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**HAZARD POTENTIAL OF THE LA HAGUE SITE:
An Initial Review**

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Abstract

This report provides an initial review of the hazard potential of COGEMA's La Hague site. Here, the word "hazard" refers to unplanned injury to workers or members of the public, or unplanned damage to the environment. The report describes the La Hague site and COGEMA's proposed changes to the operation of the site. Then, the report sets forth the requirements for a thorough analysis of La Hague's hazard potential, and contrasts those requirements with the present base of information about La Hague's hazards. Finally, the report provides a preliminary identification of the major sources of hazard at La Hague.

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About the author

This review was prepared by Gordon Thompson, who is the executive director of IRSS. Thompson studied and practised engineering in Australia, was based in the UK for the period 1969-1978, and received a DPhil in applied mathematics from Oxford University in 1973. He has been based in the USA since 1979. Dr Thompson has extensive experience in assessing the hazards associated with nuclear facilities, and in identifying alternative designs and modes of operation that can reduce a facility's hazard potential. In addition, Thompson has worked on a range of other subjects related to energy, the environment and international security.

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1. Introduction

The French company, COGEMA, performs nuclear fuel reprocessing and related activities at the La Hague site. Activities at the site, and transport operations associated with the site, create the potential for various hazards. Here, the word "hazard" refers to unplanned injury to workers or members of the public, or unplanned damage to the environment. Effects of this kind are distinct from the effects of planned events, such as routine releases of radioactivity to the environment, in at least two respects. First, unplanned events cannot be controlled and regulated in the same manner as planned events. Second, unplanned events can have effects which are much more severe than the effects of planned events.

This report provides an initial review of the hazard potential of the La Hague site. At present, there is not sufficient information in the public domain to perform a thorough review of this subject. Moreover, due to the complexity of the La Hague site, a thorough review would require time and funding considerably larger than the time period and funding that were available for this initial review. As a further reflection of time and funding limitations, transport operations are not addressed here.

Section 2 of this report gives an overview of the La Hague site and COGEMA's currently-proposed changes to site operations. Then, Section 3 sets forth the requirements for a thorough analysis of La Hague's hazard potential. Appendix A, which addresses the importance of openness and accountability in hazard assessment, supports Section 3. The currently available base of information about La Hague's hazard potential is summarized in Section 4. This base of information does not meet the requirements set forth in Section 3. Nevertheless, available information allows a preliminary identification of major sources of hazard at La Hague, as described in Section 5. Appendices B and C support Section 5. Conclusions are presented in Section 6, and a bibliography is provided in Section 7.

2. The La Hague site and COGEMA's proposed changes

2.1 An overview of site activities at present

At present, reprocessing of spent nuclear fuel is the principal activity at the La Hague site. A secondary activity, which is growing in importance at the site, is the storage of spent fuel. If the rate of reprocessing declines, as many observers recommend or expect, then storage of spent fuel may become the principal activity at the site.

In support of La Hague's present mission as a reprocessing center, a wide variety of related activities occur at the site.¹ These activities include spent fuel storage and many other functions. A brief overview of site activities is provided here.

Spent nuclear fuel arrives at La Hague in shipping casks. The fuel is removed from the casks under wet or dry conditions, and is then transferred to water-filled pools where it is stored for a period of years. Then, the fuel is reprocessed in the UP2 plant or the UP3 plant. These reprocessing plants yield two nominally useful products that can be transported away from the La Hague site -- plutonium and reprocessed uranium.² The uranium can be transported away from the site as uranium oxide (a solid) or uranium nitrate (a liquid). The plutonium can be transported away from the site as plutonium oxide or as a mixture of plutonium and uranium oxides.

In addition to yielding nominally useful products, the reprocessing plants generate a variety of radioactive wastes. These wastes are treated on the site, yielding three types of ultimate waste stream. First, some radioactive wastes are incorporated into solid packages which are stored at the site or transported away from the site. Second, some radioactive wastes in liquid form are discharged to the ocean through a pipeline. Third, some radioactive wastes in gaseous or vapor form are discharged to the atmosphere through vent stacks.³

Reprocessing is a chemical engineering operation. Thus, a variety of chemicals such as nitric acid and organic solvents are delivered to the site. Chemical wastes leave the site via atmospheric or liquid discharges, or in packages prepared for transport. In some instances, chemical and radioactive wastes are present in the same waste stream.

The primary facilities at La Hague require services such as electricity, steam and water. These services are provided by support facilities. Also, the site houses laboratories, offices, workshops and facilities to support the workforce.

The site's primary facilities -- spent fuel pools, reprocessing plants, facilities for treating and managing radioactive wastes -- are interconnected in numerous ways. Materials can be moved among those facilities in liquid form (through pipelines or transfer vessels), in gaseous form (through ducts) or in solid packages.

2.2 The reprocessing plants

¹ COGEMA, 1999.

² Plutonium and reprocessed uranium are nominally useful products in the sense that they can be used in reactor fuel. Plutonium can be used in mixed-oxide (MOX) fuel, while reprocessed uranium can be re-enriched and used in uranium oxide fuel or MOX fuel. However, the economic merit of these uses is questionable, and the use of MOX fuel has adverse implications for international security.

³ The liquid and gaseous/vapor discharges may contain small, solid particles.

In 1966 the UP2 reprocessing plant began operating at La Hague, and this plant reprocessed metallic fuel until 1987. Oxide-fuel reprocessing began at UP2 in 1976, after installation of a modified head-end facility (the HAO facility). Thus, between 1976 and 1987, UP2 reprocessed both metallic and oxide fuel. In 1994, new plant components became operative at UP2. With use of these components, the plant's nominal capacity rose from 400 tonnes of fuel per year to 800 tonnes per year. In this mode of operation, the plant is known as UP2-800.⁴

It is said that the UP2 plant can also operate in two other modes.⁵ First, only the old plant components can be used, providing a nominal reprocessing capacity of 400 tonnes of fuel per year. In that mode of operation, the plant would be known as UP2-400. Second, both the old and the new plant components can be used simultaneously. In that mode of operation, the UP2 plant would consist of two sub-plants -- the UP2-800 plant and the UP2-400 plant -- which would operate in parallel. Presumably, the combined nominal reprocessing capacity of these two sub-plants would be 1,200 tonnes of fuel per year.

A new reprocessing plant known as UP3 was commissioned at La Hague in 1989. UP3 was designed to reprocess oxide fuel, and has a nominal capacity of 800 tonnes of fuel per year. Currently, UP3 and UP2-800 are reprocessing oxide fuel from light-water reactors.⁶

A small-scale reprocessing plant -- the AT1 facility -- operated at La Hague between 1969 and 1979, reprocessing fast-reactor fuel. Some fast-reactor fuel was reprocessed at UP2 between 1979 and 1984. Mixed-oxide (MOX) fuel was reprocessed at La Hague, presumably in UP2, in 1992 and 1998. In the current period, preference is given to the reprocessing of uranium oxide fuel instead of MOX fuel.⁷

2.3 Spent fuel storage pools

At La Hague, spent fuel is stored exclusively in water-filled pools. Dry storage technology, used for spent fuel storage at many other nuclear sites, is not used at La Hague. There are said to be five spent fuel storage pools at La Hague, with a combined capacity of 14,390 tonnes of fuel.⁸ As explained in Section 2.7, four of these pools, with a combined capacity of 13,990 tonnes of fuel, are said to be located at the UP2-800 and UP3 plants. Thus, the fifth pool -- which is said to serve the HAO head-end facility at UP2-400 -- presumably has a capacity of 400 tonnes.

2.4 Treatment and management of radioactive wastes

⁴ Albright et al, 1997, pp 165-172; Deroubaix, 1999.

⁵ IRSS has no documented evidence about these potential modes of operation.

⁶ Albright et al, 1997, pp 165-172; Deroubaix, 1999.

⁷ Ibid; Rivasi, 2000.

⁸ Goumondy and Marciano, 1997.

While reprocessing is the principal activity at La Hague, the treatment and management of radioactive wastes is also a major undertaking. When spent nuclear fuel enters the site, its inventory of radioactive material is almost entirely contained within the fuel pellets and rods. (There is also a comparatively small amount of radioactive contamination on the outer surfaces of the fuel rods.) Reprocessing mobilizes the radioactive material that had previously been contained within the fuel, creating a need for the treatment and management of radioactive wastes.

HLW in liquid and solid forms

Most of the radioactive material in the fuel ultimately becomes high-level radioactive waste (HLW). When it is initially produced, HLW is in the form of a liquid. Specifically, it is a nitrate solution that is self-heating as a result of radioactive decay. Liquid HLW is an extremely hazardous material that is stored in stainless steel tanks which require constant cooling, agitation and supervision.

After a period of storage as a liquid, HLW is transferred to a vitrification facility where it is incorporated into a glass matrix inside steel canisters. Those canisters are then stored in air-cooled vaults. Vitrified HLW poses a lower hazard potential than does liquid HLW, because radioactive material is less readily mobilized from vitrified HLW. Air-cooled vaults for storing vitrified HLW can be made passively safe, in the sense that cooling of the canisters is driven entirely by natural convection of air. At La Hague, some of the vitrified HLW vaults are cooled by natural convection of air, while others require forced (fan-driven) circulation.⁹

There are undocumented reports that the stock of liquid HLW at La Hague has been reduced to a comparatively small "buffer volume". If those reports are true, then the liquid HLW stored at La Hague poses a lower hazard potential than is posed by liquid HLW at the Sellafield site in the UK. At Sellafield, about 1,300 cubic meters of liquid HLW now awaits vitrification, and this volume is expected to rise over the next several years.¹⁰ For La Hague, there is no publicly available information about the stock of liquid HLW. La Hague's stock of vitrified HLW, at the end of 1998, was 1,383 cubic meters.¹¹

Other radioactive wastes

At La Hague, low- and intermediate-level radioactive wastes emerge from a variety of treatment processes and are incorporated into solid packages of three different kinds. They are placed in a cement matrix or a bitumen matrix, or are compacted inside a canister.¹² Each type of package can be transported away

⁹ COGEMA, 1999.

¹⁰ NII, 2000.

¹¹ Rivasi, 2000.

¹² In recent years, comparatively small amounts of radioactive waste have been packaged in a bitumen matrix.

from the site. In the past, some packages have been transported to an adjacent burial facility -- Centre de Stockage de la Manche -- but this facility is now closed.

Radioactive wastes that are not packaged in solid form are either discharged in liquid form to the ocean through a pipeline, or are discharged to the atmosphere through vent stacks. Liquid and gaseous effluents from site facilities are typically not discharged directly to the environment, but are passed through treatment plants where some of their radioactive content is removed and directed to a solid waste stream. For example, the STE2 and STE3 plants treat radioactive liquid effluents from site facilities.

2.5 General site layout

The La Hague site is a roughly rectangular site whose long axis approximately follows the ridge of a peninsula. Beyond each of the long sides of the site, the land elevation generally declines from the site to the ocean. COGEMA has published overall plan views of the site, but has not published elevation views or other details of the structures on the site.¹³ A site visit was not conducted as part of this review. Available information suggests that substantial parts of the structures are above ground level. Thus, for example, the water surface in the spent fuel pools may be above ground level. Design details such as this can be significant in determining a facility's hazard potential.

2.6 Installations Nucleaires de Base

For administrative purposes, facilities at La Hague are categorized as Installations Nucleaires de Base (INB). Thus, the central part of the UP2-800 plant is known as INB 117, while the UP3 plant is known as INB 116. The HAO head-end facility at UP2 is known as INB 80, while another part of UP2 is known as INB 33. The STE3 plant, which treats radioactive liquid effluents from site facilities, is known as INB 118.

2.7 Changes proposed by COGEMA

COGEMA is seeking to modify its authorizations to operate INB 116, INB 117 and INB 118. Specifically, COGEMA seeks to make four major changes:¹⁴

(a) Increased reprocessing capacity

COGEMA seeks to increase the authorized capacity of each of the reprocessing plants UP2-800 (INB 117) and UP3 (INB 116) from a nominal 800 tonnes of fuel per year to 1,000 tonnes per year.¹⁵ This 25 percent capacity increase is to be achieved without any significant modification of either plant.

¹³ COGEMA, 1999.

¹⁴ IPSN, undated; COGEMA, 1999.

¹⁵ Apparently, COGEMA has agreed with the French government that the combined throughput of UP2-800 and UP3 will not exceed 1,700 tonnes of fuel per year. It is said that the UP2-400 plant could achieve a throughput of 400

(b) Increased storage capacity in spent fuel pools

UP2-800 (INB 117) has two spent fuel storage pools, which now have a combined capacity of 5,590 tonnes of fuel. COGEMA seeks authority to increase the combined capacity of these two pools to 6,800 tonnes. UP3 (INB 116) also has two spent fuel storage pools, which now have a combined capacity of 8,400 tonnes of fuel. COGEMA seeks authority to increase the combined capacity of these two pools to 10,800 tonnes. Overall, the capacity of the four pools at UP2-800 and UP3 will increase from 13,990 tonnes of fuel to 17,600 tonnes (a 26 percent increase). The capacity increase will be achieved by using a more compact configuration of spent fuel storage, which implies a reduction in the average center-center distance between fuel assemblies.

