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Issues and decisions for nuclear power plant management after fuel damage events

INTERNATIONAL ATOMIC ENERGY AGENCY

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FOREWORD

Experience has shown that the on-site activities following an incident that results in severely damaged fuel at a nuclear power plant require extraordinary effort. Even in cases that are not extreme but in which fuel damage is greater than mentioned in the specifications for operation, the recovery will require extensive work.

This publication includes information from several projects at the IAEA since 1989 that have resulted in a Technical Report, a TECDOC and a Workshop. While the initial purpose of the projects was focused on providing technical information transfer to the experts engaged in recovery work at the damaged unit of Chernobyl NPP, the results have led to a general approach to managing events in which there is substantial fuel damage. This TECDOC summarizes the work to focus on management issues that may be encountered in any such event whether small or large.

The draft of the document was prepared by C.A. Negin (USA), based on IAEA activities since 1989 that involved approximately 40 experts from ten countries. Four experts took part in the discussions of the draft during a consultants meeting, namely A. Borovoi of the Russian Federation, R. Deleryd of Sweden, M. Kaercher of France, and R. McGoey of the USA.

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CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Events that cause fuel damage at a nuclear power plant can have a major impact, whether or not there is fission product release to spaces within and outside the plant. Fission product releases that do not represent a public hazard and that are of much less magnitude than the accidents at the Three Mile Island NPP (TMI) and at Chernobyl NPP can nevertheless be an "economic disaster" for the plant owner.

The experience gained from past fuel damage events must not be forgotten; careful analysis and information about various actions taken must be provided to all interested parties. For this reason, in the mid 1980s the IAEA initiated the preparation of a series of documents summarizing the experience in managing the major fuel damage events. This TECDOC represents the completion of one of these initiatives for which the subject is managing on-site conditions after the initial emergency response to an event has been conducted.

During this work, one of the more important points to arise, and perhaps the most important insight that can be gained by the reader of this report, is that an event of *much less magnitude* than Chernobyl or TMI can create *on-site* conditions that will require a major effort to manage and correct. Further, even when an event is much less serious, many of the individual on-site efforts and activities are similar to those conducted after a major fuel damage event.

Although any future scenario will be different from previous events, regardless of the magnitude and seriousness, the management approach will need to address similar technical and safety issues for recovery and cleanup, and in some cases, for specific operations. Therefore, though such events are unlikely, management should be aware of the issues and decisions that will be placed upon them in the event of an occurrence of fuel damage.

1.2. PURPOSE

The purpose of this TECDOC is to provide insights so that management can be prepared for and better able to react to fuel damage events. This is accomplished by discussing issues and decisions from experience of past events for managing *on-site* recovery activities. Should such an event occur, this TECDOC can serve as an initial "management checklist." This TECDOC focuses on managing activities associated with in-plant systems, processes, and fuel. Off-site response is addressed in many other reports.

In this report, types of activities and organization functions have been identified. Clearly the degree to which any will depart from the normal plant activities and organization depends on the severity of the event. Further, because any future fuel damage event will not closely pattern any of the past with respect to the specific scenario, specific considerations within this TECDOC *are not intended to modify a plant's current management and operation*. It is noted, however, that some plant owners have implemented these ideas in the form of training courses and contingency planning, reserve equipment, and standing contracts with others for assistance, if ever needed.

1.3. SCOPE

This TECDOC addresses primary subjects for management attention in recovering from an event with fuel damage and fission product release. The order of the sections approximates the general sequence in which these subjects require attention. This sequence should not be viewed as rigid. There will be considerable overlap in the timing and schedule of all of these topics. The subjects are:

- Organization
- Planning

- Data management & analysis
- Stabilizing the conditions
- Water and gas management
- Damaged fuel removal
- Return to operation
- Managing solid waste.

This TECDOC summarizes information and is not intended to provide an extensive level of detail. Discussion has been limited to project and technical management. In general, only topics of special or unique importance to recovery are discussed. There will be many more issues to manage which are customary for standard plant operations. Reference [1] includes a comprehensive set of relevant references.

