NUREG/CR-2492
LA-9213-MS

Special Nuclear Material Self-Protection Criteria Investigation

Phases I and II

Prepared by J. J. Koelling, E. W. Barts

Los Alamos National Laboratory

Prepared for
U.S. Nuclear Regulatory
Commission

Available from

GPO Sales Program
Division of Technical Information and Document Control
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Printed copy price: $3.00

and

National Technical Information Service
Springfield, Virginia 22161

NUREG/CR-2492
LA-9213-MS

Special Nuclear Material Self-Protection Criteria Investigation

Phases I and II

Manuscript Completed: December 1980
Date Published: January 1982

Prepared by
J. J. Koelling, E. W. Barts

Los Alamos National Laboratory
Los Alamos, NM 87545

Prepared for
Division of Safeguards
Office of Nuclear Material Safety and Safeguards
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
NRC FIN A7146

TABLE OF CONTENTS

Page

I. Introduction and Task Summary 1

- A. Introduction 1
- B. Summary of Tasks 2

II. Alternatives 23

- A. Exemption Based on Integrated Dose 23
- B. Exemption Based on the Detection 23
- C. Retain the 100 rem/h Exemption but Give Credit for Fuel Enrichment and Mass 25
- D. Retain the 100 rem/h Exemption as Presently Specified in 10 CFR 73.67(b) and 10 CFR 73.6(b) 26
- E. Exempt Irradiated Fuel 27

III. Effect 29

- A. Exemption Based on Integrated Dose 29
- B. Exemption Based on the Detection of the Movement of Irradiated Fuel 29
- C. Retain the 100 rem/h but Give Credit for the Mass of ^{235}U per Fuel Element and the Fuel Enrichment 29
- D. Retain the 100 rem/h as Presently Specified 30
- E. Exempt Irradiated Fuel 30

IV. Effect of not Retaining an Exemption 32

V. Effect of Maintaining 100 rem/h at 3-ft Self-Protection on the University of Virginia Facility 33

- A. Possibility of Maintaining Fuel at Exempt Dose Rates 33
- B. Cases Where it May not Be Possible to Maintain Fuel at Self-Protecting Dose Rates 33
- C. Effect of Maintaining Fuel at Self-Protecting Dose Rates on Normal Reactor Operation 35
- D. Impact of Maintaining Fuel at Self-Protecting Dose Rates During Expended Fuel Shipment 36
- E. Effect of Maintaining Fuel at Self-Protecting Dose Rates During Unusual Occurrences 38

SPECIAL NUCLEAR MATERIAL
SELF-PROTECTION CRITERIA INVESTIGATION
Phases I and II

I. INTRODUCTION AND TASK SUMMARY

A. Introduction

The Special Nuclear Material (SNM) that is possessed by nonpower reactor (NPR) licensees is exempt from most 10 CFR Part 73 physical security requirements if the material "is not readily separable from other radioactive material" and "has a total external radiation dose rate in excess of 100 rem/h at a distance of 3 ft from any accessible surface without intervening shielding."[1] NPR licensees have sought to take advantage of the exemption to the rules provided by the radiation level requirement. However, the power levels of many of these reactors are not sufficiently high to irradiate the SNM to a point at which it has a dose rate level of 100 rem/h at 3 ft. Consequently, these licensees have proposed that the Nuclear Regulatory Commission (NRC) either lower the radiation level or use an alternative criterion.

As initially envisioned by the NRC, the 100-rem/h level was to provide a deterrence against theft. The current character of the potential adversary (determined and violent persons with equipment appropriate to their task) has caused the NRC Commissioners to request that their operational staff reassess the appropriateness of the existing criterion.

This report covers Phase I and Phase II of a Los Alamos Scientific Laboratory (LASL) project in which we examined the technical aspects of this criterion and provided technical analyses to support NRC staff policy assessments.

Phase I consisted of six tasks that were needed to provide a data base for Phase II of the study. In Phase I, existing information was collected and, when necessary, analyzed. Discussions and conclusions are given for each task in the same order as they appeared in the LASL proposal.

Phase II included recommended courses of actions, justifications for these actions, and the effect of these actions on several types of facilities. The recommended alternatives, in order of preference, are summarized in Sec. II.

B. Summary of Tasks

Task 1. Analysis of the Equipment, Expertise, and Time Required to Remove Fuel From the Core of All Types of NPRs

At an NPR facility, fuel will normally be in one or more of three locations: (1) unirradiated fuel in a vault-type room, (2) irradiated fuel in the core, and (3) irradiated fuel in a fuel storage pool. Here we are concerned only with the self-protection formed by irradiated fuel, and thus only fuel located in the core and in fuel storage areas will be examined. In some cases, all three locations are in the reactor pool.

There are two general types of NPRs: (1) reactors with the fuel completely enclosed in a tank and/or solid shielding, and (2) reactors with the fuel accessible from above the core, such as a pool reactor. The enclosed reactors usually have massive blocks of shielding that must be removed for access to the core. The top plate of a tank-type reactor or a large shielding plug must also be removed (a very difficult task). Once either is removed, removing fuel is similar to removing fuel from a pool-type reactor. Normally a crane is required for removing the shielding plug or tank top. This removal takes time under normal and theft conditions. In addition, as an extra measure of security, the crane can be locked in place and provided with on-off alarms and so on. Thus the time to obtain access depends on the reactor design and is site specific. The discussion that follows is concerned with removing fuel from a pool-type reactor and gives conservative, low fuel-removal times and doses.

The minimum equipment needed to remove irradiated fuel from an open pool are a fuel-handling tool, a truck, and radiation shielding. The fuel-handling tool could be one normally used for moving the fuel. If one is not available, the fuel-handling tool could be as simple as a hook on the end of a rope. Most fuel elements have grappling pins or holes that would be easy to grasp with a hook and then the elements can be lifted to the pool surface. At the pool surface, the elements could be shackled by hand or, to reduce the radiation dose, by a stick or rod.

A truck or other vehicle would be needed to transport the fuel from the reactor site. The volume and weight of the fuel would not be a critical factor in determining the vehicle size. Twenty-five to thirty plate-type fuel subassemblies containing 5 kg of uranium weigh less than 50 kg and can be stacked in a volume approximately 0.6 by 0.6 by 1.0 m. TRIGA fuel is about three times as dense, but can be stored in about the same volume. However, if these stacks were immersed in water and not disrupted, in most scenarios they would constitute a critical assembly.

The size of the truck would be determined primarily by the amount of shielding that the adversary group decides is necessary. The shielding could be designed to either minimize personnel dose or to minimize the possibility of detection as the truck is driven from the reactor site. The first criterion is arbitrary. The second is the more stringent, and the shielding required is determined by the detection limits of survey teams, which vary depending on the type of search equipment employed.

If the search team used a fixed-wing aircraft, a large area could be covered in a relatively short period of time. A search aircraft flying 300 m above the ground at 220 km/h with a 300-m grid spacing could cover approximately 70 km^2 in 1 h. An irradiated fuel element having an air dose reading of 560 mR/h at 1 m (unshielded) would almost certainly be detected.