(c) Expanded range of fuel types to be reprocessed

COGEMA seeks authority to reprocess an expanded range of fuel types in UP2-800 and UP3. This expanded range will include: (i) uranium oxide fuel with a maximum burnup of 75 GW-days/tonne and a maximum pre-burn enrichment of 5 percent; (ii) MOX fuel with a maximum burnup of 65 GW-days/tonne and a maximum pre-burn plutonium content of 20 percent; (iii) fast reactor fuel with a maximum burnup of 150 GW-days/tonne and a maximum pre-burn plutonium content of 45 percent; and (iv) research reactor fuel that may have been highly enriched in uranium-235. At present, UP2-800 and UP3 are not authorized to reprocess high-burnup uranium oxide fuel or the three latter types of fuel.¹⁶

(d) Expanded range of materials to be treated in UP2-800, UP3 and STE3

COGEMA seeks authority to treat a variety of radioactive materials, in solid or liquid form, at the UP2-800 and UP3 reprocessing plants and at the STE3 effluent treatment plant. These radioactive materials may come from other facilities on the La Hague site, or from other sites.

3. Requirements for a thorough analysis of La Hague hazards

3.1 The purpose of a hazards analysis

It is assumed here that COGEMA and the relevant agencies of the French government should seek a thorough understanding of the hazard potential of the La Hague site. The search for understanding should not proceed out of mere curiosity. Instead, potential hazards should be understood so that they can be

tonnes of fuel per year while UP2-800 and UP3 are operating. Thus, it appears that the combined reprocessing throughput at La Hague could be as high as 2,100 tonnes of fuel per year.

¹⁶ UP2-800 and UP3 are now authorized to reprocess uranium oxide fuel with a maximum burnup of 33 GW-days/tonne and a maximum pre-burn enrichment of 3.5 percent. It is said that fuel with a maximum burnup of 45 GW-days/tonne and a maximum pre-burn enrichment of 3.7 percent has been reprocessed at La Hague, in apparent violation of the authorization.

managed, thereby limiting or reducing the probabilities and consequences of hazardous events.

Moreover, an effective process for managing La Hague's hazard potential would necessarily involve the ongoing identification and assessment of alternative designs and modes of operation that could reduce the hazard potential. Thus, hazards analysis should not be a static function, but should be integrated with an ongoing program of hazards management and reduction.

Section 3.5 shows that openness and accountability are essential ingredients of a hazards analysis. In addition, democratic processes are essential to effective decision-making about the adoption of alternative designs or modes of operation. Authoritarian decision-making may be convenient in the short run, but has been proven to be inefficient in the long run.

3.2 Types of hazard

In this review, the word "hazard" refers to unplanned injury to workers or members of the public, or unplanned damage to the environment. The injury or damage could arise from activities at the La Hague site itself, or from transport operations associated with the site. (As mentioned in Section 1, due to time and funding limitations this review does not address transport-related hazards.) Our use of the word "hazard" does not imply that planned events at La Hague, such as routine releases of radioactivity to the environment, are harmless. Other words can be used to describe the adverse effects of planned events.

The central purpose of the La Hague site is to separate plutonium from spent nuclear fuel. Many observers argue that this activity has adverse effects on international security because separation of plutonium promotes the proliferation of nuclear weapons. The merits of that argument are not addressed here. For the purposes of this review, the word "hazard" does not encompass adverse effects on international security.

For the purposes of this review, unplanned injury or unplanned damage to the environment could involve: (a) release of radioactive material or a hazardous chemical to the environment (air, ground water or surface water); (b) exposure of persons (members of the public, or site personnel) to higher-than-permitted levels of radiation or hazardous chemicals; or (c) exposure of persons or property to the effects of fire or explosion.

By definition, these events would be unplanned. That is, there would be no specific intent by COGEMA that such an event will occur. However, the potential for such an event is inherent in many of the activities and operations performed by COGEMA. At the La Hague site there are large inventories of radioactive materials in readily mobilizable forms (e.g., liquids). A variety of scenarios can be envisioned whereby these materials are released from their intended locations. Also, at La Hague there are substantial inventories of chemically reactive materials (e.g., organic solvents) that could provide fuel for fires or explosions. A

fire or explosion could pose a direct hazard to persons or property but, more significantly, it could provide a mechanism for releasing radioactivity from its intended location.

Although the potential for a hazardous event is inherent in the activities and operations performed by COGEMA, the occurrence of an actual event would result from the occurrence of one or more triggering events. Relevant triggering events include natural forces (e.g., earthquakes), human error, equipment failure, and acts of malice or insanity.

Often the combination of events that leads to a hazardous outcome is described as an "accident". However, this is an imprecise term that may give a false impression of randomness. Experience shows that the frequency and nature of "accidents" within a system are reflections of system-wide properties.¹⁷ Moreover, the use of alternative designs and modes of operation can alter both the probabilities and the consequences of accidents within a system.

3.3 Relationships between design specifications and hazard potential

When a nuclear facility is designed and its mode of operation is planned, the designers will specify a range of conditions within which the facility is intended to operate. For example, a modern nuclear facility will typically be designed to withstand a specified intensity of earthquake. As another example, a cooling system in a nuclear facility might be equipped with three pumps, but be designed so that the system can operate while two pumps are out of service.

If a facility is designed, constructed and operated according to its specifications, then a hazardous event will not occur unless the facility experiences conditions outside the specified range. In other words, the facility is "safe" within the specified range of conditions. Often, the organization operating a nuclear facility will prepare a "safety report" that describes the manner in which this type of "safety" is achieved. In many cases, the safety report will describe potential "design-basis accidents" at the facility.¹⁸ These are potential accidents in which there occur specified human errors or equipment failures while all other aspects of facility operation are normal. Thus, design-basis accidents are a subset of the set of potential hazardous events at a nuclear facility.

Practical experience and technical analysis show that nuclear facilities can experience conditions outside the range specified during their design. Errors may be made in design, construction or operation. Malice or insanity may cause unexpected human actions. Natural forces may be greater than anticipated.

¹⁷ See, for example, Perrow, 1984.

¹⁸ As a condition for obtaining an operating license for a nuclear power plant in the USA, each plant licensee must prepare a Final Safety Analysis Report (FSAR), and must regularly update this document throughout the plant's operating life. The FSAR is open to public examination, contains detailed technical information, and describes a set of design-basis accidents.

Equipment failure may exceed the scope assumed for design-basis accidents. Thus, the potential for hazardous events arises. A safety report, as defined above, will not assess this potential. Another type of analysis is needed.

3.4 Probabilistic risk assessment

Over the past three decades, the discipline of probabilistic risk assessment (PRA) has been developed, specifically to understand the potential for hazardous events at nuclear facilities.¹⁹ PRA techniques have been developed to the point where, if properly applied, they provide a good qualitative understanding of the nature of hazardous events, and a good quantitative understanding of some of the consequences of hazardous events. There are, however, intrinsic limits to the accuracy with which PRA techniques can estimate the probability of hazardous events.²⁰

A hazards analysis for La Hague should use state-of-the-art PRA techniques to examine hazard potential on a site-wide basis. Separate analyses of individual facilities would be inadequate, because there are numerous possibilities for interactions among facilities. The site-wide hazards analysis should be subjected to peer review and should be published in toto, with clear descriptions of its assumptions and methodologies.

According to current practice, nuclear facility PRAs are performed at three levels. At Level 1, a PRA will estimate the probability of a specified type of hazardous event (e.g., severe core damage at a reactor). At Level 2, which builds upon Level 1 findings, a PRA will estimate the nature of potential radioactive releases from the facility. In turn, the Level 2 findings can be used in a Level 3 exercise, which will estimate the offsite consequences (health effects, economic effects, etc.) of radioactive releases. For all three levels, a PRA can be performed for "internal" triggering events (equipment failure, operator error, etc.) and for "external" triggering events (earthquakes, fires, etc.).²¹ A "comprehensive" PRA will consider internal and external triggering events, and will be performed to Level 3.

3.5 The need for openness and accountability in a hazards analysis

Any student of a science knows that the culture of science has some key ingredients. Among these ingredients are openness and personal accountability. Peer review is also important. These ingredients are not luxuries or optional extras, but are essential to the pursuit of a thorough understanding.

¹⁹ For nuclear power plants that use light-water reactors, the state of the art for PRA is represented by NRC, 1990.

²⁰ Hirsch et al, 1989.

²¹ In current practice, PRAs typically do not consider triggering events that involve insanity or malice. However, such events could be considered within the analytic framework provided by PRA, with recognition of the intrinsic difficulty of assigning a probability to acts of malice or insanity.

The nuclear industry is often viewed as a science-based industry. Yet, the activities of the nuclear industry are often shrouded in secrecy, decisions or technical findings are reached anonymously, and peer review is lacking. These characteristics are strongly evident in France.

Secrecy and a lack of accountability deprive the public of an effective role in making decisions that relate to the hazard potential of nuclear facilities. Moreover, secrecy and a lack of accountability have an insidious effect inside the nuclear industry. They deprive the industry's managers and regulators of a thorough understanding of the hazard potential of nuclear facilities. They promote complacency, a lack of curiosity, the persistence of unexamined assumptions, and the defense of entrenched positions. Appendix A provides illustrative examples which show how secrecy and a lack of accountability have suppressed the development of a thorough understanding of the hazard potential of nuclear facilities.

In France, as in many other countries, the nuclear industry is rich and politically powerful. Its representatives speak with confidence and apparent authority. A citizen or a political leader may feel too intimidated to question whether the industry's managers and regulators actually have a thorough understanding of the hazard potential of nuclear facilities. Yet, there is a proven method for determining the accuracy of the managers' and regulators' understanding. Applying the method would be simple. The veil of secrecy would be removed from the industry, and opportunities would be provided for independent experts to review the industry's operations and documents.

3.6 Assessing alternative designs and modes of operation

As mentioned in Section 3.1, an effective process for managing La Hague's hazard potential would necessarily involve the ongoing identification and assessment of alternative designs and modes of operation that could reduce the hazard potential. Moreover, decision-making about the adoption of alternatives will be most efficient if done through democratic processes.

Thus, a multi-stage process is needed. First, a hazards analysis for La Hague would be performed for the site on an "as is" basis. This analysis would use PRA techniques. Like all subsequent analyses, this initial hazards analysis would meet scientific standards of openness and accountability. Second, a range of alternative options would be identified. These options could include COGEMA's four proposed changes in the operation of La Hague, as summarized in Section 2.7. Third, a revised hazards analysis would assess the hazard implications of each alternative option. Fourth, the findings of these investigations would inform a public debate that leads to a democratically-based decision about which alternatives to adopt. Subsequently, fresh alternatives would be identified, assessed and considered through an ongoing process involving repeated cycles.

4. The present base of information about La Hague's hazard potential

For this review, two sources of information about La Hague's hazard potential were available. One source was a dossier compiled by COGEMA.²² The other source was a short paper from the Institut de Protection et de Surete Nucleaire (IPSN).²³

COGEMA's dossier could be described as a set of introductions to safety reports for INB 116, INB 117 and INB 118, using the definition of a safety report that is set forth in Section 3.3. Much of the information that could be expected in a safety report -- including plant design details, and descriptions of design-basis accidents - is absent from COGEMA's dossier.

Presumably, COGEMA has in its possession a variety of secret documents that provide some of the information that would be in safety reports for La Hague facilities. COGEMA may also have in its possession some documents that describe PRA-type investigations of certain hazard issues. However, it is unlikely that COGEMA has conducted the full suite of hazards analyses that would be required to thoroughly understand La Hague's hazard potential. Any hazard investigations that COGEMA has performed have been done in secret, which makes it likely that they would exhibit significant deficiencies if exposed to public scrutiny.

The IPSN paper has a limited scope. It provides some information about the hazard potential associated with La Hague's spent fuel pools. However, as discussed in Section 5.4, it leaves many important questions unanswered.

5. Preliminary identification of major sources of hazard at La Hague

5.1 Introduction

Section 3 of this report sets forth the requirements for a thorough analysis of the hazards associated with the La Hague site. These requirements have not been met, as explained in Section 4. Neither COGEMA nor any agency of the French government has published an analysis that systematically identifies and assesses the hazards associated with La Hague. Experience at other sites suggests that no such analysis exists.

This report provides an initial review of the hazards associated with La Hague. Here, in Section 5, the report provides a preliminary identification of the major sources of hazard at the La Hague site. Transport operations are not examined here. A thorough identification of sources of hazard at La Hague would require more time, funding and access to information than were available for this review.

²² COGEMA, 1999.

²³ Goumondy and Marciano, 1997.

A thorough assessment of each source of hazard, after its identification, would require additional time, funding and information.

At the La Hague site, a source of hazard is an operation or location that could, through unplanned events, be the source of: (a) a release of radioactive material or a hazardous chemical to the environment (air, ground water or surface water); (b) exposure of persons (members of the public or site personnel) to higher-than-permitted levels of radiation or hazardous chemicals; or (c) exposure of persons or property to the effects of fire or explosion. A variety of scenarios could lead to outcomes of these kinds. Each such scenario would involve one or more unplanned triggering events. Relevant triggering events include natural forces, human error, equipment failure, and acts of malice or insanity.

The preliminary identification of major sources of hazard at a site such as La Hague requires two stages of analysis. First, one identifies the operations and locations that involve significant quantities of hazardous materials -- radioactive material, hazardous chemicals, or the ingredients for fires or explosions. Second, one identifies the subset of these operations and locations for which there may be a significant probability of occurrence of a hazardous event -- a release to the environment of radioactive material or a hazardous chemical, a significant exposure of persons to radiation or to hazardous chemicals, or a fire or explosion.

In performing the second stage of analysis for a site such as La Hague, one should give special attention to the potential for fires and explosions. These events can cause direct harm to persons or property. Moreover, fires and explosions might cause a significant release of radioactive material or hazardous chemicals to the environment.

Criticality is another phenomenon that deserves attention during the second stage of analysis. A criticality event could be the direct cause of radiation exposure to persons on the site, and might cause a release of radioactive material or hazardous chemicals to the environment. Other potential events that deserve attention include human error, natural forces (e.g., earthquakes), equipment failures, and acts of malice or insanity. Such events might directly cause releases to the environment, or might trigger other potentially hazardous events such as fires, explosions or criticality incidents.