1.4. INTENDED AUDIENCE

Those responsible for the safe operation of nuclear power plants should acquire an overview of the situation that may result from an event in which there is significant damaged fuel. Compiling the major management issues for recovery from past events can provide insights for those who wish to use this information for their own planning or preparedness. Accordingly, this TECDOC is intended primarily for an audience of:

(a) Managers and directors who will have the responsibility in the event of a fuel damage event; and
(b) Safety authorities who need an understanding of some of the key issues and decisions for recovering. Its use can be either for training or for a rapid introduction to issues that will be faced in the event of a fuel damage event.

2. BACKGROUND - FUEL DAMAGE EVENTS

Commercial nuclear power plants have a design specification for failed fuel that affects parameters such as physical arrangements, shielding, water purification capability, waste conditioning capability, and radiation monitoring. This design basis is usually expressed as a fraction of core fission products released from the fuel. For a minor incident or accident resulting in fuel damage and loss of cladding integrity, handling of failed fuel assemblies is most likely done with standard tools available in the plant. Such events do not lead to fission product contamination beyond the capability of the plant's installed cleanup systems. They should be able to be managed without additional resources or extraordinary effort.

Operationally, a very small amount of fission products can be released from fuel without necessarily shutting down. Overall, experience has been excellent and operation is rarely limited by fission product release from the fuel. Indeed, at the first hint of an upward trend in fission product activity, plant operators commence an investigation to remedy the cause.

Cases of fuel damage and fission product release beyond the design basis and operating limitation are the main focus of this TECDOC. This includes cases that range from one assembly with cladding failure to major damage of a large number of assemblies of a core, the latter leading to substantial release of fission products and requiring special equipment for dealing with fuel and wastes.

At the extreme of this experience are two major accidents, at Three Mile Island (TMI) Unit 2 and Chernobyl Unit 4. In these two cases, the nuclear fuel assemblies were substantially destroyed, with significant quantities of fission products released. The TMI accident resulted in severe economic impact. Here the reactor vessel, primary circuit, and containment provided an effective barrier for release to the environment. Release of fuel material outside the primary circuit was limited to very small quantities. Recovery and cleanup of TMI-2 took about 7 years with no restart. The consequences of Chernobyl were much greater; cleanup is still not complete after 10 years.

Minor fuel damage ranging from one fuel pin up to multiple fuel pins in several fuel bundles has been experienced with causes and fixes listed in Table I. Where this has occurred, reconstitution of the failed fuel assembly by replacing the individually failed pins is standard practice. If a fuel assembly is not repaired, it results in possible decrease in power generation and increase in the amount of waste (and related high costs). If not detected and corrected quickly, high levels of contamination and personnel exposure can result.

In between the extremes of minor fuel damage and complete core destruction, there have been several events at earlier plants characterized by partial damage to fuel assemblies and cores. The events, listed in Table II along with TMI-2 and Chernobyl, encompass the major fuel damage accidents. In some of these cases, plant operation was restored; in most it was not. Although most of these plants are not typical of today's power reactors, the lessons of their stabilization and recovery are of value.

The fundamental causes of major fuel damage are similar to the causes of the minor events, however, the effects are much greater. Causes of fuel damage in both types of cases have been:

- flow blockage
- fabrication errors or contamination
- design
- equipment problems
- staff operating errors
- foreign material in core during loading
- distortion of components.

TABLE I. CAUSES OF MINOR FUEL DAMAGE

Causes (examples)	Fix
Flow blockage/foreign material - Reduction or blockage of coolant flow to a local part of a fuel assembly due to foreign material becoming lodged between fuel pins resulting in local overheating, then loss of fuel cladding causing leakage from a limited number of fuel pins. Foreign material can also abrade holes in the fuel clad.	Proper coolant filtration and control of materials during refuelling and after services.
Fabrication - Fabrication oversights have caused minor fuel failures for example, improper spring forces in spacer grids have resulted in vibration and cladding failure due to fretting. Pellet cladding interaction (PCI) caused by fabrication errors has also resulted in failures.	Close quality control of fuel design, fabrication, operation, inspections, and follow-up.
Design - When designing a reload core, fuel must be located to account for fuel bow, twist, and bulge (BWR channels). If not, experience has shown that peaks in neutron flux can cause cladding failure.	Careful reload design using state of the art analysis and design methods will preclude failures.
Operation - Examples: (a) excessive rates of plant start-up, (b) rapid transients, and (c) mechanical damage from improper fuel handling during refuelling.	Training discipline, and quality procedures for operation and maintenance.
Water chemistry - Improper water chemistry has caused chemical attack or deposits on the cladding (for example, oxide layer growth).	Proper filtration, chemistry control, post-decontamination cleaning.