The speed and area coverage of the survey are reduced considerably if a helicopter is used, but the detection limit is improved. A search helicopter flying 60 m above the ground at 130 km/h at with a 75-m grid spacing could cover approximately 10 km^2 in 1 h, a reduction by a factor of 7 in area covered compared to the fixed-wing aircraft. However, the detection limit is improved by a factor of 60 or 9 mR/h at 1 m.

If the search team used a van, the detection limit is similar to that of the helicopter. For hand-held instruments, the limit is improved over the helicopter by approximately a factor of 60.

A lead blanket could be prepared to lay over the fuel-element assembly while it is being moved from the pool to the truck. The lead shield would have to be approximately 30 mm thick to reduce the radiation dose by a factor of 10. A blanket large enough to cover three sides of a fuel element assembly weighs about 45 kg. This would be unwieldy and probably would not be practical as it would increase the residence time around each assembly. The adversary would desire to simply move the fuel element assembly as quickly as possible.

Two other types of local shielding might also be considered: lead aprons and shielded transfer casks. Lead aprons, such as used in x-ray facilities, are not practical. They are essentially useless for fission-product gamma ray energies because they give a dose reduction factor of less than 10. Most research reactors have shielded transfer casks for moving irradiated elements. These casks are very heavy (typically several thousand kilograms) and must be moved with a crane. This can be made difficult by locking the crane out, fixing the crane with an alarm, or otherwise securing it. Further, the use of a crane and shielded cask would significantly increase the time that a group must remain in the facility, thus increasing the possibility of detection by a security force.

The simplest form of shielding in a vehicle is concrete block. The weight of the block used depends on the dose attenuation required. Attenuation factors and estimated shield weights for 30 elements in a cavity 0.6 by 0.6 by 1.0 m with a shield on each of six faces are listed below.

Attenuation Factor	Shield Weight (kg)
10	910
100	1820
1000	2730
10 000	3640

Attenuation factors of 10 or 100 could be provided in a small moving truck or heavy duty pickup or van. Providing shielding above the fuel would be difficult and would add considerable weight to an already overweight vehicle.

The successful theft of NPR fuel would be much easier with the assistance of a knowledgeable insider. An insider could be aware of the details of the facility security system. Section 73.67 of 10 CFR Part 73 requires that NPRs with inventories of SNM of moderate or low strategic significance store these materials in areas that are monitored with an intrusion alarm or other systems to detect unauthorized entry or activities. The requirements also call for a security organization, periodic surveillance by the security organization, and an appropriate response force. To meet these requirements, most facilities are using intrusion alarms on all doors to fuel storage areas, motion detectors in storage areas, and other similar devices. Only a few authorized individuals have knowledge of the operation of these detectors. Further, most facilities have radiation monitors that will alarm locally if irradiated fuel is moved about in air. The alarm may attract attention and thus deter the adversary group. Only a few authorized individuals can change the set points on these monitors.

Other useful information for a successful theft includes the location of the fuel, fuel loading data, and fuel enrichment. Some knowledge of shielding and dosimetry would be useful if the adversaries wished to minimize human exposure.

Task 2. Estimate of the Range of Doses Likely to be Received by an Adversary in Attempting to Remove Material

Almost one-half of the licensed NPRs have been reviewed relative to specific site parameters to develop a nominal or average facility for calculational purposes. Based on the present rule, an element radiation level of 100 rem/h was chosen for this purpose.

The number of elements in the core varies, depending whether they are plate- or TRIGA-type elements. There are between 8 and 30 plate-type elements in a core (many cores have nearly 30 elements). Cores using TRIGA-type elements have up to 25 elements in four-rod clusters and up to 112 elements in single SNM rods.

Most plate type elements reviewed contained nearly 175 g of ^{235}U, although the range was from 120 g to 775 g. This, coupled with the nearly 30 elements per core, gave us a nominal 5 kg ^{235}U per core or a formula quality of ^{235}U. Therefore 30 elements were chosen, as many reactors contained close to this number and, at 175 g per element, these give a nearly 5-kg core loading.

1. Removal of elements to pool surface. Because elements remain under water as they are being moved to the surface of the pool, the dose received during this phase is assumed to be negligible. Removing 30 elements using either a grappling hook on the end of a line or using a core-loading tool would take an experienced handler at least 2 min per element (or 1 h) to remove the 30 elements. Under normal transfer conditions, experience has shown that the time needed is closer to 7 or 8 min per element if care is taken not to damage it during transfer. Removing the inner elements takes more time because of the physical interference from the control rod guides and

experimental equipment. No extra time has been allowed for removing these more difficult elements.

2. Transfer of elements from pool surface to truck. This phase of the theft will contribute the largest proportion of the dose received by an adversary, mainly because of the vulnerable position of the adversary relative to the element. Shielding would be impractical during the transfer, and therefore the only way for the adversary to reduce the dose he received would be to decrease his time in proximity to the element or increase his distance from the element.

The distances observed between the pool surface and closest approach for the truck ranged from 25 to 100 m, with the majority of the distances around 50 m. We chose a distance of 50 m without considering the above-mentioned obstacles, except for moving the elements with a very long handling tool (discussed later).

Distances are misleading in themselves as many corridors, doors, airlocks, and steps are encountered at these facilities. The time estimate for this phase does not include the time required to break security.

If an element is carried at arm's length (approximately 2 ft), the whole body dose rate seen is probably closer to 250 rem/h than 100 rem/h. The transit time is minimized, but the radiation level is great. Running the 50 m would require at least 20 s, and the adversary must do this 30 times. Storage would take an additional 10 s, making the total time near 15 min, or 30 s per element. The dose received for this effort would be 62.5 rem,* and the total time for this transfer phase would be nearly 25 min.

---

*(20 s + 10 s) x 30 elements x 250 rem/h-elements x h/3600 s = 62.5 rem

If an element is dragged using a rope or other piece of equipment, the dose received by the adversary would be much smaller, but the time to make the transfer would be extended greatly because of the problem of grasping the elements and going through the obstacles discussed earlier. The adversary would still have to get near the elements while storing them. The dose rate he would receive during the transfer would depend on his distance from the element. A maximum for pool reactors would be the length of a handling tool (approximately 6 m). If we take into account scattered radiation, the radiation dose received during transfer would be closer to 8 rem/h. The transit time would depend on the number of obstacles encountered, but probably would be a factor of 10 greater than for the previous scenario, especially if the element is disconnected accidentally in transit and must be reconnected. The person handling the material would receive a dose of approximately 14 rem.* The total time for this transfer phase would be approximately 115 min.

Thus an adversary could decrease his total whole body radiation dose by a factor of 4 by using a dragging tool but would increase the total expended time in the theft by a similar factor. For computational purposes, we will use the first scenerio.

3. Transfer of elements from the reactor to the processing area. This factor is nearly impossible to quantify as it depends on the specific site. For our purposes, we will assume that the adversary is allowing 30 min before running a significant risk of detection. This time will probably restrict his movement to within 15 miles of the reactor.

---

* (200 s + 10 s) x 30 elements x 8 rem/h-elements x h/3600 s = 14 rem.

With no shielding and a distance from the elements to the truck cab of 10 ft, the total radiation the adversary received during this phase would be approximately 135 rem.[*] If a ton of shielding is used, this factor would be reduced (as pointed out earlier) by a factor of 10.