The remaining parts of Section 5 provide the two-stage analysis that is mentioned above. Section 5.2 presents a scoping analysis that identifies operations and locations at La Hague which involve significant quantities of hazardous materials. Then, Section 5.3 outlines La Hague's potential for fires, explosions and criticality incidents. Finally, Sections 5.4 through 5.6 discuss the potential for hazardous events at La Hague's spent fuel pools, HLW facilities, and other locations, respectively.

5.2 A scoping analysis

A scoping analysis can provide a preliminary identification of the operations and locations at La Hague which involve significant quantities of hazardous materials. To perform such an analysis, one requires some comparatively simple indicators.

Cesium-137 as an indicator of radioactivity

The isotope cesium-137 provides a useful indicator of the inventory of radioactive material at La Hague. This isotope has a 30-year half-life and emits strong gamma radiation. Cesium is comparatively volatile and is therefore released comparatively liberally during nuclear facility accidents. When released in an atmospheric plume, cesium is deposited on the ground and other surfaces as the plume travels downwind. After deposition, cesium tends to adhere strongly to surfaces. Thus, a cesium-contaminated area will typically remain contaminated for long periods.

When discharged from a reactor, spent PWR fuel with a burnup of 45 GW-days/tonne contains about 1.5 kilograms of cesium-137 per tonne of fuel.²⁴ For comparison, note that the 1986 Chernobyl reactor accident released about 27 kilograms of cesium-137 to the atmosphere, and that cesium-137 is responsible for most of the offsite radiation exposure from the Chernobyl accident. Also, fallout in the Northern hemisphere, through 1980, from atmospheric testing of nuclear weapons contained about 220 kilograms of cesium-137. In the fallout case, cesium-137 is responsible for about half of the Northern hemisphere radiation exposure through 2000.²⁵

La Hague's inventory of cesium-137

The spent fuel pools at La Hague contain one of the site's major stocks of long-lived radioactivity. Another major stock is contained in the site's high-level radioactive waste facilities, which contain a stock of liquid HLW, said to be a comparatively small buffer volume, and a stock of vitrified HLW. Other, smaller stocks are present in the vessels and piping of the UP2 and UP3 reprocessing plants, and in La Hague's facilities for managing low- and intermediate-level radioactive wastes.

As mentioned in Section 2.7, the four spent fuel pools at UP2-800 and UP3 now have a combined capacity of 13,990 tonnes of fuel, and COGEMA seeks authority to increase their capacity to 17,600 tonnes. Thus, as a rough indication of the amount of cesium-137 that might be in these pools at some future time, assume that the pools contain 10,000 tonnes of spent fuel that has aged for 10 years after being discharged from reactors with a discharge burnup of 45 GW-days per tonne.²⁶ In that case, the pools would contain about 12,000 kilograms of cesium-137.

²⁴ Thompson, 1999, Appendix A.

²⁵ Thompson, 1998, Appendix D.

²⁶ At the end of 1998, the La Hague spent fuel pools contained 8,020 tonnes of fuel of varying ages after discharge. See Rivasi, 2000.

As a continuation of this illustrative example, assume that La Hague's high-level radioactive waste facilities contain liquid and solid HLW from 10,000 tonnes of fuel with the same specification as in the preceding paragraph, except that the age after discharge is 20 years. (As background to these assumptions, note that UP2-800 and UP3 now have a combined nominal reprocessing capacity of 1,600 tonnes of fuel per year.) Given these assumptions, La Hague's HLW facilities would contain about 9,500 kilograms of cesium-137.

Thus, La Hague's spent fuel pools and HLW facilities contain very large stocks of cesium-137 and other long-lived radio-isotopes. Their stocks of cesium-137 are several hundred times larger than the release of cesium-137 from the Chernobyl accident. If there is a significant probability that a substantial fraction of these stocks can be released from their intended locations, then it is clear that the pools and HLW facilities are major sources of hazard at La Hague. As shown in Sections 5.4 and 5.5, available information suggests that there is a significant probability of a large release, at least from the pools and the liquid HLW tanks.

The stocks of radioactive material in the vessels and piping of the UP2 and UP3 reprocessing plants, and in La Hague's facilities for managing low- and intermediate-level radioactive wastes, are much smaller than the stocks in the spent fuel pools and HLW facilities. However, as discussed in Section 5.6, there may be a comparatively high probability that radioactive material is released within the reprocessing plants or the low- and intermediate-level radioactive waste facilities, or from these locations to the environment.

La Hague's inventory of separated plutonium

A large and increasing stock of separated plutonium is held at La Hague. At the end of 1998 this stock was 50 tonnes, having risen from 45 tonnes at the end of 1997.²⁷ This stock could have adverse implications for international security, but those implications are not addressed here. From the hazard perspective, a stock of 50 tonnes of plutonium arouses concern. If a fraction of this stock were dispersed in a manner such that it could be inhaled by workers or members of the public, substantial radiation exposure could result. As discussed in Section 5.6, the probability of plutonium being dispersed in this manner is difficult to estimate, given the available information about management of separated plutonium at La Hague.

La Hague's inventory of hazardous chemicals

The most common chemicals on the La Hague site are nitric acid, nitrate solutions and organic solvents. If released from their intended locations, these chemicals could cause injury to persons or pollution of the environment. IRSS's tentative conclusion, however, is that the potential for offsite injury or pollution from a release of chemicals at La Hague is substantially lower than the potential for offsite injury or pollution from a release of radioactive materials. Thus, the direct effects of hazardous chemicals are not considered further in this review.

The ingredients for fires and explosions at La Hague

As explained in Section 5.3, there is a significant potential for fires and explosions at La Hague. Large stocks of the necessary ingredients are available in the spent fuel pools, in the reprocessing plants, and in facilities for managing radioactive wastes.

5.3 The potential for fires, explosions and criticality incidents

Experience and analysis show that reprocessing plants have a significant potential for fires and explosions. In illustration, in a 1991 joint report by the UK Nuclear Installations Inspectorate and the equivalent agency in Germany, on the subject of safety standards for the design of reprocessing plants, the following statement is made:²⁸

"Fire and explosion represent significant hazards in a reprocessing plant. In addition to the large volumes of flammable solvents which are used in the extraction process, there is a potential for the generation of radiolytic hydrogen and a possibility of 'red-oil' reactions. (Red-oil reactions are those group of heat generating chemical reactions which can occur when heavy metals, organic materials and nitric acid come into contact.)"

²⁷ Rivasi, 2000.

²⁸ The full citation is provided by Thompson, 1998, page G-2.

Appendix B discusses some actual fire and explosion events at reprocessing plants, some recent UK investigations into the potential for future events, and the lessons of this experience for La Hague. Actual fire and explosion events include the explosion of a liquid HLW tank at Kyshtym in 1957 with an energy yield of at least 5 tonnes of TNT equivalent, destructive explosions at Savannah River in 1975 and Tomsk in 1993, and a 1997 fire in a radioactive waste facility at the Tokai reprocessing plant.

Spent fuel pools are normally filled with water. In that condition, they will not experience fires or explosions. However, a variety of exothermic reactions can occur if water is lost from a pool. For example, the zirconium cladding of light-water reactor fuel will react vigorously and exothermically with air or steam at temperatures above 1,000 degrees Celsius. Cladding temperatures in this range can be experienced by comparatively recently-discharged fuel if water is lost from a high-density pool. The potential for exothermic reactions in fuel pools is pursued further in Section 5.4.

IRSS's tentative conclusion about fires and explosions at La Hague is that their direct effects -- heat, smoke and blast -- would probably not extend beyond the site boundaries. However, fires and explosions could have major indirect effects, by releasing radioactive materials or hazardous chemicals from their intended locations. Thus, locations where fires and explosions could occur are potentially major sources of hazard at La Hague.

Criticality

Numerous criticality incidents have occurred at nuclear facilities around the world. For example, a criticality incident occurred at a nuclear fuel processing facility in Japan in September 1999, causing two worker fatalities. At La Hague, a potential for criticality incidents exists in the spent fuel pools, as discussed in Section 5.4, and in the reprocessing plants and facilities for managing separated plutonium, as discussed in Section 5.6.

5.4 Spent fuel pools

At first sight, the storage of spent nuclear fuel in water-filled pools might not appear to be a hazardous activity. However, closer examination reveals that spent fuel pools can be a major source of hazard.

Higher storage density and its hazard potential

A hazard arises because the density of storage in spent fuel pools has been increasing over recent decades. In illustration of current trends, COGEMA seeks authorization for a 26 percent increase in the capacity of the pools at UP2-800 and UP3. Clearly, COGEMA is taking this action for two reasons. First, COGEMA anticipates a need to store increasing quantities of spent fuel. Second, COGEMA wishes to avoid the expense of constructing new storage capacity.

Higher storage density for spent fuel creates an increased hazard potential through two inter-related mechanisms. First, the suppression of criticality during high-density storage of intact, light-water fuel requires that fuel assemblies are separated from each other by neutron-absorbing material. In modern, high-density spent fuel racks, each fuel assembly is surrounded by a full-length, neutron-absorbing tube. Second, the presence of the neutron-absorbing tubes suppresses heat transfer if water is lost from a pool, thus creating the potential for runaway exothermic reactions in the pool.

In the early years of the nuclear power industry, PWR spent fuel was stored in open-frame racks with a typical center-center distance of 50-55 cm. At that spacing, criticality would be suppressed even if the pool was filled with fresh, unirradiated fuel. If water were lost from such a pool, thermal radiation and convection of air or steam would be comparatively effective in removing decay heat from the fuel assemblies. Over the years, center-center distances have decreased significantly. For example, the licensee of the Harris nuclear power plant in the USA is currently seeking authorization to store PWR spent fuel in pools at a center-center distance of 23 cm, which is close to the lower limit that is achievable for intact fuel. At such a high density, the suppression of criticality requires not only the presence of neutron-absorbing tubes, but also the use of administrative controls to prevent placement of low-burnup fuel in the pool. Moreover, radiative and convective heat transfer will be comparatively ineffective if water is lost from the pool.²⁹

Configuration of the La Hague pools

There is almost no publicly available information about the present or proposed configuration of the spent fuel pools at La Hague. For this review only one source of information could be obtained -- a short paper published by the Institut de Protection et de Surete Nucleaire.³⁰ This paper describes the present arrangement of pool D at La Hague. The pool has a storage capacity of 3,590 tonnes of fuel and a heat extraction capacity of 16 MW. Fuel is stored in 9-celled baskets in a 3x3 configuration. The baskets are placed in 54 rows with 13 baskets per row, for a total of 6,318 fuel assemblies. No dimensions or design details are provided in the IPSN paper. Illustrations in the paper suggest that the baskets are not distributed uniformly throughout the pool area, but are located in clusters. Each 3x3 basket appears to have a relatively small center-center distance, perhaps in the vicinity of 25 cm. It can be assumed that neutron-absorbing material is present in the walls of the nine cells in each basket.

Criticality

At present, most spent fuel pools in Western Europe and the USA employ racks which surround each spent fuel assembly with a neutron-absorbing tube, in order

²⁹ Thompson, 1999.

³⁰ Goumondy and Marciano, 1997.

to suppress criticality. That appears to be true for the La Hague pools. In the USA, many pools also rely on burnup to suppress criticality. However, relying on burnup is a qualitatively different approach than using neutron-absorbing tubes. If burnup is to be used as a criticality-suppression measure, then administrative controls must be employed to prevent the placement of low-burnup fuel in the pool. On each occasion when fuel is placed in the pool, there is the possibility that the administrative controls will fail, with the result that low-burnup fuel is inadvertently placed in the pool. By contrast, when neutron-absorbing tubes are installed in a pool, these tubes subsequently serve their criticality-suppressing function without the need for further human action.

In the USA, it is normal for the water in a spent fuel pool to contain soluble boron, which functions as an additional criticality-suppressing measure. At the concentrations typically used, soluble boron will suppress criticality even if low-burnup or fresh fuel is placed in a pool that relies on burnup for criticality suppression. In other words, soluble boron and burnup can be separate, redundant measures for criticality suppression. However, a variety of scenarios can lead to a reduced concentration of soluble boron in pool water. Intervenors in licensing proceedings in the USA have argued that neither burnup nor soluble boron should be relied upon as measures for criticality suppression. Litigation on this matter is ongoing.

There appears to be no publicly available information about the criticality-suppression measures used at the La Hague spent fuel pools. However, it is clear that the changes currently proposed by COGEMA have significant adverse implications for criticality, in two respects. First, COGEMA wishes to increase the overall storage capacity of the La Hague pools by 26 percent, to be achieved entirely through an increase in the density of storage. Second, COGEMA seeks authority to reprocess fuel types (including fast reactor and research reactor fuels) that are highly reactive in their pre-burn condition. As a result, it is likely that the La Hague pools will begin relying, or will increase their reliance, on burnup and/or soluble boron as measures for suppressing criticality. This change will increase the probability of a criticality event in the La Hague pools.

There is a general absence of systematic analysis on the probability and consequences of criticality events in spent fuel pools. On an initial examination, it appears that a criticality event in one of the La Hague pools could cause injuries or death among members of the workforce. Also, such an event might cause offsite radiation exposure above regulatory limits. However, it appears that the potential release of radioactive material to the environment, following a criticality event in a La Hague pool, would be substantially smaller than the potential release arising from exothermic reactions in a La Hague pool.

