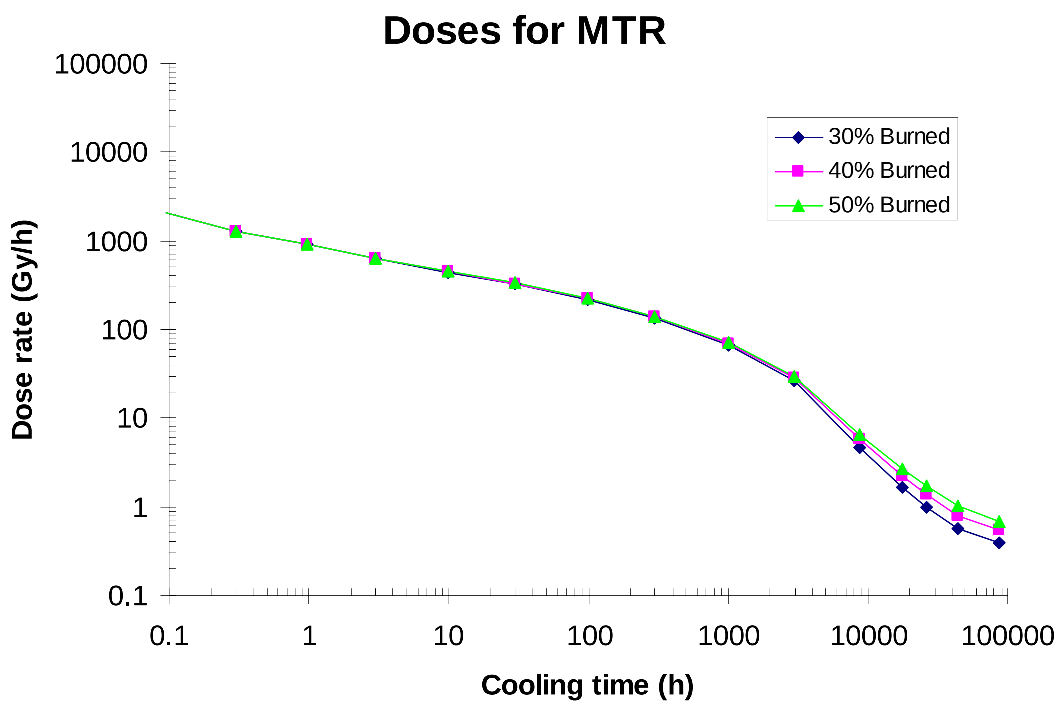

Fig. 5. Dose rate at 1 m versus burnup (percentage of ^{235}U burned) and cooling times for 19-plate MTR fuel design.

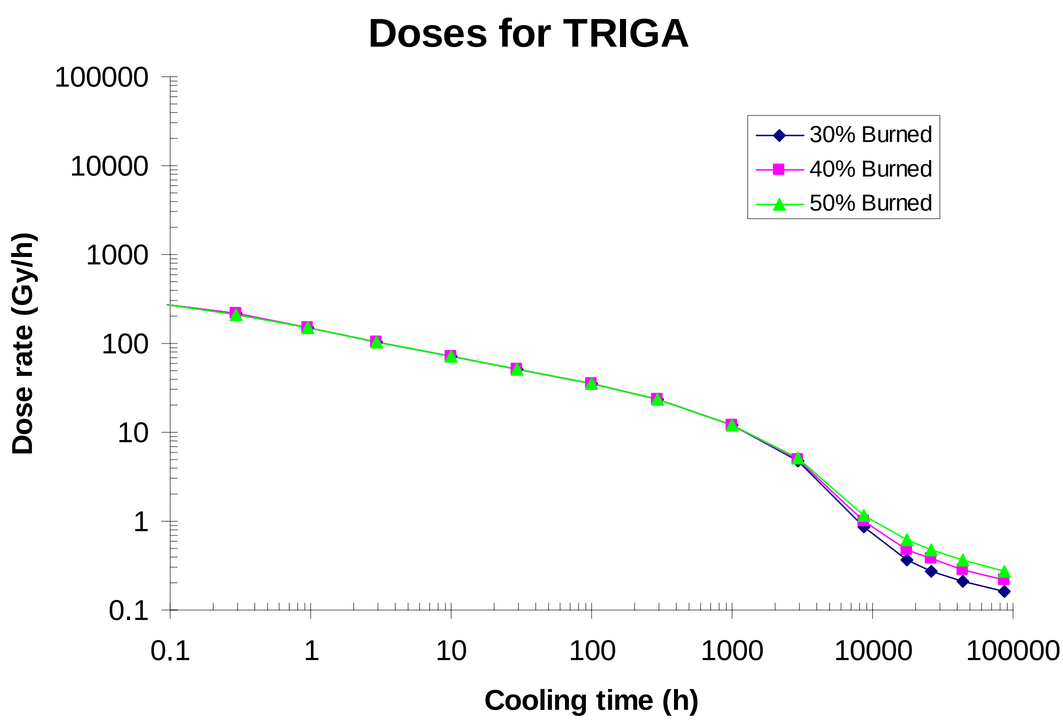

Fig. 6. Dose rate at 1 m versus burnup (percentage of ^{235}U burned) and cooling times for single-pin TRIGA fuel design.