4. Total dose during theft. The total dose to the adversary during these various phases would be approximately 80 rem if he chooses to make the theft quickly and uses a pickup truck with a ton of shielding.
The total time needed for the theft would be approximately 2 h. If he chooses to be more careful, he could reduce the total dose to 30 rem, but he would increase the theft time to 5.5 h.

We have shown that the greatest contribution to the dose would, under most conditions, come from the transfer of fuel from the pool surface to the truck. There are great differences between sites in the distance and the number of obstacles that would be encountered during theft. To show these differences, we will describe two existing NPR sites.

Site A. The reactor building is made of heavy-gauge steel with a steel roll-up door mounted between the reactor pool and the closest approach of the vehicle (25 m). The vehicle loading dock is ideal for an unimpeded transfer once the door is in a rolled-up position. Fuel can also be removed through three office-type doors and down a small flight of steps. The distance traveled is approximately 60 m.

Site B. The reactor building is part of a large concrete building set

---

[*] 30 elements x 100 rem/h element x 9/100 x 0.5 h = 135 rem.

into the side of a hill. There are two massive drive-through doors between the bottom of the pool room (beam room) and the outside. The closest approach for a vehicle is three stories below the pool surface. The total distance is approximately 25 m. If the vehicle does not penetrate the building (that is, stays outside of the doors), the total distance is approximately 125 m. The other way to remove fuel is to go through an airlock, down several flights of stairs, and through several office-type doors, a total distance of approximately 200 m.

Several factors could cause a higher total dose. The calculations are based on elements with a uranium loading of about 175 g each. Moving more elements with less loading requires longer exposure times. In addition, the calculations are also based on a dose rate of 100 rem/h for all elements. The elements would likely be more radioactive, some significantly so.

In most reactor cores, the neutron flux is not flat across the core, and thus the individual element radioactivity varies as the core is traversed. The peak-to-edge ratio of element activity could easily reach 5 for a water-reflected core. As an example, consider a core array of 5 elements by 6 elements. Assuming 100 rem/h on the outside elements and an increase of 3 for the adjacent ring and 5 for the inner elements, the total radiation level for all 30 elements is 5800 rem/h, or an average of 193 rem/h for each element. Thus instead of seeing 3000 rem/h from the total 30 elements, the dose rate would really be closer to twice this value because of the cosine flux profile. Some cores are reflected with more efficient materials, some with reflection on all sides, and some with partial reflection. For a full graphite-reflected core, this ratio between peak to edge could be reduced to a few percent—making the individual element activity nearly constant. Thus the total dose to an individual could be increased by a factor of 2 or 3 from this effect alone, or could be increased by only a few percent for well-reflected cores.

If these two factors were added to the site-specific characteristics for increasing the transit time of fuel removal from the core to the vehicle, the total dose could conceivably be increased up to around 1000 rem.

On the other hand, there are factors that could cause a lower total dose. The time needed to transport the elements to the truck may be less than we noted. In some situations, the truck might be close enough so that the transfer could be done in 10 to 15 s. The dose during loading can be reduced by increasing the shielding and by using less care, such as throwing the elements in the truck in a random fashion. The dose during driving can be reduced by using more shadow shielding and moving the fuel to the back of the truck bed, thus placing a greater distance between the fuel and the driver, and by having a shorter driving time. Finally, the dose per person can be further reduced by using more people to transfer the elements.

Thus the doses received by the adversary can range from tens to hundreds of rem. The most likely dose to a careful adversary is approximately 50 to 100 rem based on elements at 100 rem/h at 3 ft.

A 100-rem dose is not incapacitating; nausea might be the only noticeable physical affect. An increase of the total dose to 1000 rem and an accompanying increase of the self-protection limit to 1000 rem/h at 3 ft would still not be incapacitating, although the long-term health effects could be serious or fatal To be a truly incapacitating dose, the dose rate must be increased at least another order of magnitude to 10 000 rem/h at 3 ft (incapacitating dose will be discussed later). As a reference, measurements of irradiated fuel have been made at the University of Michigan and the University of Virginia.[2] Both of these reactors regularly operate at 2 MW. Only six NPRs operate at a higher power level. The highest dose rate regularly measured 3 ft from an irradiated element in air was about 2000 rem/h 1 month after the reactor shut down. After approximately 2 months, the element had decayed below 1000 rem/h. Apparently, almost no NPRs could maintain fuel at 10 000 rem/h, and only a few can irradiate fuel to give a dose of 1000 rem/h at 3 ft a few months after shutdown.

Task 3. The Technical Feasibility of Providing Tamper-Proof Radiation Detection to Prevent the Theft of Irradiated NPR Fuel

A tamper-proof radiation detector should have the following characteristics.

(1) Alarm at an off-site location if the radiation exceeds a preset level

(2) Alarm at an off-site location if an attempt is made to change the alarm set point or to disable the device

(3) Not be readily shielded

(4) Not interfere with the normal operation of the facility

(5) Offer an advantage to NPR operations as compared to maintaining fuel at 100 rem/h

Additionally, there must be a guard force that will respond to the alarm.

Approximately one dozen companies were asked about the availability of radiation monitors that give an off-site signal and will alarm if an attempt is made to disable the device. Of the six that replied, two or three have on-the-shelf devices that, with slight modifications, will meet the requirements. The devices include internally set alarm points that can be easily modified to alarm if the set point is changed. These radiation detectors can be purchased for approximately $2000.

Most NPRs are in large, high-ceilinged buildings. A radiation detector could be mounted on a high wall or on the ceiling in an area where local shielding for the detector would be difficult to construct. Shielding the detector would require an insider's knowledge of its location, the alarm set point, and the activity of the fuel. In addition, local shielding (shadow) would be rendered ineffective by scattered radiation.

Most NPRs have radiation monitors in reactor rooms and fuel storage areas. These monitors are designed to indicate high radiation levels and will alarm unless their set points are changed during special operations such as manipulations of fuel or radioactive samples. Typically, these monitors are set to alarm at 10 to 100 mrem/h and are located at reactor floor level.

A detector 30 ft above floor level set to alarm at 10 to 100 mrem/h should not be inconvenient during normal operations. Specifically, a source at ground level that gives a dose rate of 1 to 10 rem/h at 3 ft would be required to trigger this alarm. Lower set points could also be used. The proposed irradiation history described in Sec. II, Alternative 5 gives this dose rate.

A tamper-proof radiation detector alarming at a security office is an improvement over intrusion alarms and motion detectors because the radiation detector will not allow a defeat of its purpose at the site. Motion detectors and intrusion alarms can be turned off with key switches at the site, whereas tamper-proof radiation detectors cannot. There may be cases when the facility operator wishes to deactivate the radiation detector. This action could be accompanied by a coded phone call (with a call back) to the off-site security office and be allowed only during normal working hours. Thus a new and different level of security can be provided by a tamper-proof radiation alarm.

Task 4. Evaluation of the Physical Separability of Fuel Elements Before the Theft of Various NPR Fuels

In this case, physical separability refers to the breakdown of a fuel element assembly into fuel elements, each of which would give a lower dose rate than the whole. The chemical dissolution of fuel is not considered. Three principal items are of concern:

(1) plate-type fuel element assemblies normally containing 10-20 plate-type fuel elements, each swaged into end pieces;

(2) four-rod cluster TRIGA fuel assemblies; and

(3) special containers that may be constructed to contain elements that do not meet the self-protection criteria.