Exothermic reactions following a loss of water

As mentioned above, a high-density spent fuel pool could potentially experience runaway exothermic reactions if water is lost from the pool. Appendix C discusses the circumstances that could cause a loss of water, the factors that would

determine whether exothermic reactions are initiated, and the release of radioactive material that could be caused by exothermic reactions.

Given the information that is now publicly available, it is impossible to independently determine if exothermic reactions would be initiated at the La Hague pools following a loss of water. However, there is some evidence that such reactions could occur. A previously-mentioned IPSN paper discusses calculations which showed that the air temperature in the building that houses pool D at La Hague would rise to 1,000 degrees Celsius following a loss of water.³¹ The fuel cladding temperature would be higher than the building air temperature. Thus, it can be expected that a self-sustaining fire would begin under these conditions.

It appears that the IPSN paper assumed that the configuration of pool D, and the type of fuel stored in the pool, would be as now authorized. The changed authorizations that COGEMA is seeking would substantially increase the potential for a pool fire to occur following a loss of water. The fire potential would be increased in two ways. First, COGEMA seeks to increase the density of storage in the La Hague pools, a change which would increase the temperature of the fuel cladding following a loss of water. Second, COGEMA seeks to store higher-burnup fuel and MOX fuel in the La Hague pools, a change which would increase the propensity for exothermic reactions following a loss of water.

The IPSN paper does not describe the technical analysis that underlies its statements. However, as described in Appendix C, available information suggests that IPSN does not have a thorough understanding of the potential for exothermic reactions in a La Hague pool. Such incomplete understanding of safety issues is often found when the nuclear industry and its regulating bodies operate in secrecy and without personal accountability. Appendix A provides some illustrative examples of this phenomenon.

Design alternatives that could avoid exothermic reactions in pools

The potential for exothermic reactions in pools has been known for many years. For example, this issue arose two decades ago during a debate about establishing a site at Gorleben, Lower Saxony, that would have been an analogue of the La Hague site. Members of a scientific review group commissioned by the government of Lower Saxony described the potential for a steam-zirconium reaction following a loss of water.³² The center-center distance for PWR fuel storage in the proposed Gorleben pools would have been 29 cm. The review group also described the potential for a large release of radioactive material from the liquid HLW tanks that were proposed for Gorleben.³³

³¹ Ibid.

³² Thompson et al, 1979.

³³ Ibid.

After a public debate on the review group's findings, the government of Lower Saxony ruled that the design options (high-density pools and liquid HLW tanks) proposed by DWK (the project proponent) for storing spent fuel and HLW at Gorleben were unacceptable. Specifically, the government stated:³⁴

"The State Government recognizes that the stores, which contain over 95% of the radioactive plant inventory, constitute a special hazard potential. This radioactive potential is so immense that it must not be possible to release it by an incident.

The State Government is not willing to license the concept of DWK in its present form. They insist that:

- the entry store for spent fuel elements is made inherently safe such that the cooling does not depend on the functioning of technical equipment or on human reliability;
- high-activity wastes are, in normal operation, not stored in liquid form and that buffer tanks, if such are necessary, are made inherently safe."

As a direct result of this ruling, all proposed and actual away-from-reactor spent fuel storage facilities in Germany have employed dry casks instead of pools. Dry casks and other technologies for dry storage of spent fuel have also been widely used in other countries. When properly designed and constructed, a dry storage facility does not have the potential for exothermic reactions that exists in a high-density pool. A sabotage event at a dry storage facility could involve the burning of fuel cladding, and the event could release a significant fraction of the radioactive material in the affected fuel. However, the event would typically affect only a single cask or storage module. By contrast, runaway exothermic reactions in a pool could release radioactive material from thousands of tonnes of fuel.

The IPSN paper describes a potential design modification that might prevent exothermic reactions if water is lost from a pool. This modification would bring comparatively cool air into the fuel pool building. As discussed in Appendix C, this modification would be effective under some conditions but not others. Other design modifications to spent fuel pools could also be envisioned, with the objective of decreasing the probability of water loss and/or decreasing the probability that exothermic reactions will occur following water loss. Modifications of this type deserve to be assessed, although they may not reduce the hazard potential to the level achievable with dry storage.

5.5 High-level radioactive waste facilities

³⁴ Albrecht, 1979.

As described in Section 2.4, HLW is stored at La Hague in two forms -- as a liquid, and as a vitrified solid. Vitrified HLW poses a lower hazard potential than does liquid HLW, assuming that each has the same radioactive content, because radioactive material is less readily mobilized from vitrified HLW.

According to undocumented reports, the stock of liquid HLW at La Hague is a comparatively small buffer volume. If the reports are true, then the consequences of a release of liquid HLW to the environment would be limited by the size of the buffer volume. Nevertheless, those consequences could be very severe. As a hypothetical illustration, suppose that the buffer volume of liquid HLW is 200-300 cubic meters, and that 100 cubic meters of this liquid is inadvertently released to the environment. If the liquid HLW has a composition similar to that at Sellafield, then 100 cubic meters of this liquid would contain about 160 kilograms of cesium-137, which is substantially greater than the 27 kilograms released during the Chernobyl accident.³⁵

The potential for a release of liquid HLW to the environment has received considerable attention in the context of the Sellafield site.³⁶ Investigations of this potential are ongoing, but it is clear that a substantial release from the Sellafield liquid HLW tanks could occur. The triggering events for such a release could include an earthquake, an explosion in or near the HLW tanks, or an act of malice or insanity. The release could occur as an atmospheric plume or as a liquid release to the ocean. In the absence of better information, it is reasonable to assume that the liquid HLW tanks at La Hague could experience a release in the same manner as the Sellafield tanks.

Section 2.7 describes four major changes that COGEMA seeks to make in its operations at La Hague. Three of those changes should be investigated to determine if they could increase La Hague's stock of liquid HLW. Two mechanisms might cause such an outcome. First, an increased reprocessing throughput might yield an output of liquid HLW which exceeds the available vitrification capacity. Second, the reprocessing of an expanded range of fuel types and an expanded range of materials might yield a stream of liquid HLW which is more difficult to vitrify than the present stream of liquid HLW.

Some of the vitrified HLW storage vaults at La Hague are cooled by natural convection of air, while others employ forced (fan-driven) circulation of air. Vaults in the latter category might be vulnerable to overheating if electrical power to the cooling fans is interrupted. An investigation of this vulnerability would require access to detailed design information. Given the information that is publicly available, one cannot determine the vulnerability of the La Hague vitrified HLW vaults to any triggering event.

5.6 Other sources of hazard

³⁵ Thompson, 1998, Appendix C.

³⁶ NII, 2000; Thompson, 1998.

Other potential sources of hazard at La Hague are the UP2 and UP3 reprocessing plants, the facilities for managing low- and intermediate-level radioactive wastes, and the facilities for managing separated plutonium. These facilities are diverse and complex, and are interconnected in numerous ways. A systematic assessment of their hazard potential would require access to detailed design information, together with time and funding beyond those available for this review. Thus, only broad, qualitative statements can be made here.

At these facilities, there are numerous opportunities for fires and explosions. Opportunities for criticality incidents arise at locations where separated plutonium is handled. Human error, equipment failure, natural forces, or acts of malice or insanity could trigger a wide variety of event sequences that might proceed to a hazardous outcome.

It can be assumed that the facility designs and operational procedures used at La Hague can accommodate many event sequences, thereby preventing a hazardous outcome. At the same time, experience at other sites suggests that there are many possible event sequences that would proceed to a hazardous outcome. For some hazardous events, the effects would be experienced entirely within a facility or within the site boundary, while for other hazardous events there would be a release of radioactive material that yields significant effects offsite.

Overall, the probability of a hazardous event at the facilities considered here (Section 5.6) is likely to be higher than the probability of a hazardous event at La Hague's spent fuel pools and HLW facilities. However, the consequences of hazardous events at the pools and HLW facilities could be much greater, because large stocks of radioactive material are stored at those locations.

La Hague's stock of separated plutonium deserves special mention. As indicated in Section 5.2, this stock totalled 50 tonnes at the end of 1998. The release of a fraction of this stock in respirable form could cause substantial radiation exposure. Available information about La Hague is not sufficient to allow an independent assessment of the potential for such a release.

Section 2.7 describes four major changes that COGEMA seeks to make in its operations at La Hague. Three of those changes should be investigated to determine if they could increase the potential for hazardous events at the facilities considered here (Section 5.6). One change involves a greater reprocessing throughput, which would increase flow rates and the general tempo of operations, potentially increasing the probability of hazardous events. Two other changes involve the reprocessing of an expanded range of fuel types and an expanded range of materials. Those changes might increase the probability of fires, explosions, criticality incidents or other potentially hazardous events.

6. Conclusions

C1. Hazardous events have occurred at sites analogous to La Hague. Studies of such sites have shown that they have a potential for hazardous events in the future.

C2. The La Hague site houses large inventories of long-lived radioactive material, especially in the spent fuel pools and high-level radioactive waste facilities. For example, the stock of cesium-137 in the fuel pools at La Hague is hundreds of times larger than the amount of cesium-137 that was released in the 1986 Chernobyl reactor accident. (Cesium-137 accounted for most of the offsite radiation exposure from the Chernobyl accident.)

C3. Analytic techniques have been developed that can identify and characterize potential hazardous events at sites such as La Hague. The effective application of these techniques requires openness, accountability and peer review.

C4. The design details of La Hague remain a secret, and no hazards analysis has been published for any facility on the site. A thorough, independent analysis of hazards cannot be performed using the available information. Experience suggests that, behind the veil of secrecy which surrounds La Hague, neither COGEMA nor any agency of the French government has a thorough understanding of the site's hazard potential. Available information suggests that La Hague could experience fires, explosions and substantial releases of radioactive material.

C5. Alternative designs and modes of operation could be adopted at La Hague, thereby reducing the site's hazard potential. For example, spent fuel could be stored using dry storage technology. Effective decision-making about the adoption of alternatives can only occur through democratic processes, and must be preceded by a systematic, open assessment of each alternative's characteristics, including its hazard potential.

C6. COGEMA seeks to modify its authorizations to operate INB 116, INB 117 and INB 118, through four major changes. Each of those changes could significantly increase La Hague's hazard potential. COGEMA has not presented any analysis of the hazard implications of the proposed changes.

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APPENDIX A

THE NEED FOR OPENNESS AND ACCOUNTABILITY IN ASSESSING NUCLEAR HAZARDS: SOME ILLUSTRATIVE CASES

1. Introduction

Nuclear facilities can pose significant hazards. Decisions about managing those hazards can have significant financial and political implications. Thus, officials in the nuclear industry and relevant governmental bodies are often tempted to place a veil of secrecy over their management of nuclear hazards.

However, secrecy is ultimately counter-productive. Effective management of nuclear hazards requires openness and accountability, for at least four reasons. First, openness and accountability help to build public trust in government, thereby improving the quality of decision-making at the policy level and enhancing the ability of government to carry out its decisions. Second, openness and accountability, together with peer review and the use of empirical investigations to the extent possible, are essential to the achievement of a good scientific understanding of nuclear hazards. Third, openness and accountability are essential if nuclear industry personnel are to adequately understand the risks under their control. Fourth, openness and accountability improve the prospects that safety standards will be upheld.

Some evidence to support these points is presented here, with a focus on the need for openness and accountability in assessing nuclear hazards. Evidence is presented here for four illustrative cases. One of these cases -- the RBMK reactor -- is widely known. The Institute for Resource and Security Studies (IRSS) has been directly involved in the other three cases, which feature experience in the United States and the UK.

For the first three cases, the material in this appendix has previously appeared in Appendix E of a June 1998 report by IRSS.³⁷ Citations to supporting literature, if not provided here, can be found in the June 1998 report. The citations provided here are to literature that is listed in the bibliography of the main report.

³⁷ Thompson, 1998.

2. The RBMK Reactor

The 1986 Chernobyl reactor accident occurred at a 1,000 MWe reactor of the RBMK type. This reactor design was unique to the USSR, and evolved from military production reactors. Prior to the Chernobyl accident, Soviet nuclear industry officials had considered the RBMK to be their "national" reactor and showed considerable pride in its development. They saw numerous advantages in the design, and planned to scale up the design to capacities as large as 2400 MWe per reactor.

The sequence of events which precipitated the Chernobyl accident was a series of operator actions that put the reactor into a dangerous condition. Contrary to some allegations, the operators did not violate established safety rules. They were simply unaware of the implications of their actions. The nature of the resulting accident was dictated by a basic feature of the RBMK reactor -- its positive void coefficient. This feature meant that reactivity increased if voids formed in the cooling water.³⁸ Another RBMK feature -- the design of the control rods -- caused a pulse of reactivity when the rods entered the core. Together, these features meant that the inappropriate series of operator actions culminated in a violent surge of power. The reactor exploded, and the parts which remained in place then burned.

It is now clear that the RBMK reactor has a built-in tendency to explode and burn. This tendency can be kept in check only by unremitting adherence to correct operating procedures. Yet, few people in the USSR -- even in the nuclear industry -- knew of this tendency before 1986. Ironically, the inappropriate operator actions at Chernobyl were taken to test a procedure in which turbogenerator inertia provides a short-term supply of electricity. The managers and operators involved in this test -- which was done in the name of safety -- did not understand the risk they were running. A few engineers and scientists in the Soviet nuclear industry did understand the explosive tendency of the RBMK reactor. Perhaps, in the years before 1986, some of these people wondered privately what would happen if an RBMK reactor exploded, and thought about the emergency response measures that might be implemented to minimize the consequences of such an event. If they did think about these matters, they never succeeded in convincing Soviet institutions to develop appropriate emergency response measures. The emergency measures that were taken after the Chernobyl accident were developed on the spot, in haste and confusion.