TABLE II. EVENTS WITH MAJOR FUEL DAMAGE

Plant (year)	Country	Primary cause	Brief description
NRX (1952) water cooled, heavy water moderated	Canada	Design, operator error	A reactor runaway from a combination of design flaws & operator error resulted in damage of fuel & leakage of moderator water, flooding the building. Returned to service [2]
Windscale (1957) gas cooled graphite pile	UK	Lack of information for operators	Uncontrolled release of Wigner energy, fire & destruction of a substantial portion of air cooled core, some fission products released to the environment [3]
SL-1 (1961) small prototype PWR	USA	Design	Prompt critical while shutdown with head off, reconnecting control rod-to-drive mechanism, destruction of the core, substantially contained within the building [4]
Fermi 1 (1968) sodium cooled	USA	Design	"Splitter plates" below the core vibrated loose and blocked fuel channels, causing melting of several assemblies, contained within primary system. Returned to service [4]
Ågesta (1968) water cooled	Sweden	Design	Spacer grid spring relaxation and flow vibration. 15 fuel assemblies failed. Returned to service with modified fuel [5]
St. Laurent (1968) gas cooled, graphite moderated	France	Procedure	Flow reducer for a control channel placed in a fuel channel. Fuel overheating and destruction of 5 cartridges. Returned to service [6]
Lucens (1969) experimental gas cooled, heavy water moderated	Switzer-land	Channel flow blockage	Coolant leakage, followed by moderator tank rupture, and severe damage to a single fuel assembly [7]
A-1 (1977) gas cooled, heavy water moderated	CSSR	Blocked fuel channel, opera-tor confusion	Rupture of fuel cladding and de-cladding of fuel occurred in the upper 30 to 100 cm of fuel elements; 148 assemblies affected [1]
Three Mile Island (1979) PWR	USA	Operator confusion, relief valve stuck open	Failed to keep core covered with water, destruction of the core with large fraction melted, fuel contained within systems [8]
Chernobyl (1986) water cooled, graphite moderated	USSR	Design, violation of operating procedures	Prompt critical reaction caused destruction of the reactor with substantial distribution of fuel and fission products outside the primary envelope and to the environment [9]

These past events have demonstrated that recovery operations can be effectively managed. And, while the chances of such events are extremely small, such accidents exceeding design limits can result. If one does, it can result in substantial economic loss, may lead to unacceptable releases to the environment, and will be a major management challenge.

3. ORGANIZATION

The existing plant and utility staff will respond to the initial demands of the fuel damage event. Their primary and immediate responsibility is to gain control of plant conditions and obtain data on the amount of core damage and fission product spread. Subsequent activities may require augmenting and/or modifying the existing organization depending on the complexity of the situation.

3.1. ORGANIZATION STRUCTURE

The severity of the fuel damage and fission product spread will determine the need for additional personnel and organization structure. As soon as possible after the immediate emergency response is handled, this need should be assessed. The International Nuclear Event Scale (INES) can be used as an aid for initial planning and decision making [10]. Figure 1 illustrates this concept:

- Events of Scale 1 and 2 are classified as incidents and anomalies. They can typically be managed by the existing plant organization using established procedures.
- Events of Scale 3 to 5 include the range up to an accident with off-site risk. These events will most likely require additional resources, that is, personnel, skills, and special equipment. A special recovery project is appropriate. In most of these cases the existing plant management structure may be sufficient to manage the recovery, with additional resources. The management effort is compared to an extended outage for major plant modifications. However, in some cases, because of other than technical factors, management may choose to organize the recovery as in the next paragraph.
- Events of Scale 6 and 7 are serious or major accidents. These events have large financial implications and complex technical challenges. Recovery will require a substantial effort in addition to that needed to control plant systems and equipment. A special recovery project organization will be needed to address the complex problems that are outside the plant staff's usual activities. Reporting to a senior level of management higher than the normal plant organization is necessary to allow rapid decision making for unusual and complex issues. The plant staff will necessarily concentrate on establishing and maintaining the plant in a stable condition.