In some cases, a facility may have lightly loaded irradiated elements (control-rod fuel or special experimental elements) that cannot be made as radioactive as normal elements. To meet the 100 rem/h criterion for the container as a whole, these elements may be assembled with a more radioactive one in a special container that is not easily separable.

In all cases, to achieve significant dose reduction, the fuel element assembly must be separated underwater, and the fuel plates or rods removed individually. This would require the design of special tools that could impart significant forces to fuel assemblies while operating under water. For example, in the TRIGA four-rod cluster, the top of each pin is supported by a spacer that is bolted in place, and each pin is screwed into a bottom plate. Two bolts must be removed, and each pin must be unscrewed.

A significant point about the separability of the fuel in an element is not whether it can be done, but what is gained by the adversary. He does not gain a reduction in dose to himself because, although each piece is not as radioactive as the whole, he must handle many more pieces. The time to remove the fuel will be increased, and the total dose will remain essentially the same. Furthermore, the possibility of detection by the reactor facility security force is increased because the time spent in the facility will be increased by the actions of separating and handling the pieces.

In our opinion, to disassemble fuel element assemblies is not practical. Disassembly would neither make the fuel significantly easier to handle nor lower the dose. Separating the fuel elements remotely would also be very difficult and could significantly increase the time for the theft.

Task 5. The Appropriateness of Using Radiation Level Based on a Deterrence Rather Than an Incapacitating Dose

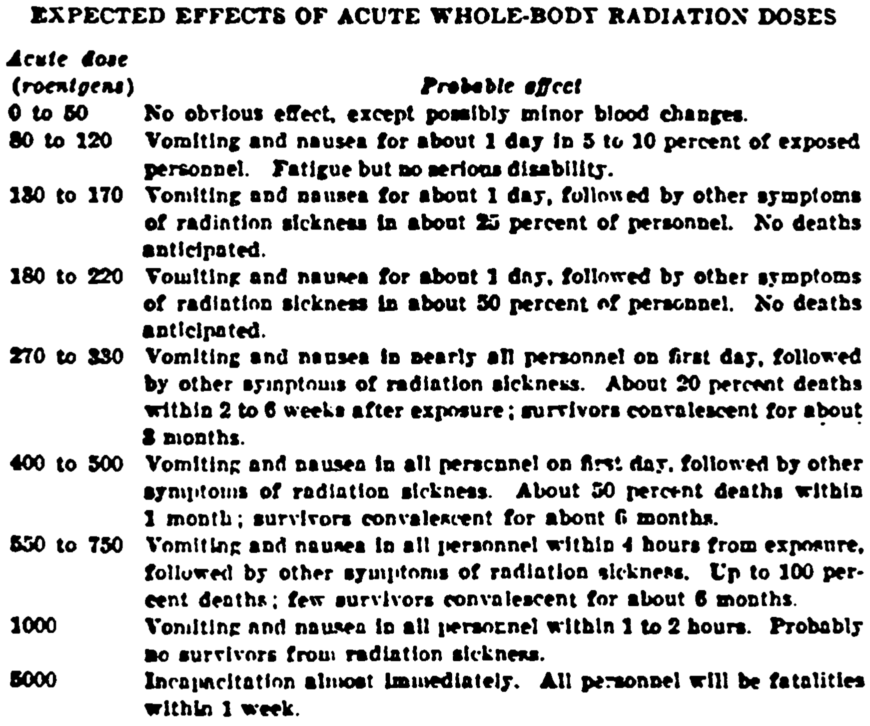
Deterrence is difficult to quantify. An adversary group would be uncertain about the activity level of the fuel, the dose the group will receive, and the effect of the radiation on the group. That radioactive fuel can be a powerful deterrent is shown by public concern when even small amounts of radioactivity are released from power plants. This feeling is likely to be present to some degree in the adversaries, and the knowledge that the fuel was irradiated in recent months could be a sufficient deterrent. If we give the adversary the intelligence to perform the theft, we must also give him the intelligence to be aware of the radiation level and the physiological effects of the radiation.

Fig. 1. Radiation dose vs effect.

The dose required to produce death or some degree of radiation sickness in a given percentage of individuals irradiated is shown in Fig. 1.[3] The doses are given in roentgens, but for all practical purposes can be given in rads, as the errors associated with the curves exceed the difference between the exposure and absorbed doses. The reference is 20 yr old, but still reflects the present day thinking on the acute radiation syndrome.

The dose required to cause death in 10, 50, and 90% of those irradiated is approximately 300 R, 450 R, and 600 R, respectively. These doses are referred to now as the LD-10_{30}, LD-50_{30}, and LD-90_{30} doses. With the now accepted value of 500-600[3,4] rem for LD-50_{30}, but the still-accepted value of 300 rem for LD-10_{30}, these curves have too large a slope, and the LD-50_{30} and LD-90_{30} values should be shifted upward by 50 to 100 R.

TABLE I



EXPECTED EFFECTS OF ACUTE WHOLE-BODY RADIATION DOSES

Acute dose (roentgens)	*Probable effect*
0 to 50	No obvious effect, except possibly minor blood changes.
80 to 120	Vomiting and nausea for about 1 day in 5 to 10 percent of exposed personnel. Fatigue but no serious disability.
130 to 170	Vomiting and nausea for about 1 day, followed by other symptoms of radiation sickness in about 25 percent of personnel. No deaths anticipated.
180 to 220	Vomiting and nausea for about 1 day, followed by other symptoms of radiation sickness in about 50 percent of personnel. No deaths anticipated.
270 to 330	Vomiting and nausea in nearly all personnel on first day, followed by other symptoms of radiation sickness. About 20 percent deaths within 2 to 6 weeks after exposure; survivors convalescent for about 3 months.
400 to 500	Vomiting and nausea in all personnel on first day, followed by other symptoms of radiation sickness. About 50 percent deaths within 1 month; survivors convalescent for about 6 months.
550 to 750	Vomiting and nausea in all personnel within 4 hours from exposure, followed by other symptoms of radiation sickness. Up to 100 percent deaths; few survivors convalescent for about 6 months.
1000	Vomiting and nausea in all personnel within 1 to 2 hours. Probably no survivors from radiation sickness.
5000	Incapacitation almost immediately. All personnel will be fatalities within 1 week.

The various sickness symptoms produced at lower doses are shown in Table I.[3]

The term "incapacitating dose" is poorly defined. Several authors state that the acute radiation syndrome does not incapacitate until the acute dose reaches approximately 5000 rad.[4-6] Even at this level, we have no guarantees that a person would not be able to complete his assigned task. In several cases individuals received acute doses of this level or higher and did not immediately become incapacitated.[7]

(1) LASL, August 1945. A reflector was being stacked around a plutonium core when one of the pieces slipped, making the assembly superprompt critical. A burst of 10^{16} fissions gave the worker an exposure of approximately 800 rd. The worker unstacked the assembly, making it subcritical. He died 28 days later.

(2) LASL, May 1946. A beryllium-reflected plutonium metal system was being demonstrated to several people. The upper beryllium hemisphere slipped, giving a fission burst of 3×10^{15} and giving the operator a dose of approximately 900 rd. The worker was not immediately incapacitated, but died 9 days later.