It is fair to say that the ultimate cause of the Chernobyl accident was secrecy, assisted by its close companion, complacency. As is well known, Soviet society had very low levels of openness and accountability. In the case of the RBMK reactor, these characteristics of Soviet society meant that doubts or criticisms

³⁸ Three reactivity coefficients determine the reactivity dynamics of the RBMK reactor core. The coolant void and graphite temperature coefficients are positive. Only the fuel temperature coefficient is negative.

about the safety of the reactor were suppressed, to such an extent that nuclear safety engineers working with the reactor did not understand its hazard potential. To illustrate the way in which criticisms were suppressed, consider the experience of Ivan Zhezherun, senior scientist at the Kurchatov Institute. It was revealed in the Soviet press in July 1988 that Zhezherun had written to numerous officials since 1965, pointing out the potential for an RBMK reactor to explode. He had accumulated more than 1,000 pages of correspondence with officials, and the only result had been that efforts were made to dismiss him from the Kurchatov Institute. Had Zhezherun attempted to discuss his concerns outside official circles, he would have been imprisoned.

3. The Savannah River Reactors

Five heavy-water reactors were built at the Savannah River site in the 1950s, to produce plutonium and tritium for US nuclear weapons. Initially, the reactors were fuelled with natural uranium and had a design power of 320-390 MWt. Subsequently, highly enriched uranium fuel was used and power levels rose to almost 3,000 MWt. This evolution reflected the vigorous nuclear arms race which accompanied the Cold War, and the resulting demands for plutonium and tritium.

For many years, the Savannah River reactors operated behind a veil of secrecy. At various times, doubts about their safety were expressed, but only within the bureaucracy. For example, the Advisory Committee on Reactor Safeguards (ACRS) wrote to the chairman of the US Atomic Energy Commission in June 1958, expressing concern about the reactors' safety, especially at the higher power levels then being introduced. The ACRS stated that the reactors' operation could only be justified by their contribution to national security. Over the years, various safety features were added, partly in response to ACRS concerns, but ACRS oversight of these reactors ended in November 1974 when the Atomic Energy Commission was reorganized. Despite the addition of safety features, the risk associated with the reactors remained high. For example, there were no confinement filters until 1961, and those filters would have rapidly overheated in a severe accident until a confinement heat removal system was added in 1979.

The veil of secrecy over these reactors began to lift in the mid-1980s, especially after the Chernobyl reactor accident. In 1987, a committee of the National Research Council was examining the safety of these reactors and became aware of concerns within DuPont -- then the operating contractor -- about the effectiveness of the emergency cooling system (ECS) at each reactor. As a result, power levels were reduced to 50 percent of full power. In August 1988 the reactors were shut down for extensive refurbishment, with the goal of meeting the safety standards applicable to older commercial reactors. This action reflected rising public concern and increased public demand for information about the reactors. For the period 1989-1993, about 4 billion dollars were allocated to the refurbishment effort.

During the refurbishment effort, a variety of safety issues were subjected to a more detailed investigation than they had previously received. These investigations were stimulated by intense public concern, and many of the findings were made available to the public. As an illustration, some of the refurbishment budget was spent on new investigations of the effectiveness of the ECS. Much of this work followed a traditional approach but in mid-1990 it occurred to Westinghouse -- the operating contractor at that time -- that the ECS investigations should systematically consider the implications of the heating of core components by gamma radiation. By early 1991 Westinghouse had concluded that gamma heating was a very significant factor in limiting the effectiveness of the ECS. When gamma heating was accounted for, it appeared that the reactors might not be safe to operate at power levels more than a fraction (perhaps 20 percent) of their rated power.

In April 1993 the US government abandoned its effort to refurbish the reactors. Investigations had revealed so many safety problems, which would have been so expensive and time-consuming to correct, that a continued refurbishment effort was judged to be not cost-effective, despite the previous expenditure of billions of dollars. Moreover, safety considerations may have required these reactors to operate at such low power levels and capacity factors that their productive value would have been limited.

From the four-decade history of the Savannah River reactors one can glean two major lessons. First, the veil of secrecy over these reactors during their first three decades of operation, together with the pressure to produce plutonium and tritium for nuclear weapons, led to a level of safety that was well below commercial reactor practice. Second, the full hazard potential of these reactors was not known until public concern and public scrutiny stimulated a range of safety investigations which began in the late 1980s.

4. Size of the Emergency Planning Zone for US Nuclear Power Plants

In 1980, regulations were promulgated in the United States regarding emergency response planning for accidents at commercial nuclear reactors. Among other requirements, the regulations required specific response planning steps to be taken within an Emergency Planning Zone (EPZ) with a 10-mile radius around each reactor.

These regulations proved inconvenient for the owners of the Seabrook unit 1 reactor when they sought an operating license in the latter part of the 1980s. The reactor is located in the state of New Hampshire, but the EPZ extends into Massachusetts. Public officials and citizens in Massachusetts studied the hazard potential of the reactor, relying in part on a PRA that was published in 1983. They also examined the potential for evacuation and sheltering in the Massachusetts portion of the EPZ, and concluded that an adequate emergency response could not be mounted. This position was sustained by the Governor of Massachusetts, who ordered the relevant agencies in his state to not cooperate in the development of emergency response measures. If the reactor had already

possessed an operating license, the Governor's action would probably not have provided a legal basis for withdrawing that license. However, his action did present a legal obstacle to the granting of an operating license for Seabrook unit 1.

Seabrook's owners engaged in a long legal battle to secure their operating license, and were strongly supported in this endeavor by the federal administrations of Ronald Reagan and George Bush. Ultimately, the endeavor was successful, and an operating license was granted despite the objections of Massachusetts. However, before this occurred the Seabrook owners tried a different idea -- lobbying the US Nuclear Regulatory Commission (NRC) to reduce the radius of the EPZ from 10 miles to a smaller distance, perhaps 1 mile. Technical arguments for this proposal were prepared, but it was clear to all concerned that the owners' primary objective was to reduce the size of the EPZ so that no part of it was in Massachusetts, thus removing a legal obstacle to the granting of an operating license. Of course, if the owners had succeeded in reducing the size of the EPZ for Seabrook, this would have established a precedent for other reactors.

Technical arguments in favor of a reduced EPZ were prepared for the Seabrook owners by a consulting firm. In essence, these arguments were based on the assertion that an accident at the Seabrook reactor would be less severe than had been assumed in the technical studies that had led to the emergency planning regulations.³⁹ Drawing upon these technical arguments, representatives of the Seabrook owners began lobbying the NRC staff at meetings whose purported function was to exchange views on technical matters. This became known to the Massachusetts Attorney General, who demanded representation at the meetings. An IRSS staff member represented the Attorney General at meetings at Brookhaven National Laboratory in October 1986 and NRC headquarters in March 1987, and also testified to the ACRS. It rapidly became clear at these meetings that the state of knowledge within the NRC and the US national laboratories about reactor accidents did not support the arguments for a reduced EPZ. The effort to reduce the EPZ subsequently faded away.

These events occurred in a highly charged political atmosphere, with large amounts of money at stake. The US nuclear industry saw the licensing of Seabrook as a test of its political strength. Yet, openness and accountability were sufficiently well established within the NRC that it was possible to focus attention on the fundamental technical issues related to EPZ size. The state of knowledge on those issues did not support a reduced EPZ.

5. Hazard Potential of the Liquid HLW Tanks at Sellafield

At the Sellafield site operated by British Nuclear Fuels (BNFL), 21 above-ground steel tanks hold high-level radioactive waste (HLW) as a hot, acidic liquid which

³⁹ Specifically, it was argued that, in the event of a core melt, the probability of early containment failure would be very low.

requires constant cooling, agitation and supervision. The tanks are located at the B215 facility. They currently contain about 1,300 cubic metres of liquid, within which there are about 2,100 kilograms of cesium-137.

Liquid HLW is produced at Sellafield by reprocessing Magnox fuel in the B205 facility and oxide fuel in the THORP facility. Comparatively dilute liquid HLW is transferred from B205 and THORP to B215, where it is concentrated in evaporators and then placed in the steel tanks. After a period of storage in those tanks, liquid HLW is transferred to a vitrification plant, where it is incorporated into glass that is cast into steel containers. The containers are stored in an air-cooled vault. Unlike the HLW tanks, the vault achieves a state of "passive safety".

Two vitrification lines are in operation at Sellafield, and a third line is being commissioned. BNFL predicts that vitrification will reduce the stock of liquid HLW to a small "buffer volume" by about 2015, although the stock will exceed 1,300 cubic metres throughout the period 2000-2005. There is reason to doubt that the 2015 target date for tank "emptying" will be achieved.

A senior scientist at Sellafield wrote in 1958 that liquid storage of HLW "can only be regarded as an interim measure" because of the potential for a release to the environment, which would lead to "gross contamination over a wide area". However, BNFL has never performed a systematic assessment of the hazard posed by the liquid HLW tanks. Until the mid-1970s, the public was not aware that this hazard existed.

In 1976 a UK Royal Commission mentioned the hazard posed by the liquid HLW tanks. Responding to this information, citizen participants in the 1977 Windscale Public Inquiry forced the release of some information about the hazard, although the level of secrecy remained high. Thereafter, no significant progress was made in understanding the hazard until 1994, when a group of UK local governments sponsored a study on the offsite consequences of potential releases from the liquid HLW tanks. Publication of this study aroused considerable public interest, which obliged the UK Nuclear Installations Inspectorate (NII) to publish in 1995 its first report on the safety of the HLW tanks.

NII's 1995 report provided a limited amount of information about the hazard posed by the HLW tanks. The report stated that the HLW tanks are "acceptably safe", but did not provide any technical analysis to support that claim. With support from UK local governments, independent investigations of the HLW tank hazard were undertaken. In 1998, IRSS published a detailed analysis of the hazard, and this report aroused considerable public interest.⁴⁰ The heightened public attention obliged NII to publish in February 2000 its second report on the HLW tanks.⁴¹

⁴⁰ Thompson, 1998.

⁴¹ NII, 2000.

NII's second report identifies safety issues that were neglected or wrongly dismissed in the Inspectorate's first report, and describes a variety of ongoing investigations and backfits that NII has recently required BNFL to perform. The unresolved safety issues identified in NII's February 2000 report include:

- Safety assessments by BNFL have failed to address important accident phenomena, and have made claims about accident probability that are not based on engineering analyses.
- Devices for transferring liquid HLW from a defective tank will work only over a narrow range of temperature.
- Nominally separate cooling circuits for the HLW tanks are not truly independent.
- Remote inspection techniques must be developed to determine the internal structural integrity of the HLW tanks and evaporators.
- B215 structures are being modified to increase their resistance to earthquakes, but BNFL has not performed a seismic probabilistic safety assessment that meets prevailing standards.
- Ventilation, control and instrumentation systems in the B215 facility do not meet prevailing standards.
- BNFL has failed to perform an integrated safety assessment for linked facilities, and therefore does not properly understand the potential for inadvertent forwarding of organic chemicals from B205 or THORP to B215. (These chemicals could cause violent explosions in B215.)
- Investigations of the potential for violent chemical explosions in B215 are incomplete.
- BNFL has not analyzed the development of potential severe accidents in B215 or the opportunities for mitigating such accidents.
- It is unlikely that BNFL will succeed in emptying the HLW tanks by 2015, in part because of pipeline blockages in the vitrification plant.

No comprehensive assessment of the hazard posed by Sellafield's liquid HLW tanks has yet been made. BNFL's investigations are ongoing, and are being conducted in secrecy. Nevertheless, NII has been obliged to admit that its 1995 report did not correctly describe the hazard, and to require investigations by BNFL that might ultimately contribute to a thorough, science-based understanding of the hazard.

From this record, it is clear that whenever NII and BNFL have been insulated from public attention by a veil of secrecy and a lack of accountability, they have taken a complacent attitude to the hazard posed by the HLW tanks. During the 1990s, outside pressure has goaded a reluctant NII into addressing safety issues that would otherwise have been neglected, and into publishing information that would otherwise have remained secret.

APPENDIX B

THE POTENTIAL FOR FIRES AND EXPLOSIONS AT REPROCESSING PLANTS

1. Introduction

A nuclear facility can undergo hazardous events that are initiated by, or are accompanied by, fires or explosions which occur inside or outside the facility. The potential for such events is best addressed as part of a comprehensive probabilistic risk assessment (PRA) for the facility. However, many nuclear facilities have not yet been analyzed using PRA techniques, and these techniques are most highly developed in connection with light-water commercial reactors.

This appendix addresses the potential for fires or explosions at nuclear fuel reprocessing plants. Much of the material in this appendix has previously appeared in Appendix G of a June 1998 report by the Institute for Resource and Security Studies (IRSS).⁴² IRSS's June 1998 report focussed on the storage of high-level radioactive waste (HLW) as a liquid at the Sellafield site, which is owned and operated by British Nuclear Fuels (BNFL). Citations to supporting literature, if not provided here, can be found in the June 1998 report. The citations provided here are to literature that is listed in the bibliography of the main report.

Section 2 of this appendix briefly reviews the potential for fires and explosions as a generic safety issue associated with nuclear fuel reprocessing. Then, Section 3 summarizes some fire and explosion incidents at sites around the world. Investigations of the fire and explosion potential at Sellafield are reviewed in Section 4. Some lessons relevant to La Hague are set forth in Section 5.

2. Fire and Explosion Potential as a Generic Safety Issue in Reprocessing

In 1991 the UK Nuclear Installations Inspectorate (NII) and the analogous agency in Germany published a joint report on safety standards for the design of reprocessing plants. In their report they stated:

"Fire and explosion represent significant hazards in a reprocessing plant. In addition to the large volumes of flammable solvents which are used in the extraction process, there is a potential for the generation of radiolytic hydrogen and a possibility of 'red-oil' reactions. (Red-oil reactions are those group of heat generating chemical reactions which can occur when heavy metals, organic materials and nitric acid come into contact.)"