As soon as sufficient information is available, executive management must first decide whether the recovery can be managed by the existing structure, or whether a project-structured additional organization is needed. If the latter is the case, then it must also be decided whether the additional project organization will report via the existing plant structure or directly to senior management.

3.2. RECOVERY PROJECT ORGANIZATION

Recovery from fuel damage/fission product release typically has unique circumstances. As the recovery proceeds, the severity and consequences will become better understood. The organization must be flexible and adjust quickly to changing conditions and needs. A project management style of organization with defined goals and responsibilities is best suited for such circumstances. Senior individuals who have had management experience under these type of conditions should be used. The full capability of the pre-event plant operational organization must also be retained as there will be many plant operations to be conducted.

Figure 2 illustrates this dual purpose organization structure; that is, the existing operational organization with a parallel recovery project organization.

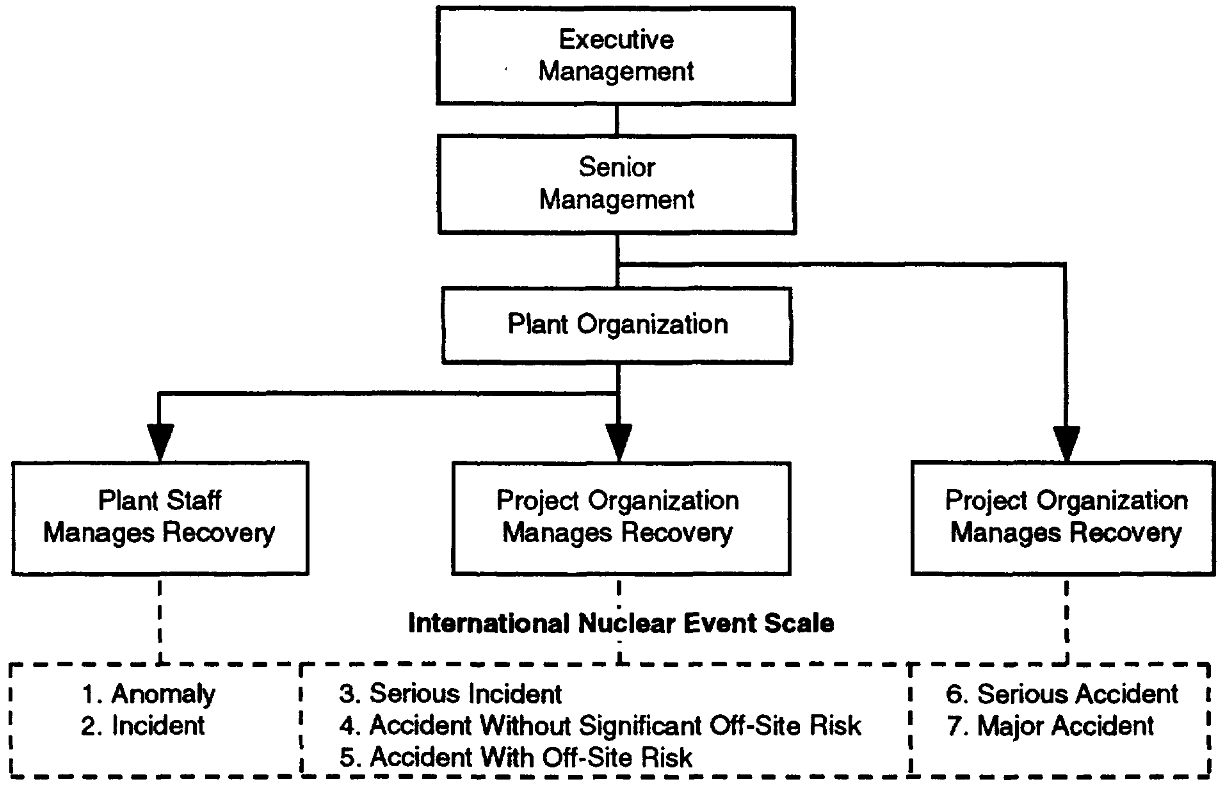

FIG. 1. Recovery organization management structure and INES Event Scale.