(3) LASL, December 1958. While a physical inventory was being performed on a plutonium solution process line, the solution became reflected when a mechanical stirrer rearranged different stratified phases into a critical configuration. The system became superprompt critical, releasing approximately 4×10^{17} neutrons. A worker received approximately 12 000 rd. Whether he was immediately incapacitated is unclear, but he died 36 h later.

(4) Wood River Junction, July 1964. A concentrated uranyl nitrate solution was hand-poured into a geometrically unsafe container at the scrap recovery plant. A burst of 10^{17} fissions gave the worker a dose of 10 000 rd. The worker was knocked to the floor, but got up and ran from the area to an emergency building 200 yds away. He died 49 h later.

(5) Vinca, Yugoslovia, October 1958. The accident occurred during a planned subcritical operation of the unreflected natural uranium-heavy water critical facility. The detecting chambers had saturated, and the assembly power increased undetected to a very high level. Six workers received doses of 400, 700, 850, 850, 850, and 1100 rd. They were not immediately incapacitated. The worker receiving 1100 rd died; the others survived. All of these individuals were treated medically using specialized blood transfusion techniques.

In an article in Scientific American[6] on the neutron bomb, Kaplan discusses the concept of incapacitating dose as follows.

Radiation doses are measured in rads, 1 rd being the absorption of 100 ergs of energy per gram of any material. If tactical nuclear weapons are to be useful in a war, they must kill their intended victims as quickly as possible. Immediate permanent incapacitation, according to recent US Government tests conducted with mammals, requires 8000 rd. Because modern tanks have a radiation-protection factor of roughly 0.5, tanks must be exposed to 16 000 rd in a short period of time. However, the NATO military doctrine has recently been revised to read that "immediate transient incapacitation," which requires only 2500 to 3500 rd (or, given tank protection, 5000 to 7000 rd), may be sufficient to neutralize invaders for military purposes.

Within 5 min, a person exposed to 8000 rd is incapacitated, and he remains incapable of performing physically demanding tasks until his death, which occurs within 1 or 2 days. A dose of 3000 rd also incapacitates a person within 5 min, but the victim may partially recover within 30 min; however, the dose is still fatal and he will die 4 to 6 days later. Although he may also remain helpless, he may not. These values are consistent with those observed in the Stratton document.[7]

Apparently, to have close to an immediately incapacitating dose, the dose rate per element must reach at least several thousand rem per hour at 3 ft. Based on the examples cited earlier from Stratton's document, a dose rate of 10 000 rem/h would probably be necessary to assure this. We previously noted that increasing the defined self-protection value above 1000 rem/h at 3 ft would be beyond the capability of nearly all NPRs for any significant decay times. Therefore we conclude that we must consider a radiation level based on deterrence or on detection rather than on an incapacitating dose.

Task 6. Estimation of the Quality and Quantity of SNM That Will be Allowed Relative to the Definition of Formula Quantity

As indicated in 10 CFR Part 73, the regulations apply to "any site or contiguous sites subject to control by the licensee who possesses uranium-235 (contained in uranium enriched to 20 percent or more in the U-235 isotope), uranium-233, or plutonium alone or in any combination in a quantity of 5,000 grams or more computed by the formula, grams = (grams contained in U-235) + 2.5 (grams U-233 + grams plutonium)."[1]

The formula puts the same significance on 20% enriched fuel as it does on 93% enriched fuel. During the NRC/NPR licensee meeting held at the University of Michigan in September 1978, Koelling [8] showed the variation of critical mass with enrichment. The functional relationship between critical mass and enrichment has also been well documented in other sources.[9,10] A very close function has been previously used by the NRC in its definition of "effective kilograms." There is little doubt that this variation should be used in any criterion related to the construction of a critical device.

In the regulations, the dose level is given without reference to the quantity of ^{235}U. The formula quantity of 5 kg of SNM and 100 rem/h at 3 ft are not connected in any way. Five kilograms with a dose rate of 100 rem/h are treated in the same manner as ten 0.5 kg sources, each with a dose rate of 100 rem/h. In the latter case, a person would have to handle all of the pieces of SNM and be exposed to 10 times the dose that would be involved in the former case. Therefore the amount of fuel per fuel element should logically be considered in the self-protection criterion.

II. ALTERNATIVES

A. Exemption Based on Integrated Dose

A rule can be written that would allow each facility to demonstrate that an adversary would receive a specified integrated dose while removing a certain quantity of fuel. The greatest advantage of this rule is that it could be written to allow flexibility in dose estimates based on the facility design. Considering the wide differences in facility design, the rule would be advantageous for those sites having a large distance between the fuel and the location of the removal vehicle. The dose received by an adversary depends on this distance as shown earlier. If a licensee wished to increase the time needed for transfer, barriers, doors, or any other hindrance could be used instead of increasing the distance.

The integrated dose alternative has very little physical significance. This dose could be based on the amount of radiation required to trip an alarm, a dose required to give the adversary a variety of physical symptoms, or an incapacitating dose. These options range in dosage from approximately 1 rem up to 10 000 rem, although the higher values would be very difficult or impossible to obtain in NPRs.

In addition, if the integrated dose was set at a level that produces higher absorbed doses than those given for the current fuel dose-rate scenarios, the higher level would strongly conflict with the As-Low-As-Reasonably Achievable (ALARA) rule. In fact, the self-protection rule and the ALARA rule are in conflict at any level.

B. Exemption Based on the Detection

A rule can be written that will allow each facility to ensure that an alarm signal will be transmitted to a security force if exempted fuel is moved from the facility. The alarm signal can be triggered by any one of several actions such as a high radiation signal, motion of a crane that is required to move shielding blocks, motion detectors, intrusion alarms, and so on. The facility must demonstrate that the alarm signal cannot be overridden by the adversary group.

We reemphasize that a tamper-proof radiation detector alarming at a security office is an improvement over intrusion alarms and motion detectors because the radiation detector will not allow a defeat of its purpose at the site.

A facility may also use other detection methods. For example, some NPRs keep fuel in shielded storage pits or in reactors that are encased in concrete. Access to these areas requires that massive concrete blocks be moved with a facility crane. It would be easy to lock out the crane or to provide a signal that will alarm in a security office if the crane is moved during off hours, which would provide an adequate deterrent. Provisions would be made to prevent the use of a portable crane by the adversary group. This should not be difficult because the use of a portable crane would extend the time the group spends in the facility and would probably require using a large access door. Each facility would be required to prove that the proposed system is adequate to allow exemption of the fuel.

Other facilities might use intrusion alarms, motion detectors, and so on. The facility must demonstrate that the alarm system it uses is tamper-proof.

C. Retain the 100 rem/h Exemption but Give Credit for Fuel Enrichment and Mass

The rule as it is now written makes no provision for fuel form, enrichment, or the connection between the dose rate and the quantity of fuel. The fallacy implied in this omission is that the dose to an adversary group would be the same if it had to move many elements, each reading 100 rem/h, as if it had moved only a few elements at the same dose rate.