⁴² Thompson, 1998.

The same report outlined some design features that are intended to prevent fire and explosion. These features include "temperature and pressure controls and limits, coupled with strict measures to prevent organic materials entering the evaporators".

Organic materials, nitric acid and heavy metals -- the precursors of "red oil" reactions -- are present in large amounts at reprocessing plants such as those at La Hague. In a typical contemporary reprocessing plant, spent fuel is dissolved in nitric acid. The constituents of the spent fuel are then separated in several process stages that involve contact between an organic solvent and a nitrate solution. Tributylphosphate (TBP) diluted in odourless kerosene (OK) is the organic solvent in common use. Heavy metals are present in the form of uranium, plutonium and other transuranics. Other soluble and insoluble constituents of spent fuel include fission products, plus zirconium or magnesium from fuel cladding.

Since the early years of reprocessing, evaporators have been recognized as plant components that are prone to explosions. For example, in December 1950 an explosion occurred at a pilot-scale military reprocessing plant in Canada, operated under a UK-Canadian agreement. The explosion occurred in an evaporator containing radioactive ammonium nitrate, killing one worker and injuring four others. When the first non-active tests of the Windscale reprocessing plant began in 1951, a "virtual explosion" of Butex occurred in an evaporator, after which the plant was modified. Records show that the designers of France's first large reprocessing plant, built at Marcoule, became concerned about the potential for explosions in uranyl nitrate evaporators when they learned that such explosions had occurred in the USA.

Process components other than evaporators are also known to pose a fire and explosion hazard. For example, consider mixer-settlers, which are extensively used in reprocessing plants. In a mixer-settler, an organic solvent (oil) stream and an aqueous (water) stream pass alternately through mixing and settling compartments. In the settling compartments an oil layer floats on a water layer. There is concern that a fire in the oil layer could cause boiling of the underlying water layer, thus leading to the rapid release of a large amount of solvent vapor into the cell space, where this vapor could burn explosively.

A comprehensive PRA for a site such as La Hague would, among its other functions, examine a large number of potential fire and explosion events, both inside and outside the various structures on the site. The probabilities and consequences of these events would be assessed, and an integrated picture of the fire and explosion risk would be developed, as part of an assessment of the site's overall risk. In such an assessment, attention should be given to interactions among facilities and events. For example, an unusual occurrence at one part of the site, not necessarily involving a fire or explosion, might help to initiate a fire or explosion elsewhere on the site. Section 4 discusses a potential interaction of this type at the Sellafield site, in which an unusual occurrence at a reprocessing

plant causes a large amount of organic material to be forwarded to the facility where liquid HLW is stored.

3. Some Fire and Explosion Incidents

A variety of fire and explosion incidents have occurred at reprocessing plants, in addition to the Canadian and UK evaporator events mentioned above. Some of these incidents are briefly reviewed here. These incidents had varying characteristics and were of varying degrees of severity.

The 1957 Kyshtym Incident

In September 1957, a liquid HLW tank exploded at the Chelyabinsk-65 nuclear complex near Kyshtym (USSR). The following summary of this incident draws from available reports, which leave a variety of questions unanswered. The tank was one of a group of 20 tanks housed in a concrete structure. It was made of stainless steel, had a capacity of 300 cubic meters, and contained 70-80 tonnes of HLW. Beginning in 1956, cooling was supplied to this tank intermittently rather than continuously, apparently because leaks in the cooling system caused radioactive contamination of the cooling water, and continuous decontamination of the cooling water would have required a reduced production of plutonium at the site.

It is believed that the intermittent nature of the cooling led to evaporation of the HLW solution and the formation in the tank of dry sodium nitrate and acetate salts. These salts exploded with an energy release of 5-100 tonnes of TNT equivalent. About 20 MCi of radioactivity were released, of which about 10 percent (including 108 kCi of Sr-90) was carried downwind and subsequently deposited. About 10,000 people were evacuated from contaminated land, over an area of about 1,000 square km. In the evacuated area, the concentration of Sr-90 exceeded 3 Ci per square km while in a surrounding area of 15,000 square km, occupied by about 270,000 people, the Sr-90 concentration was in the range 0.1-3 Ci per square km.

The 1975 Savannah River Incident

Red oil explosions occurred at the Savannah River site (USA) in 1953 and 1975, at the Oak Ridge site (USA) in 1959, and at the Uranium Trioxide Plant (Ontario, Canada) in 1980. The 1975 event at the Savannah River site was well documented and is summarized here.

The 1975 event occurred at a facility which converted uranyl nitrate [UO₂(NO₃)₂] solution to uranium trioxide powder. Uranyl nitrate was received at this facility from a Purex process, and some entrained organic material (30 percent TBP, 70 percent normal paraffin) was usually present in the uranyl nitrate solution. The organic material was normally removed from the uranyl nitrate by allowing it to float to the top of storage vessels, while the nitrate solution was pumped from the bottom without agitation. On this occasion, however, operational errors

allowed about 110 kg of TBP to pass through two consecutive stages of evaporation and enter a denitrator (the paraffin was almost entirely absent after the second stage of evaporation). The TBP entered the denitrator as an adduct $[\text{UO}_2(\text{NO}_3)_2(\text{TBP})_2]$.

As the temperature of the denitrator contents approached about 170 degrees C, thermal decomposition of the adduct began. The operators observed brown fumes, turned off the denitrator and left the room. An explosion occurred as they were departing. This explosion blew out the lightweight walls of the surrounding building, and generated deposits of a pumice-like material (thereby indicating high temperature and pressure levels during the explosion). It is believed that decomposition of the TBP adduct yielded flammable gases which ignited at ceiling level in the surrounding building. The estimated energy release from burning of these gases (which were derived from the decomposition of 110 kg of TBP) was 3.1-3.6 GJ, or about 2.9 GJ if loss of flammable material is accounted for. Note that an energy yield of 2.9 GJ is equivalent to the energy released by exploding 690 kg of TNT.

The 1993 Tomsk Incident

A red oil explosion occurred at the Tomsk-7 reprocessing plant (near Novosibirsk, Russia) in April 1993. The explosion occurred in a 31 cubic meter capacity vessel which was being used to prepare a uranium solution for a process step that would remove residual plutonium and fission products. The uranium solution had come from a Purex process which employed an organic solvent consisting of 30 percent TBP in a hydrocarbon diluent. Three batches of uranium solution were added to the vessel. The first batch (4 cubic metres) had been stored for many months, while the second two batches (totalling 19.5 cubic metres) were concentrated in an evaporator shortly before they were added to the vessel.

An unknown amount (perhaps 100-200 liters) of organic material was present in the vessel, apparently floating on the aqueous uranium solution in the tank. This organic material must have come from the Purex process, and would initially have consisted mostly of TBP and diluent.⁴³ Apparently, the organic material entered into a runaway reaction with concentrated nitric acid which was added to the vessel about two and a half hours before the explosion. About 1.5 cubic meters of 14.2M nitric acid was added, and it is believed that this acid pooled on top of the uranium solution with little initial mixing (the operator neglected to activate a mixing system that employed air bubblers). Some slow mixing of the organic material and the nitric acid must have occurred. Reaction between these liquids developed progressively over a period of about 2 hours, and became evident about 13 minutes before the explosion, from a positive pressure reading

⁴³ During storage, hydrolysis of TBP may have led to the formation of butyl nitrate, which is more reactive toward nitric acid than is TBP. Also, comparatively reactive organic compounds may have been formed by nitration of the hydrocarbon diluent.

in the vessel and the emergence of brown fumes (presumably nitrogen oxides) from the canyon stack.

During the explosion, the vessel ruptured, the concrete shield plug at the top of the vessel's cell was lifted, an unreinforced masonry wall of the surrounding building was blown out, and the roof above the vessel collapsed. An offsite downwind area of about 90 square km was contaminated by fission-product radioactivity (a threshold of 15 microrad per hour was used to designate the extent of contamination), but the deposited fission products (primarily Zr-95 and Nb-95) were comparatively short-lived.

It is not clear whether damage to the surrounding building should be attributed to the pressure wave resulting from vessel rupture, or to explosion of flammable gases released into the building after vessel rupture. Note that gaseous products of TBP-nitrate reactions can be flammable without addition of oxygen, because they contain both oxidants (nitrogen oxides) and fuels (CO and hydrocarbons). Calculations suggest that the vessel experienced internal pressurization of 16-40 atmospheres. There has been speculation that ignition of flammable gases in the head space of the vessel was the immediate cause of vessel rupture.

An interesting feature common to the 1993 Tomsk incident and the 1975 Savannah River incident was that pressure in the surrounding buildings was relieved when relatively weak walls were blown out. If the same explosion were to occur inside a reinforced concrete cell with few openings, internal pressure could rise to a higher value, damage to equipment inside the cell could be greater, and the mode of pressure relief could be comparatively violent.

Miscellaneous Incidents

The three incidents described above were comparatively severe. Many fire and explosion incidents of lesser severity have occurred at reprocessing plants, and four of these incidents are briefly summarized here.

In September 1973, an incident occurred in the B204 reprocessing plant at Windscale (now Sellafield). The plant had been modified to provide "head end" reprocessing of oxide fuels, and began performing that role in 1969. During plant operations, kilogram quantities of insoluble fission products, zirconium fines and other solids had accumulated in a constant-volume feeder. As a new reprocessing campaign was initiated, these solids reacted exothermically with acidified butex (butex was the organic solvent used in B204). Ignition of zirconium may also have occurred. The exothermic reactions produced gases which escaped from the process cell and spread through the upper floors of building B204, carrying Ru-106 contamination. Subsequently, the plant was closed.

In January 1981, a fire occurred in a radioactive waste storage silo at La Hague. The silo contained solid material including uranium metal, magnesium and graphite, which presumably arose from the reprocessing of metallic (Magnox-

type) fuel. It is believed that the uranium metal was in a finely-divided, pyrophoric form, and that its ignition was triggered by a mechanical shock arising from the addition of solid material to the silo. The fire released radioactive material from the silo, including 0.7-1.9 TBq (0.2-0.6 g) of cesium-137.⁴⁴

In March 1997, a fire and a subsequent explosion occurred at the Tokai reprocessing plant in Japan. These incidents occurred in a facility that incorporated low-level radioactive waste into a bitumen matrix. The initial fire occurred in a drum that had just been filled with bitumen and waste. Operators employed a sprinkler system to extinguish this fire, but did not confirm that the fire was out. Ten hours later an explosion (whose origin is unknown by IRSS) occurred in the room where the fire had occurred, blowing out windows, severely deforming a roller shutter door, and causing extensive damage inside the building. Three of nine monitoring stations around the site showed elevated levels of Cs-134 and Cs-137 after the explosion.

In May 1997, an explosion occurred at the plutonium finishing facility which is part of the reprocessing plant at the Hanford site, USA. The explosion occurred in a tank into which about 200 gallons of a solution of nitric acid and hydroxylamine nitrates had been placed in 1993. Slow evaporation of water had reduced the volume of liquid to less than 40 gallons. An autocatalytic reaction occurred in the tank, which exploded. The roof of the surrounding building was breached by debris, a fire suppression line was ruptured, and brown fumes were observed to rise from the facility exhaust stack. Radioactive materials were not involved in this incident.

4. Investigations of the Fire and Explosion Potential at Sellafield

The potential for fires and explosions at the Sellafield site has been a subject of public discussion during the past five years. This discussion has focussed on the potential for an explosion to cause a release of radioactive material from the B215 facility at Sellafield. Other scenarios for fires and explosions at Sellafield can be envisioned, but have not received the same attention.

The B215 facility houses twenty-one liquid HLW tanks and three operable HLW evaporators. Comparatively dilute liquid HLW is transferred to B215 from the two operable reprocessing plants at Sellafield: (a) the THORP plant; and (b) the B205 reprocessing plant for Magnox fuel. The transfer occurs through shielded, overhead pipelines. At B215, the concentration of the liquid HLW transferred from THORP and B205 is increased in the evaporators, and the concentrated liquid HLW is stored in tanks. After storage for some years, liquid HLW is removed from the tanks and vitrified in an adjacent facility. At present, about 1,300 cubic meters of liquid HLW are stored in the tanks at B215, containing about 2,100 kilograms of cesium-137.

⁴⁴ Groupe RNC, 1999.

The Nuclear Installations Inspectorate's Position in 1995

The quote at the beginning of Section 2, from a report published in 1991, indicates that NII has been aware, for at least a decade, of the potential for fires and explosions at reprocessing plants. Nevertheless, in a 1995 report about the safety of the liquid HLW tanks at Sellafield, NII dismissed the fire and explosion hazard in a few short paragraphs.

Most of NII's brief discussion of the fire and explosion hazard in its 1995 report was devoted to the possible accumulation in the HLW tanks of radiolytically produced hydrogen. NII dismissed this as a concern, stating that: (a) hydrogen concentrations in the tank offgas have always been below the level of detection; and (b) if a tank's ventilation system failed, an explosive concentration of hydrogen would not occur because buoyancy would cause hydrogen to move upwards and out of the tank. No technical evidence was presented to support either assertion.

To close its 1995 discussion of the potential for fires and explosions related to the HLW tanks, NII stated:

"NII has not identified any other mechanism by which an in-process fire or explosion hazard could occur in the HASTs [liquid HLW tanks]. We have included in our considerations the possibility of reactions with the organic solvent used in the reprocessing plants."