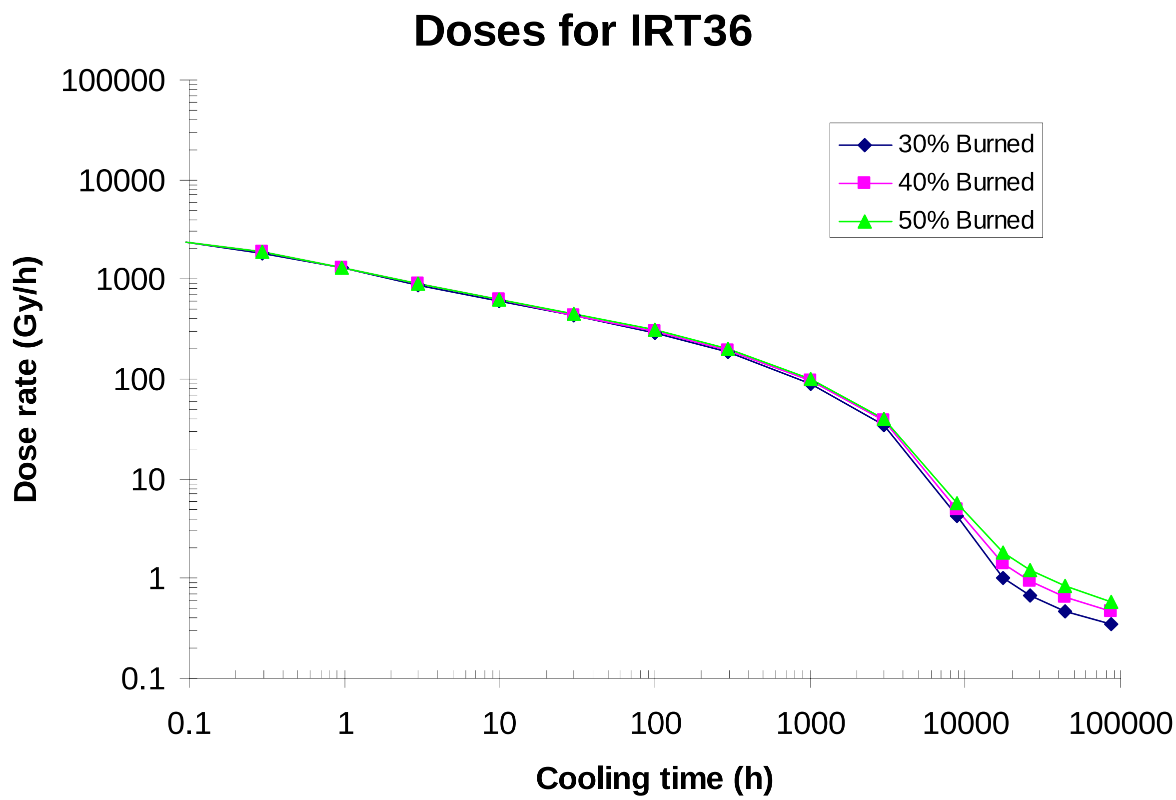

Fig. 7. Dose rate at 1 m versus burnup (percentage of ^{235}U burned) and cooling times for 4-tube IRT (36 wt % enrichment) fuel design.

5. SUMMARY

Self-protection of nuclear material has been revisited in the context of work efficiency and incapacitation. The problem of doing work in a transient state has been defined and a methodology has been provided that allows calculation of effectiveness degradation during task execution. An alternative approach to effectiveness degradation that looks at the problem in an end state of time-to-complete versus incapacitation is delineated and presented graphically.

The relative abundance of materials from various research reactors (considered to be targets for malevolent use) is outlined. Cooling time to various levels of radiation has been calculated and is presented graphically.

The dose rate of prevalent materials in storage at research reactor sites worldwide will fall below 100 Gy/h at ~2 h, ~100 h, and ~600 h for TRIGA, MTR, IRT-36, respectively. The assumed 100-Gy/h dose rate (used in Table 3) from spent fuel is, in fact, an upper bound expected. The current threshold dose rate for self-protection is 1 Gy/h (100 rad/h) at 1 m. A dose rate of 100 Gy/h (10,000 rad/h) at 1 m was determined to be the level that significantly affected performance and offered limited self-protection (in the range of minutes). Most research reactor spent fuel worldwide falls below this level after a short time in storage (in the range of hours to weeks). Based on this analysis, this report finds that for research reactor spent fuel, self-protection from a committed terrorist does not exist.

The ultimate issue of self-protection is one for policy makers to determine after considering all factors that have been presented. The data provided herein are intended to facilitate such consideration. The estimates of self-protection based on 100 Gy/h relied on a very cautious model of incapacitation and could be substantially lower. Further work is needed to validate the assumptions, sharpen the model, and produce supplementary data supporting these results.

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