This can be corrected by making the exemption specific to fuel loading and uranimum enrichment. An example would be to exempt fuel by a formula based on the nominal reactor used in Sec. I :

$$\frac{100\ \text{rem/h}}{175\ \text{g}} \times E^2 = 0.57\ mE^2\ \text{rem/h at 3 ft} \quad ,$$

where E is the fractional enrichment ($1/E^2$ is the approximate slope of the critical mass versus enrichment curve),[9] and m is the ^{235}U mass in grams with a nominal fuel element mass of 175 g. This formula would not significantly change the requirements for some facilities. As an example, for 165-g elements with a 93% enrichment, the dose rate for exemption would be 81 rem/h at 3 ft. The total dose to an adversary group would not be significantly altered with this change, that is, the most likely dose to an adversary would be about 50--100 rem as noted in Sec. I.

This alternative has the advantage of including fuel form in the regulations. It has the disadvantage of penalizing some facilities with greater than 175-g fuel element loadings (shown in Sec. III) by requiring greater than 100 rem/h for their fuel. However, this alternative is also based on the 100 rem/h number, which has no justifiable physical basis in this case. Fuel more radioactive than that which gives a dose rate of 100 rem/h at 3 ft would clearly increase the hazard when spent fuel must be shipped. This problem can be avoided by placing an upper limit, such as 100 rem/h, on all fuel.

D. Retain 100 rem/h Exemption as Presently Specified in 10 CFR 73.67(b) and 10 CFR 73.6 (b)

The obvious advantage of retaining the present 100 rem/h rule is that no action is required. Many NPRs have adjusted their inventories and procedures to accommodate the rule and assume that they will remain in Category II or III. Some have done this by returning fuel to the Department of Energy (DOE) so that their inventories are less than 5 kg, and others have instituted procedures to irradiate and shuffle fuel and measure dose rates.

Retaining the 100 rem/h rule as it is has three obvious disadvantages:

(1) it will retain a rule containing a numerical value that has no physical basis,

(2) it is inconsistant with the ALARA philosophy, and

(3) it increases the potential hazard to the public in the event of sabatoge more than some of the other choices.

The 100-rem/h value was apparently chosen as a deterrent with the idea that an adversary group would receive a sufficiently high dose that it would not be able to complete its mission of removing the fuel. We developed scenarios in the Phase I report in which the most likely total dose to a group is about 100 rem. This dose distributed among several people is not great enough to impair the actions of the group, that is, 100 rem will not make the persons sick enough so that they could not complete the job in a reasonable time. Thus 100 rem/h, although it may be a psychological deterrent, would not be a physical deterrent. To be a physical deterrent to a group of people, the total dose would have to be approximately 10 000 rem, which would necessitate 10 000-rem/h fuel, a level that (as pointed out earlier) no NPR could maintain. Thus retaining the rule would retain a number that has no physical basis and is just a psychological deterrant.

Maintaining reactor fuel with the present self-protection radiation level of 100 rem/h at 3 ft is difficult at many NPRs. Although many facilities have adapted their procedures to keep fuel self-protecting, these procedures involve increased manipulation of fuel and operational schedules designed primarily to keep fuel radioactive. The rule presents particular problems when spent fuel must be shipped. The best time to ship fuel is when its radioactivity level is as low as possible. Under the 100-rem/h rule, it must be shipped before it is allowed to decay below this level. These actions, which require manipulation of very hot fuel, are inconsistent with the NRC-mandated ALARA program. As pointed out earlier, this inconsistency becomes greater if the self-protection level is raised.

The 100-rem/h rule requires that reactors maintain a large inventory of radioactive fission products. In the event of sabatoge, those fission products could be released to the surrounding environs. To minimize the hazard to the public, a facility should keep the fission product inventory as low as possible, which is inconsistent with the present self-protection rule.

E. Exempt Irradiated Fuel

At one time 10 CFR 73.50 exempted all fuel that had been irradiated in a reactor. An exemption for any fuel that had been in an operating reactor has little physical basis. However, an exemption for fuel that has been irradiated to a minimum specified level may be justified in the sense of deterrence. It is a psychological deterrent to an adversary group to know that the fuel is radioactive. However, we do grant that this psychological effect has not been felt as strongly in adversary groups as it has in the general public. An important aspect of the deterrence factor or irradiated fuel is the uncertainty of the effect of the dose on the people involved. Irradiated fuel in a storage area usually contains elements with various irradiation histories. Typically, there will be fuel that is very radioactive and older fuel that has decayed considerably. This mixture causes the total dose a group would receive to be uncertain and is a deterrent to the group.

A proposed exemption for irradiated fuel is exempting all fuel that has been operated in a reactor for at least 1.5 MW-days/kg of ^{235}U in the previous 12 months. The effect of this value will be shown in Sec. III. The 1.5 MW-days/kg provides a radiation level of 1—10 rem/h at 3 ft as described in Sec. I, Task 3.

The principal advantage of this alternative is that it will not require that dose rates be measured. Any time fuel is moved, there is an additional risk of radiation exposure. This is consistent with the ALARA philosophy because it minimizes fuel handling and the possibility of radiation exposure to personnel. This alternative will allow fuel to cool below the 100-rem/h level and reduce the hazard to the public if a sabatoge attempt is made.

Note that although the dose rate may be lower under this proposal, the fuel will still be radioactive, which will help in the recovery of the fuel if it is removed from the facility. Although the dose rate from a single element is less, the dose rate from the number of elements needed to constitute a formula quantity will be significant with respect to detection and recovery.

III. EFFECT

To determine the effect of a change in the regulations, each facility should be considered in detail. We will make some general statements about each of the alternatives and their effect on a few reactors.

A. Exemption Based On Integrated Dose

A general statement about the effect on individual facilities cannot be made without specifying an integrated dose. Even if the rule was specified, the calculation of the integrated dose would be site-specific and beyond the scope of this report.

B. Exemption Based on the Detection of the Movement of Irradiated Fuel

A general statement about the effect on facility operation cannot be made because each facility would select the mode most appropriate for detecting the movement of fuel. This approach should be more in accordance with the ALARA philosophy and have a positive effect on the sabotage threat because in all probability it will allow lower radioisotope inventories. However, it might involve a capital outlay of several thousand dollars for many facilities.

C. Retain the 100 rem/h But Give Credit for the Mass of ^{235}U per Fuel Element and the Fuel Enrichment

The effect of the formula $0.57\ m\ E^2$ rem/h at 3 ft, where m is the grams ^{235}U per fuel assembly and E is the fractional enrichment, has been shown for several types of reactors, and the results are summarized in Table II. The dose rate increases in most of the cases.

TABLE II

EFFECT OF CREDIT FOR QUALITY AND QUANTITY OF FUEL

Reactor	Mass of ^{235}U per fuel assembly (grams)	Enrichment (%)	Calculated Dose[a]
Georgia Tech	190.0	0.93	94.0
Virginia Polytechnic Institute	265.0	0.90	122.0
U. of Virginia	170.0	0.93	84.0
U. of Michigan	140.0	0.93	69.0
National Bureau of Standards	250.0	0.93	123.0
U. of Missouri (Columbia)	780.0	0.93	384.0
Washington State U.	510.0	0.70	142.0
U. of Wisconsin	460.0	0.70	128.0
Texas A M	500.0	0.70	140.0
M I T	450.0	0.93	222.0
Oregon State U.	550.0	0.70	154.0
Union Carbide Corporation	200.0	0.93	99.0

---

[a] Dose 0.57 mE^2 rem/h at 3 ft

D. Retain the 100 rem/h as Presently Specified

The effect on individual facilities may be significant, although many have adapted to the rule. The effect on one facility, the University of Virginia, is included in Sec. V. This would conflict with the ALARA philosophy, and it would have a significant effect on sabatoge and should be examined closely.