As in other areas of accident analysis, the nature of NII's "considerations" remained secret. However, it seems that a key part of NII's thinking was that organic chemicals are highly unlikely to reach the liquid HLW tanks. This view was communicated to representatives of IRSS and other organizations when they met with NII officials in June 1996. A similar view was articulated by BNFL officials at a meeting in June 1997. Indeed, at the latter meeting a BNFL official appeared to argue that the presence of organic chemicals in the liquid HLW tanks is deterministically precluded.

If the presence of organic chemicals in the B215 facility were deterministically precluded, then NII's 1995 position might be sound. Fires and explosions would lack fuel, and the production of radiolytic hydrogen in the HLW tanks would be low. However, if the presence of organic chemicals in vessels within the B215 facility -- such as the evaporators -- is possible, then NII had no basis for its position. A fire or explosion could occur in an evaporator or other process vessel within the B215 facility, potentially initiating an accident at a HLW tank. Furthermore, if organic chemicals can be present in the HLW tanks themselves, then potentially damaging explosions could occur inside those tanks.

Presence of Organic Chemicals in the B215 Facility

There is clear evidence that organic chemicals can be present in the HLW tanks and elsewhere in the B215 facility. In a 1986 paper about the vitrification of liquid HLW (which would be extracted from the HLW tanks), a BNFL author stated:

"The waste solution may contain organic materials such as the degradation products dibutylphosphoric acid and monobutylphosphoric acid dissolved in the solution, as well as kerosene and tributylphosphate, present as an emulsion."

Also note the following statement published in 1958 about evaporation of liquid HLW during the early years of reprocessing at Sellafield (then known as Windscale):

"The possibility of a dangerous reaction occurring between acid liquor and entrained solvents during evaporation was recognized and overcome by stripping the entrained solvent from the aqueous stream by means of steam before the evaporator, and by subjecting the fresh solvent to rigorous purification treatments which removed non-volatile impurities by hydrolysis with nitric acid.

These precautions eliminated not only any uncontrolled vigorous solvent-acid reactions, but also excessive foaming in the evaporators which was found to occur in the presence of reactive organic matter."

Clearly, the presence of organic material in the B215 facility is not deterministically precluded. Instead, technical and administrative measures are taken, with the objective of preventing access of organic material to the HLW evaporators and tanks. It follows that NII's 1995 position must have rested on a probabilistic judgement. NII presumably believed either or both of the following propositions: (a) the presence of a significant quantity (not defined) of organic chemicals in building B215 is of such low probability (not defined) that it need not be considered; or (b) given the presence of organic chemicals, the probability that these chemicals will react to produce a significant (not defined) fire or explosion is so low (level not defined) that it need not be considered. No technical basis was provided to support either proposition. Indeed, NII did not articulate any rationale for dismissing the potential for fires or explosions in B215.

In the THORP plant, dilute HLW from the first separation column is subjected to steam stripping to remove entrained organic material (see the quote above). Also, liquid HLW streams arise at two other THORP process locations -- the solvent wash facility, and the plant wash facility. In both cases, solvent is separated from aqueous solution by floating off. Overall, it is clear that the entrainment of organic material in liquid HLW sent from THORP to building B215 is prevented, not by any physical barrier, but by the continuing operation of instruments and control equipment, and by the continuing vigilance of the plant operators.

A similar situation pertains at the B205 Magnox reprocessing plant, although its instrumentation and control systems are less sophisticated than those at THORP. In illustration of the procedures used at the Magnox reprocessing plant, note that a check of the plant's solvent inventory is said to be performed every shift (i.e., three times per day) to assist in the early detection of bulk solvent loss.

When dilute liquid HLW reaches the B215 facility, the passage of entrained solvent, into and through the facility, is not prevented by any physical barrier. As at the reprocessing plants, the prevention of solvent passage relies on instruments, control systems, and human vigilance. Experience shows that systems and procedures of this kind can fail.

Conclusions by IRSS in 1998

In a 1998 report, IRSS concluded that the position articulated by NII in 1995 was not credible.⁴⁵ IRSS saw no evidence that NII or BNFL had employed PRA techniques to systematically assess the probabilities and consequences of a range of accident scenarios involving the entry of organic material into the B215 facility. Thus, neither organization had a good understanding of the fire and explosion potential in B215.

Given the limited information that was publicly available in 1998, IRSS could not perform a thorough, independent assessment of the fire and explosion potential in B215. Using the available information, IRSS reached three interim findings, as follows.

First, many kilograms of organic material could enter the HLW tanks or evaporators at B215. Moreover, conditions could arise whereby this material would react violently with nitrates or nitric acid. Each kg of organic material could contribute to an energy release equivalent to that from 5 kg or more of TNT.⁴⁶

Second, organic material in a HLW tank could cause an explosive hazard indirectly, by contributing to the production of radiolytic hydrogen. This hydrogen could accumulate in the tank head space and ventilation system, the accumulation perhaps being exacerbated by a partial blockage of the ventilation system, and the accumulated hydrogen could explode.

Third, there are a variety of ways in which an explosion in the B215 facility could cause a release of radioactivity. For example, an explosion in a liquid HLW tank could breach a tank and its cell, causing a liquid release. An evaporator explosion could breach a nearby cell and tank. A tank explosion or an evaporator explosion could cause irrecoverable damage to the cooling and ventilation

⁴⁵ Thompson, 1998.

⁴⁶ Thus, for example, the inadvertent forwarding of 200 kg of organic material to B215 could cause an explosion in a B215 evaporator with an energy release equivalent to that from 1 tonne of TNT.

systems of one or more liquid HLW tanks, after which those tanks would dry out and an atmospheric release would follow. Other scenarios can be envisioned.

The NII's Revised Position in 2000

In response to public pressure arising from the publication of IRSS's report in June 1998, NII required BNFL to perform a wide variety of investigations into the hazard posed by the B215 facility. These investigations have identified safety problems that are, to some extent, being addressed by plant modifications. Much of this work is ongoing. Several of the new investigations have focussed on the potential for fire and explosion in B215. In February 2000, NII published an interim report setting out its current position on the hazard posed by B215.⁴⁷ NII has promised to publish an addendum to this report when BNFL's ongoing investigations and plant modifications have been completed.

NII's February 2000 report, like the Inspectorate's 1995 report, provides no technical analysis or data to support its findings. Like its predecessor, the new report asserts that B215 is "acceptably safe". Nevertheless, the new report confirms, as IRSS concluded in 1998, that BNFL has operated the B215 facility for decades without properly understanding its hazard potential, and that NII has accepted this situation.

The new NII report confirms that BNFL has not applied contemporary PRA techniques to the B215 facility. BNFL has made claims about the probabilities of hypothetical accidents at B215, but these claims are not based on engineering analyses. Moreover, BNFL has made no systematic effort to analyze the development of potential severe accidents at Sellafield or the opportunities for mitigating such accidents. Also, BNFL has failed to systematically analyze the potential for incidents in one facility to affect other facilities at Sellafield.

The latter point is especially significant in connection with the potential for fires or explosions in B215. As mentioned above, the inadvertent forwarding of organic material from B205 or THORP to B215 could cause an explosion in B215. Yet, BNFL's "safety case" for B215 has not considered this interaction among facilities. In its February 2000 report, NII calls upon BNFL to rectify this error. NII also calls upon BNFL to complete a variety of theoretical and experimental investigations into the potential for "red oil" and hydrogen explosions in B215.

Thus, it is clear that in 1995 the NII had no technical basis for dismissing the fire and explosion potential at B215. There has never been any thorough assessment of this potential. Ongoing studies by BNFL might provide such an assessment, if conducted thoroughly and openly, and subjected to peer review in open fora. There is no sign that BNFL will perform its work in this manner. Thus, for the present, the three interim findings of IRSS's 1998 report, as stated above, provide the best available guidance on the fire and explosion potential at B215.

⁴⁷ NII, 2000.

5. Lessons Relevant to La Hague

Neither COGEMA nor any other entity has published a thorough assessment of the potential for fires and explosions at La Hague. In the absence of such an assessment, experience at other sites provides the best available guidance about La Hague's fire and explosion potential.

Worldwide experience shows that fires and explosions can occur at reprocessing plants, potentially leading to significant releases of radioactive material to the environment. There is no evidence that the design principles and modes of operation used at La Hague are significantly different from those used elsewhere. Thus, it can be assumed that La Hague's fire and explosion potential is similar to the potentials at other sites.

The fire and explosion potential at Sellafield's B215 facility provides a different lesson. In that case, the safety regulator (NII) initially assured the public that the facility's fire and explosion potential is negligible. When publicly challenged, the regulator looked at this problem again, and then admitted that the potential is actually unknown. This experience warns the public to be very cautious about accepting undocumented assertions by any entity, including a regulatory agency.

APPENDIX C

A PRELIMINARY REVIEW OF THE POTENTIAL FOR A LARGE ATMOSPHERIC RELEASE FROM LA HAGUE SPENT FUEL POOLS

1. Introduction

At first sight, the storage of spent nuclear fuel in water-filled pools might not appear to be a hazardous activity. However, closer examination reveals that spent fuel pools can be a major source of hazard. These pools typically contain a large inventory of radioactive material. If water is lost from a pool, a substantial fraction of the radioactive inventory can become mobilized and enter the atmosphere as a plume which travels downwind.

This appendix provides a preliminary review of the potential for an atmospheric release from the spent fuel pools at La Hague. The information, time and funding available for this review were not sufficient to allow more than a preliminary investigation. However, the potential for a large atmospheric release has been studied in the context of spent fuel pools at other sites, and there is a body of relevant literature in the public domain. The configuration of the La Hague pools is similar to the configuration of pools whose release potential has been studied. Thus, it is clear that the La Hague pools could be operated in a mode such that they would experience a large atmospheric release if water is lost.

Section 2 of this appendix provides a brief overview of the circumstances and phenomena that are relevant to a pool's potential for a large atmospheric release. Then, Section 3 discusses the scenarios that could lead to a loss of water from the La Hague pools. Section 4 discusses the potential initiation and propagation of exothermic reactions at the La Hague pools, following a loss of water. Section 5 discusses the atmospheric release of radioactive material that could be caused by exothermic reactions. Design alternatives, and their hazard implications, are discussed in Section 6. Finally, Section 7 addresses the role of the Institut de Protection et de Surete Nucleaire (IPSN). Citations in this appendix are to literature listed in the bibliography in the main report.

2. An Overview of the Release Potential

The potential for an atmospheric release of radioactivity now exists because the density of storage in spent fuel pools has been increasing over recent decades. In illustration of current trends, COGEMA seeks authorization for a 26 percent increase in the capacity of the pools at UP2-800 and UP3. This capacity increase will be achieved by increasing the density of storage, not by expanding the pools.

Higher storage density for spent fuel creates an increased hazard potential through two inter-related mechanisms. First, the suppression of criticality during high-density storage of intact, light-water reactor fuel requires that fuel assemblies are separated from each other by neutron-absorbing material. In modern, high-density spent fuel racks, each fuel assembly is surrounded by a full-length, neutron-absorbing tube. Second, the presence of the neutron-absorbing tubes suppresses heat transfer from the fuel assemblies if water is lost from a pool. If heat transfer is suppressed, decay heat will accumulate in the fuel and its cladding temperature will rise, thus creating the potential for runaway exothermic reactions in the pool.

In the early years of the nuclear power industry, PWR spent fuel was stored in open-frame racks with a typical center-center distance of 50-55 cm. At that spacing, criticality would be suppressed even if the pool was filled with fresh, unirradiated fuel. If water were lost from such a pool, thermal radiation and convection of air or steam would be comparatively effective in removing decay heat from the fuel assemblies. Over the years, center-center distances have decreased significantly. For example, the licensee of the Harris nuclear power plant in the USA is currently seeking authorization to store PWR spent fuel in pools at a center-center distance of 23 cm, which is close to the lower limit that is achievable for intact fuel. At such a high density, radiative and convective heat transfer will be comparatively ineffective if water is lost from the pool.⁴⁸

Water Loss and its Implications for Heat Transfer

Section 3 discusses scenarios for water loss from the La Hague pools. Here (Section 2), it suffices to note that fuel assemblies could be partially or totally exposed to air for extended periods, and that the water level could fall, rise or remain static at different phases of a scenario.

In a situation of complete pool drainage, fuel assemblies will be cooled by two heat transfer mechanisms -- by thermal and gamma radiation, and by upward convection of air through the fuel assemblies.⁴⁹ In a situation where fuel

⁴⁸ Thompson, 1999.

⁴⁹ To complete the convective circulation loop, a downward flow of cooler air into the pool must occur. This flow will occur around the edges of the pool or in locations where fuel assemblies are absent.

assemblies are partially exposed to air, the exposed portion of each assembly will be cooled by radiation and by upward convection of steam.⁵⁰

The temperature of the fuel cladding will vary over time, and will depend upon: (a) the exposure scenario; (b) the physical configuration of the fuel racks and the pool; and (c) the decay heat output of the fuel. A higher-density configuration, or a higher decay heat output, will lead to higher cladding temperatures.

Exothermic Reactions

As the temperature of fuel cladding rises, the cladding will begin to swell (at about 600 degrees C) and will subsequently rupture under internal pressure.⁵¹ The swelling will inhibit heat transfer, thereby promoting a further temperature rise. As temperature rises beyond about 800 degrees C, the zirconium alloy cladding will begin to react exothermically with steam (if the assemblies are partially exposed) or air (if the pool is completely drained). These exothermic reactions become vigorous at temperatures above 1,000 degrees C. The rate of reaction increases more than proportionally with temperature. Thus, once they are initiated, these reactions can exhibit runaway behavior. Section 4 discusses the initiation and propagation of exothermic reactions in the La Hague pools.