Once it has been decided that a recovery project organization is needed, the foundation must be built to provide unique functions and special expertise. Obtaining help from outside the company will probably be necessary. This is an important planning stage which requires close co-ordination between recovery management and existing plant management to ensure that duplication of effort is avoided.

Existing plant and company staff should be used to set up the recovery organization to the maximum degree possible to avoid the time lost in training individuals who are not familiar with the plant. Reasons for augmenting the existing staff with support from outside sources are: (a) to allow existing staff to concentrate on daily operations and mind the power plant, and (b) need for special expertise not available from existing personnel.

The recovery organization should be located to allow for efficient communication and to optimize integration with the plant staff. Experience has shown that the organization should be on-site to the maximum extent achievable. Off-site activities such as engineering and training are possible, but should be minimized to maintain a focus and the sense of urgency. Local fabrication capability is also helpful to expedite special tools and fixtures that may be needed.

3.3. PROJECT FUNCTIONS

Recovery for event categories from serious incidents to major accidents will require augmenting the existing staff with additional skills and expertise. The possible skill needs can be technical, operational, labour, financial, public relations, regulatory affairs, to name a few.

The right branch of Fig. 2 shows some of the special project functions that may be required. There may be a need for other special functions to address project specific issues such as logistics, regulatory interaction, public relations, etc.

3.3.1. Project staff functions

A planning function will develop strategic and technical plans, working closely with the line organization. The assigned group should ensure that information is distributed within and outside the organization, support the resource planning, and act as the interface with the technical and safety advisors and the Safety Authority. The planning staff can also be assigned responsibility for arranging outside expertise and services when needed.

A project schedule and budget must be developed and maintained. This will be a difficult challenge because: (a) there are few precedents and no standards for estimating costs of recovery activities, and (b) the project may change relatively rapidly as information about fuel and plant conditions are developed.