E. Exempt Irradiated Fuel

The effect of exempting all fuel that has been operated in a reactor for at least 1.5 MW-days/kg of ^{235}U/yr has been determined for several reactors. The numbers are given in Table III. The only reactor that would immediately be affected is the reactor at Virginia Polytechnic Institute (VPI). For all other reactors considered, the normal number of full-power days per year of operation exceeds the requirement for at least 1.5 MW-days/kg of ^{235}U/yr.

TABLE III
EFFECT OF EXEMPTING IRRADIATED FUEL

Reactor	Power (MW)	Core Loading (Kg ^{235}U)	Normal Operation Full Power Days/Yr	Required Operation[a]
Georgia Tech	5.0	3.01	87	1
VPI	0.1	3.19	42	48
U. of Virginia	2.0	3.3	83	3
U. of Michigan	2.0	4.5	238	3
National Bureau of Standards	10.0	5.7	283	1
U. of Missouri (Columbia)	10.0	6.2	325	1
Washington State U.	1.0	6.7	38	10
U. of Wisconsin	1.0	8.0	Not Available	12
Texas A & M	1.0	8.62	100	13
MIT	4.9	9.0	204	3
Oregan State U.	1.0	11.17	21	17
Union Carbide Corp.	5.0	5.0	325	2

---

[a] Required Operation $= \dfrac{1.5\ \text{MW - days}}{\text{kg } (^{235}\text{U}) - \text{year}} \times \dfrac{\text{kg } (^{235}\text{U})}{\text{Power MW}} \ \dfrac{\text{Full-Power Days}}{\text{Year}}$

IV. EFFECT OF NOT RETAINING AN EXEMPTION

As long as the 5-kg formula quantity value is retained for Category I facilities, an exemption must be retained for irradiated fuel. Some nominal core loadings discussed in an American Nuclear Society text[11] are listed below.

Reactor	Core Loading (Kg)
Union Carbide Corp.	5.0
Georgia Tech	3.0
VPI	3.2
U. of Virginia	3.3
U. of Michigan	4.5
National Bureau of Standards	5.7
U. of Missouri (Columbia)	6.2
Washington State*	6.7
U. of Wisconsin*	8.0
Texas A & M*	8.6
MIT	9.0
Oregon State*	11.6

As is evident from this list, many facilities would be forced to shut down or provide security at the Category I level if an exemption is not retained. Note that the exemption is not used to reduce the level of security to irradiated fuel to a degree less than required by 10 CFR 73.67.

---

*TRIGA FLIP fuel, 70% enriched.

V. EFFECT OF MAINTAINING 100 REM/H AT 3-FT SELF-PROTECTION ON THE UNIVERSITY OF VIRGINIA FACILITY

A. Possibility of Maintaining Fuel At Exempt Dose Rates

Normally the University of Virginia Reactor (UVAR) fuel (typically 3.3 kg) can be maintained at the specified self-protection dose rate of 100 rem/h at 3 ft with the present operating schedule. However, there are some cases when this may not be practical. These are discussed below.

The CAVALIER fuel (presently 2.27 kg) cannot be self protecting. Therefore less than 3 kg (a normal UVAR fuel loading) of excess nonexempt material can be maintained on site.

Apparently, fuel can normally be maintained at self-protecting dose rates to limit the nonexempt inventory to less than 5 kg. However, this may cause operational difficulties and increased radiation exposure to personnel as discussed below. In addition, if the UVAR core is allowed to decay to less than self-protecting levels, it will exceed the allowed 5-kg limit.

B. Cases Where It May Not Be Possible To Maintain Fuel At Self-Protecting Dose Rates

1. Prolonged Reactor Shutdowns. As noted above, the present UVAR operating schedule is adequate to maintain fuel at self protecting dose rates. However, a prolonged reactor shutdown may result in fuel decaying to lower dose rates, so that the fuel is not exempt. A prolonged reactor shutdown could occur for many reasons, but the most likely would result from the failure of required equipment or systems.

To minimize this possibility, the reactor facility would be required to stock many additional components, such as nuclear instruments and control-rod drive mechanisms, so that any failures could be quickly repaired. We estimate that an additional $30 000 would be needed to provide adequate assurance that the required long-lead-time equipment was in stock. Even in this case other unforeseen items (such as a major pool leak) might occur that could not be quickly corrected.

2. Delays in Shipment of Expended Fuel. There is a possibility that a spent-fuel shipping cask could not be scheduled before the fuel decays below the self-protecting levels. The availability of shipping casks is, at best, uncertain. If there is any reactivity remaining in the fuel, it could be reloaded and irradiated. This procedure would take about 1 week, which would interrupt ongoing research programs. In addition, the increased personnel radiation exposures and shipment costs associated with shipping of self-protecting fuel make it undesirable to maintain the specified dose rates during shipment. This is discussed below.

3. Receipt of New Fuel. Receipt of new fuel may be more limiting than the availability of a shipping cask for fuel shipments. The CAVALIER reactor has a loading greater than 2 kg of unprotected fuel. If a new core with more than 3 kg were delivered, the formula quantity would be exceeded until the new core was irradiated. Note that CAVALIER fuel and UVAR fuel are not normally interchangeable. The CAVALIER fuel has flat-plate elements, and new UVAR fuel contains curved plates. Thus the CAVALIER fuel cannot be made self protecting by moving it to the UVAR because of its incompatibility.

4. Lightly Loaded Elements. Some fuel elements have lower uranium loadings than others. For example, the control rod fuel elements contain only

half as much uranium as the normal elements. These elements will decay below the self-protection levels before the rest of the core decays. This is a particularly serious problem because the process of connecting and disconnecting the control rod follower to the fuel is complicated and involves a considerable manipulation of the fuel. The operation increases the possibility of radiation exposure to personnel and conflicts with the ALARA philosophy.

5. Imperfect Fuel Elements. Some fuel elements develop fission product leaks that prevent their further operation in the core. When these elements decay below self-protecting levels, they cannot be reirradiated. To ship even a single element from a reactor requires a shipping cask and the associated security measures (at an estimated cost of about $20 000, which does not include the increased security cost noted below).

C. Effect of Maintaining Fuel At Self Protecting Dose Rates on Normal Reactor Operation

Because UVAR fuel can normally be maintained at self-protecting levels, this requirement affects the reactor operating schedule, manpower requirements, and associated costs.

The normal reactor operating schedule is adequate to maintain the control rod fuel elements at self-protecting dose rates for at least 4 months after they are removed from the reactor. This time depends on the actual operating history of the fuel. Thus the control rod fuel elements must be changed about three times a year to ensure that both sets are maintained at self-protecting levels. Because of the fuel loading procedures, this requires complete removal and replacement of the core, calibration of the control rods, and measurement of rod times.