Release of Radioactive Material

If fuel cladding enters into vigorous exothermic reactions, substantial amounts of radioactive material will be liberated from the fuel pellets. Cladding rupture is likely to have occurred before the exothermic reactions become vigorous, so the liberated radioactivity will readily escape from the fuel pellets and will then be swept upward into the region above the pool. From this region, some or all of the radioactive material will be released to the atmosphere as a plume. Section 5 discusses the release of radioactive material.

⁵⁰ The steam will be generated in water surrounding the submerged portion of the fuel assemblies. The heat that generates this steam will be decay heat in the submerged portion of the assemblies, together with heat transferred downward (by conduction and radiation) from the exposed portion of the assemblies.

⁵¹ NRC, 2000, Appendix 1.

Development of Knowledge about this Hazard

The potential for exothermic reactions in spent fuel pools has been known for many years. For example, this issue arose two decades ago during a debate about establishing a site at Gorleben, Lower Saxony, that would have been an analogue of the La Hague site. The center-center distance for PWR fuel storage in the proposed Gorleben pools would have been 29 cm. Members of a scientific review group commissioned by the government of Lower Saxony described the potential for a steam-zirconium reaction following a loss of water from the pools.⁵² The review group's discussion of water loss was focused on scenarios in which water is lost by evaporation, and these scenarios necessarily involve a period of partial exposure of fuel assemblies. During partial exposure, a steam-zirconium reaction will occur instead of an air-zirconium reaction.

In 1979, the US Nuclear Regulatory Commission (NRC) published its first report on the implications of a loss of water from a high-density spent fuel pool. Since then, the NRC has published a number of reports on this issue. Unfortunately, the NRC's studies on this issue are all predicated on the assumption of instantaneous, total drainage of a pool. That assumption excludes from consideration some important phenomena. The NRC's present understanding of the probability and consequences of loss of water from a spent fuel pool is set forth in a draft report published in February 2000.⁵³ The NRC's Advisory Committee on Reactor Safeguards (ACRS) has recently challenged the scientific basis for this report.⁵⁴

3. Scenarios for Loss of Water from Pools

Design details are not available for the La Hague pools, but it can be presumed that they are similar to modern pools at other sites. Spent fuel pools are typically made of reinforced concrete, and are quite robust. Their cooling and water purification systems are typically designed so that leakage from these systems will not lead to extensive drainage from the pool. Thus, it could be assumed that the probability of a substantial loss of water from a La Hague pool is comparatively low. However, the consequences of an atmospheric release of radioactive material from a La Hague pool could be extremely high. Thus, it is important to develop a thorough understanding of possible scenarios for loss of water from the La Hague pools.

One set of possible scenarios involves a loss of water by evaporation, following an interruption of pool cooling. For this to occur, site personnel would have to be unable or unwilling to restore cooling or to supply water makeup. This situation might arise during a time of war or civil unrest. Alternatively, a hazardous event at the site (e.g., an explosion in a facility that contains a

⁵² Thompson et al, 1979.

⁵³ NRC, 2000.

⁵⁴ Powers, 2000.

substantial inventory of radioactive material) might contaminate the site with radioactivity to a level such that access by personnel to the site is precluded.

Another set of possible scenarios involves a loss of water through a breach in the wall or floor of a pool or a connecting chamber. The breach might be caused by an earthquake, the dropping of a heavy object (e.g., a shipping cask), an act of war, or an act of sabotage.

A third set of possible scenarios involves a loss of water by siphoning or pumping. These scenarios might feature design error, equipment failure, operator error, or acts of malice or insanity.

Scenarios could exhibit a slow or a rapid loss of water. Water makeup might occur during certain phases of a scenario. Thus, the water level might fall, rise or remain static at different phases of a scenario.

4. Initiation and Propagation of Exothermic Reactions

A variety of exothermic reactions can occur after a loss of water from a spent fuel pool. Two of those reactions have been mentioned above, namely reactions between the zirconium alloy fuel cladding and steam or air. Both reactions proceed vigorously at temperatures above 1,000 degrees C.

Types of Exothermic Reaction

The steam-zirconium reaction yields zirconium oxide and hydrogen gas. This reaction occurred during the 1979 accident at the Three Mile Island nuclear power plant. The resulting hydrogen gas first accumulated inside the reactor pressure vessel and then escaped into the reactor containment building, where it exploded and yielded a pressure spike of about 2 bar.⁵⁵ At La Hague, it appears that each pool is enclosed by a building. Accumulation of hydrogen in one of those buildings could result in an explosion which breaches the building.

The reaction between air and zirconium has two exothermic components. One component is a well-known reaction between oxygen and zirconium. The other component, whose significance has been appreciated relatively recently, is a reaction between nitrogen and zirconium.⁵⁶ Especially in air-limited conditions, the nitrogen-zirconium reaction can produce a zirconium nitride layer under an outer zirconium oxide layer. This phenomenon can lead to shedding of the oxide layer, which has a protective function. Thus, an air-zirconium reaction can proceed more vigorously than an oxygen-zirconium reaction.

⁵⁵ The design pressure capacity of the TMI containment building exceeded 2 bar. However, it seems unlikely that the buildings surrounding the La Hague pools are designed for high internal pressure.

⁵⁶ Powers, 2000.

High-density spent fuel pools require the presence of a solid neutron-absorbing material between fuel assemblies. A material that is commonly used for this purpose is Boral, which consists of boron carbide in an aluminum matrix, clad in stainless steel. No information is available regarding the material used at La Hague. If a material similar to Boral is used, then it is important to consider the potential for that material to enter into exothermic reactions.

The aluminum matrix in Boral will melt at about 640 degrees C, and will then begin to leak out of its stainless steel cladding. Steel and zirconium form a eutectic mixture at about 940 degrees C, while steel and boron carbide form a eutectic mixture at about 1,150 degrees C.⁵⁷ Thus, if fuel cladding and rack temperatures rise to the vicinity of 1,000 degrees C, there will be opportunities for liquefaction and mixing of aluminum, zirconium and stainless steel. Such mixing could initiate an exothermic reaction between aluminum and stainless steel and, potentially, between aluminum and zirconium.⁵⁸

All of the above-mentioned exothermic reactions require comparatively high temperatures for their initiation. However, there is at least one reaction that could occur at ambient temperatures. Zirconium hydride precipitates have been observed to form in the cladding of fuel that has been taken to a high burnup. If exposed to air, zirconium hydride could potentially ignite spontaneously, at ambient temperatures.⁵⁹

Initiation of Exothermic Reactions

All the above-mentioned exothermic reactions, other than the reaction of zirconium hydride in air, require comparatively high temperatures (in the vicinity of 1,000 degrees C) for their initiation. Thus, it is important to determine the temperatures that fuel assemblies and fuel racks will exhibit following a loss of water. As mentioned in Section 2, the temperatures of these structures will vary over time, and will depend upon the exposure scenario, the physical configuration, and the decay heat output of the fuel. It should also be noted that swelling and rupture of the fuel cladding, and potential liquefaction of parts of the fuel assemblies and racks, will tend to inhibit heat transfer and therefore promote a further rise in temperature.

This situation is difficult to analyze, and the available analytic models have a number of significant deficiencies.⁶⁰ Rectification of those deficiencies will require empirical investigations and the development of more elaborate analytic models.

Using present models, the NRC has analyzed a typical high-density pool configuration to determine the age after discharge at which spent fuel is no

⁵⁷ NRC, 2000, Appendix 1.

⁵⁸ Powers, 2000.

⁵⁹ Ibid.

⁶⁰ NRC, 2000; Powers, 2000.

longer susceptible to the initiation of a runaway air-zirconium reaction if there is a total, instantaneous loss of water. Framing the analysis in this way reflects the fact that the decay heat in a fuel assembly declines with the assembly's age after discharge from a reactor. Also, age is a practical parameter for purposes of spent fuel management. For uranium oxide PWR fuel with a burnup of about 60 GW-days/tonne, the NRC has estimated that fuel aged more than five years after discharge is no longer susceptible to a runaway air-zirconium reaction.⁶¹

In scenarios involving partial exposure of fuel, heat transfer would be less effective than in the case studied by the NRC, with the result that older fuel would be susceptible to runaway exothermic reactions.⁶² Consideration of clad swelling and rupture, liquefaction of fuel and rack structures, and the full range of exothermic reactions would also extend the age at which fuel is susceptible to runaway exothermic reactions. Indeed, the presence of zirconium hydride, which is characteristic of high-burnup fuel, might cause a runaway reaction to commence in very old fuel. It should also be noted that spent MOX fuel generates substantially more decay heat than spent uranium oxide fuel of the same age after discharge. Thus, MOX fuel must be substantially older than uranium oxide fuel if it is to be no longer susceptible to runaway reactions.

Propagation of Exothermic Reactions

Following a loss of water from a pool, runaway exothermic reactions will be preferentially initiated in regions of the pool where decay heat levels are comparatively high and the configurations are comparatively dense. In regions where decay heat levels or densities are lower, runaway reactions may not be initiated. However, runaway reactions may propagate to less susceptible (cooler) regions through three mechanisms. First, heat may be transferred directly from hotter to colder regions of the pool by radiation and conduction. Second, heat may be transferred from hotter to colder regions by air and steam convection loops inside the pool building. Third, liquefaction and collapse of fuel and rack structures in hotter regions may alter flow paths and thereby inhibit convective circulation to colder regions.

The La Hague Pools

The preceding discussion is generic. In the case of the La Hague pools, the available information does not allow an independent assessment of the potential for runaway exothermic reactions following a loss of water. However, a paper from the IPSN provides an indication that runaway reactions can be initiated. That paper discusses calculations which showed that the air temperature in the building that houses pool D at La Hague would rise to 1,000 degrees Celsius following a loss of water.⁶³ The fuel cladding temperature would be higher than

⁶¹ NRC, 2000, Appendix 1.

⁶² Thompson, 1999.

⁶³ Goumondy and Marciano, 1997.

the building air temperature. Thus, it is likely that runaway reactions would begin under these conditions.

Apparently, the IPSN paper assumed that the configuration of pool D, and the type of fuel stored in the pool, would be as currently authorized. The changed authorizations that COGEMA is seeking would substantially increase the potential for runaway reactions following a loss of water. This potential would be increased in two ways. First, COGEMA seeks to increase the density of storage in the La Hague pools, a change which would increase the temperature of the fuel cladding following a loss of water. Second, COGEMA seeks to store higher-burnup fuel and MOX fuel in the La Hague pools, and both changes would increase the propensity for exothermic reactions to occur following a loss of water.

5. Release of Radioactive Material

If the cladding of exposed fuel ruptures, but the fuel otherwise remains intact, then a "gap" release of radioactive material will occur. In this situation the radioactive material available for release will be material that has previously escaped from the fuel pellets and has then been confined in the gap between the pellets and the cladding.

If, at a later stage, runaway exothermic reactions begin, then radioactive material will be released from the pellets themselves. Comparatively volatile elements such as cesium can be evaporated and will subsequently condense as small, airborne particles. Refractory elements can be entrained as small particles in flowing air and steam, especially under oxidizing conditions.

No information is publicly available regarding the confinement capabilities of the buildings that house the fuel pools at La Hague. However, it is unlikely that these buildings were designed to confine the type of release that would accompany runaway exothermic reactions. If those reactions include a steam-zirconium reaction, then the resulting accumulation of hydrogen could lead to an explosion which breaches the building.

6. Design Alternatives and their Hazard Implications

The potential for the La Hague pools to experience a large release of radioactive material could be modified by adopting alternative designs or modes of operation. A wide variety of alternatives can be identified.

One alternative option would be to re-configure the La Hague pools so that fuel is stored at a low density. With such a configuration, the temperature of the fuel cladding will remain comparatively low if water is lost from a pool. In this way, all potential exothermic reactions other than the air-zirconium hydride reaction could be precluded. The potential for the latter reaction, and the available means for avoiding or mitigating the reaction, require further investigation.

Additional storage capacity, to replace the capacity lost by re-configuring the La Hague pools, could be provided by employing dry storage technology. Proven technology for dry storage is available. Dry storage capacity could be built at La Hague or elsewhere.

An alternative option that has been identified by IPSN would involve the introduction of large holes in the walls and roof of the pool building.⁶⁴ The holes in the walls would allow comparatively cool (ambient) air to enter the building and provide natural convective cooling to the fuel assemblies if water is lost from a pool. After providing this cooling function, the air would leave the building through holes in the roof.

This arrangement could be effective if the density of fuel storage were comparatively low. However, it would have little effect if the pool were densely packed, or if fuel assemblies were partially submerged. In either case, convection within and around the fuel racks would be inhibited, and the presence of comparatively cool air above the racks would have little effect. Moreover, if exothermic reactions were initiated in a pool of this kind, the presence of holes in the pool building would have two adverse effects. First, the holes would feed, rather than starve, any reactions that involve air. Second, the holes would allow radioactive material to pass directly to the atmosphere.

7. Role of the IPSN

This reviewer is not familiar with the duties, powers and resources of the IPSN. However, from their paper on the La Hague spent fuel pools it appears that IPSN has the capability to perform extensive theoretical and empirical investigations of hazard-related issues.⁶⁵ Thus, IPSN has a responsibility to ensure that the potential for a large atmospheric release from the La Hague pools is assessed using the best available scientific knowledge and methods.

It is not clear that IPSN is fulfilling this responsibility. The Institut's investigations are performed in secret, and are therefore subject to misconception, incompleteness or error. From their paper, it is not evident that IPSN has considered the full range of phenomena that are relevant to the potential for an atmospheric release from a spent fuel pool.

⁶⁴ Ibid.

⁶⁵ Ibid.