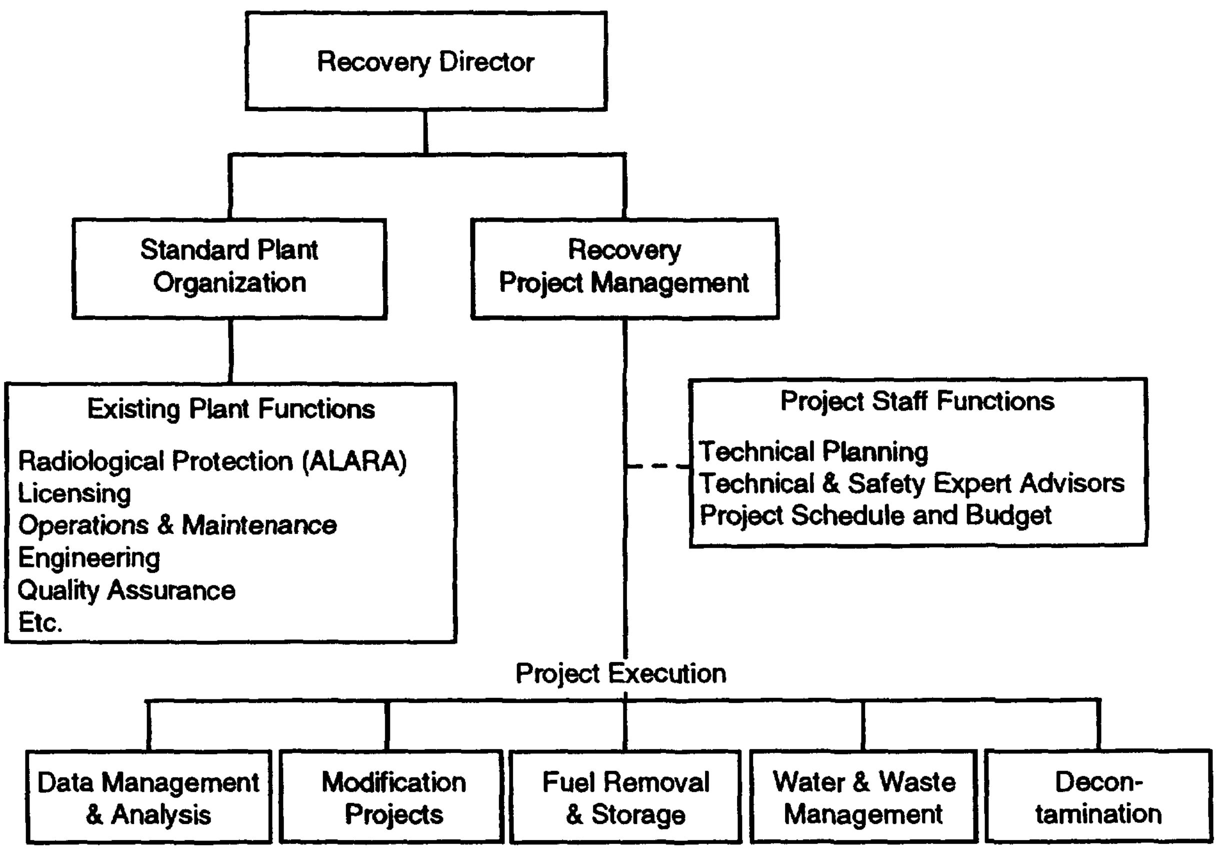

FIG. 2. Organization that includes parallel operations and recovery project management.

Independent technical advisors can bring a depth of technical experience that will enhance the perhaps narrower experience of day-to-day engineers and managers. They can prove useful for a technical critique of plans and operations. Their role is to evaluate the recovery plans in relations to what has proven successful in other industries as well as the nuclear industry.

Independent safety advisors are useful for evaluating the cleanup in terms of how the work relates to public and worker health and safety. This type of advice should focus on regulations, risk assessment, radiological protection, project organization, procedures, planning, and public communication.

A public communications interface may be needed. There may be many outside influences on the ability to progress technically. An effective communications group is needed to translate the complexities of the technical situation into explanations for less technical or less involved individuals.

3.3.2. Data management and analysis

Centralization of data management and analysis within the organization is required to ensure sufficient resources and to emphasize the importance of reliable data. Providing a common point for obtaining and sharing data by all elements of the organization is also important. This group plans and co-ordinates the gathering, maintenance, analysis, and distribution of technical data to support waste management, decontamination, and fuel removal.

This group can also take on the responsibility for arranging special tasks related to the needs for data and conduct of analyses. Such arranging can be for activities such as on-site and off-site chemical, radiochemical, and metallurgical analysis, investigation and procurement of special examination devices and methods, inspections to determine physical conditions, establishing data bases, and many others.

3.3.3. Modification tasks and projects

Where not handled by other groups, project management and project engineering will be required to manage the implementation of modified and new facilities, equipment, and systems. The project management responsibility is best placed close to the plant because there will be a continuous need for direct information from the plant.

A group of mechanical, nuclear, structural, electrical, and chemical engineers and designers may be required to design modifications and new equipment/systems. This group can be off-site in a classical situation of architect-engineer or turnkey suppliers. However, such off-site location will create a potential for progress that is too slow. Close and intensive co-ordination will be required.

3.3.4. Fuel removal and storage

Removing and storing damaged fuel requires expertise in fuel handling, measuring, remote technology, custom fabrication, etc. There may be a need for special hardware and its design, fabrication, and test. Mockups may have to be set up. Selection and training of fuel handlers and support personnel will be required. Measurements, evaluation and safety analyses will be required. A project group should be assigned the responsibility for damaged fuel characterization, handling, packaging, and storage.

3.3.5. Water, gas, and waste management

In the early phases of a recovery, water management will have a strong influence on the ability to proceed. Water must be processed to remove radioactivity. Water storage may become critical, especially if large volumes have been contaminated during the event and recovery. Release of processed water will have to be closely monitored.

Waste gases may contain hydrogen, gaseous fission products, and other radioactive airborne constituents. Gaseous releases may be required from enclosed spaces to allow human access or to prevent potentially flammable mixtures. Purging of gas build-up from damaged fuel and waste canisters prevents build-up of pressure or flammable mixtures. These activities would normally be conducted by the operations staff. However, because there may be conditions not encountered during normal operation, there may be a need for management by the waste group.