The core replacement described above requires three people for 1 week. Thus a total of 9 man-weeks of effort and a loss of 3 weeks of reactor operation are required each year to ensure that fuel is maintained at self-protecting levels. In addition, the surveillance items necessary to confirm that fuel is self protecting require an additional 6 man-weeks work per year. This work would cost about $8000/yr and result in the loss of about $20 000 in research funds per year. Thus the total cost of this requirement is about $30 000/yr.

In addition, the extra handling of fuel will increase the reactor staff's total radiation exposure. Although this increased exposure is expected to be small, it is still undesirable. Also, the extra handling increases the probability of having an incident that could result in a significant radiation exposure or damage a fuel element. Both items should be evaluated from an ALARA viewpoint.

D. Impact of Maintaining Fuel At Self-Protecting Dose Rates During Expended Fuel Shipment

Maintaining fuel at self-protecting dose rates will have a significant effect on the personnel radiation exposures and the cost associated with the shipment of expended fuel.

As the UVAR reactor room crane has a capacity of only 5 tons, a shipping cask to handle spent fuel (typically 12--15 tons) cannot be lowered into the reactor pool. All transfers must be made outside the building. To accomplish this, operators must lower the shipping cask into a 12-ft-diam, 12-ft-high tank of water using an auxilliary crane outside the building. The fuel elements are moved one at a time from the reactor pool in a small handling cask (~ 2 tons) to the outside of the building and lowered into the tank beside the shipping cask. The element is transferred to the shipping cask by using handling tools from the top of the tank.

During previous fuel shipments, the fuel was allowed to decay to low levels before shipment. The measured dose rates directly above the fuel element were about 1.5 rem/h when the fuel was in the small transfer cask. Using this method, the maximum exposure to personnel was about 10 mrem.

If this procedure is used for the next fuel shipment in 1980 and the fuel has dose rates of 100 rem/h at 3 ft, the total radiation exposure would be increased by a factor of about 100 to about 1 rem. About 10 people would be exposed to radiation during this operation.

Although these exposures are within the limits allowed by the NRC, they are above those normally experienced by personnel at this facility and are inconsistent with the ALARA philosophy.

In addition, the NRC has recently issued an interim final rule that requires extensive security arrangements for shipping any amount of fuel if it exceeds the 100 rem/h dose rate. The requirements of this new rule include the use of trained armed guards, notification and approval of the planned route by the NRC and local law enforcement agencies, and so on. Although no formal cost estimate has been made on the additional cost of shipments meeting the new requirements, one shipper estimates that transportation costs will increase by a factor of 2 or 3. Again, the shipment of highly radioactive fuel is not consistent with ALARA-preferred exposures because the radiation exposure to the shipper's personnel and the general public will be increased.

E. Effect of Maintaining Fuel At Self-Protecting Dose Rates During Unusual Occurrences

There can be many additional situations where maintaining fuel at self-protecting dose rates is undesirable, but they cannot be evaluated in detail.

In the past it was necessary to drain the UVAR pool to repair a leak. To minimize the personnel exposure during the repair, some of the fuel was transferred to the hot cell for storage. If this occurred today, storing all of the fuel in the hot cell could be impractical, and the staff's radiation exposure during transfer would be greatly increased. Thus either the allowed radiation exposures would be significantly increased or a prolonged shutdown, as discussed in Sec. V. B., would be required.

A second, greater concern is the effect of sabotage when higher dose rates are involved. The probability of attempted sabotage is as great as the possibility of theft of SNM. Although many of the controls designed to minimize the possibility of theft will also deter sabotage, both situations should be considered when evaluating the desirability of maintaining fuel at high dose rates.

REFERENCES

1. Code of Federal Regulations, Title 10, Part 73 (U.S. Government Printing Office, Washington, D.C.), p. 520-522.

2. T. G. Williamson, "Determination of Dose Rate from Research Reactor Fuel Elements," Univ. of Virginia report UVA/532177/NEEP79/101 (June 1979).

3. S. Glasstone, Ed. The Effects of Nuclear Weapons (U.S.A.E.C., Washington, D.C., 1962).

4. K. Z. Morgan and J. E. Turner, Principles of Radiation Protection (John Wiley and Sons, Inc. 1967).

5. E. L. Saenger, Ed., Medical Aspects of Radiation Accidents (U.S.A.E.C., Washington, D.C., 1967).

6. F. M. Kaplan, "Enhanced Radiation Weapons," Scientific American 5, 238 (1978).

7. W. R. Stratton, "A Review of Criticality Accidents," Los Alamos Scientific Laboratory report LA-3611 (January 1967).

8. J. J. Koelling, "Lower Enrichment Credit," Nonpower Reactor Licensee Meeting, Ann Arbor, Michigan (September 1978).

9. J. T. Thomas, Ed., Nuclear Safety Guide, Rev. 2, Oak Ridge National Laboratory report TID 7016 (June 1978).

10. H. C. Paxton, J. T. Thomas, D. Callihan, and E. B. Johnson, "Critical Dimensions of Systems Containing U-235, Pu-239, and U-233," Los Alamos Scientific Laboratory and Oak Ridge National Laboratory report TID-7028 (June 1964).

11. R. R. Burn, Ed., Research, Training, Test and Production Reactor Directory (American Nuclear Society, La Grange Park, 1980).

NRC FORM 335
(7-77)

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

1. REPORT NUMBER *(Assigned by DDC)*
NUREG/CR-2492
LA-9213-MS

4. TITLE AND SUBTITLE *(Add Volume No., if appropriate)*
Special Nuclear Material Self-Protection
Criteria Investigation
Phases I and II

2. *(Leave blank)*

3. RECIPIENT'S ACCESSION NO.

7. AUTHOR(S)
J. J. Koelling and E. W. Barts

5. DATE REPORT COMPLETED
MONTH December
YEAR 1980

9. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, New Mexico 87545

DATE REPORT ISSUED
MONTH January
YEAR 1982

6. *(Leave blank)*

8. *(Leave blank)*

12. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
Division of Safeguards
Office of Nuclear Material Safety and Safeguards
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

10. PROJECT/TASK/WORK UNIT NO.

11. CONTRACT NO.
FIN A7146

13. TYPE OF REPORT
Formal Final Technical Report

PERIOD COVERED *(Inclusive dates)*

15. SUPPLEMENTARY NOTES

14. *(Leave blank)*

16. ABSTRACT *(200 words or less)*

The report was prepared to assist the NRC in reviewing the technical basis for the 100 rem per hour self-protection exemption from physical security requirements as allowed in 10CFR73.6. The report analyzes the risks and difficulty of stealing fuel from a non-power reactor core, the feasibility of detecting the theft of irradiated fuel, and the radiation dosages necessary to incapacitate a potential thief. Alternatives to the current 100 rem per hour exemption are proposed and evaluated.

17. KEY WORDS AND DOCUMENT ANALYSIS

17a. DESCRIPTORS

17b. IDENTIFIERS/OPEN-ENDED TERMS

18. AVAILABILITY STATEMENT
Unlimited

19. SECURITY CLASS *(This report)*
Unclassified

21. NO. OF PAGES

20. SECURITY CLASS *(This page)*
Unclassified

22. PRICE
S

NRC FORM 335 (7-77)

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

POSTAGE AND FEES PAID
U.S. NUCLEAR REGULATORY
COMMISSION

U.S. MAIL