As the recovery proceeds large amounts of wet and dry solid wastes will be generated from water processing, decontamination, and fuel removal operations. Solid waste management will require an increasing amount of attention for characterizing, conditioning, packaging, storing on-site, and shipping to off-site disposal.

These challenges may be either beyond the experience of the normal plant operators, or of a magnitude that would strain normal plant resources. In such cases, a project group can be created to manage, plan, design, construct, and recommend how to operate water and waste systems and facilities. Waste management must work closely co-ordinating its plans and activities with the decontamination group and with those responsible for radiation protection as each of these functional responsibilities are connected to the others.

3.3.6. Decontamination

An early high priority will be to gain access as quickly as possible to the damaged fuel and damaged equipment to conduct assessments to support planning for fuel removal. It is extremely important that decontamination priorities be based on criteria which support the ALARA principles for accomplishing access and other priority tasks. Decontamination solely for the purpose of cleaning must be viewed as a low priority in the early stage of the recovery.

A decontamination management group may be required if there is substantial contamination that must be dealt with in order to proceed. This group can be responsible for selection of methods, schedule co-ordination, procedure writing, and arranging for decontamination staff and equipment. Early decontamination efforts may require large numbers of people. The deployment of contractors of special skills in these fields may be advisable. To maintain priorities properly, management of the decontamination group should be by the plant owner, even if contractors are used to doing the work.

4. PLANNING

Recovery project planning is conducted for engineering, construction, and operations types of activities to characterize, cleanup, remove, and dispose of the fuel and related waste. Each recovery project will have to establish its own specific plans and organization for planning. This section provides some insights as to how others have approached planning with regard to pre-event contingency planning and post-event recovery planning.

4.1. PRE-EVENT PLANNING

Pre-event planning refers to contingencies that are established prior to a fuel damage event so as to be prepared for one. Accidents are sufficiently different to preclude the possibility of providing contingencies and detailed preparations for all eventualities. However, some companies may wish to establish contingency plans for those actions, situations, and conditions that are most likely. Suggestions follow.

4.1.1. Management

- Assign responsibility for specific areas of recovery after the immediate accident response to managers or groups within the company who are not normally directly involved with plant activities, but may be heavily involved in the initial plant response.

- Establish a special communication plan. This is for communication with those outside the direct recovery programme who will have a related responsibility or whose interests are substantially affected. Examples include regulators, local government officials, government agencies who can lend support, owners and shareholders, and the press. Consideration of the latter should include selecting the primary individual with special skills for press briefings.
- Identify institutions, agencies, or companies that should sponsor and manage technological developments to support dealing with damaged fuel and abnormal waste if the need arises.

4.1.2. Training

- Conduct training sessions of lessons learned from accidents. Documents like this TECDOC and its references provide insights and will help increase awareness of issues to be addressed and actions to be conducted.
- When conducting practice drills, establish scenarios that simulate unique conditions to exist. For example, postulate contamination of a major secondary circuit that additionally causes contamination of a plant area not typically restricted to human access.

4.1.3. Technical contingency planning

- Have provisions to deal with some limited amount of fuel failure. For example, have canisters available for the storage of one or more fuel assemblies, which may have undergone significant damage.
- Conduct an assessment of the flexibility of liquid, gas, and HVAC systems as well as plant areas to accommodate hookups to temporary systems to transfer material for additional storage or processing.
- Review provisions and methods of collecting samples should water, gas, and air handling systems be contaminated well beyond expected values. Off-site private and government laboratory and hot cell facilities should be identified in advance as a contingency.
- Develop a list of suppliers of special services for help in water processing, sample analysis, decontamination, laundry cleaning, which may be needed on short notices. This may go as far as to establish standing contingency contracts with special vendors for quick response.
- If modifications to existing plant systems are made to enhance capability to support normal operations, consider what may be included at the same time to deal with possible accident conditions. Examples include shielding, connections, access paths for remotely operated vehicles, etc. These are in the general category of facilitating access with non-fixed equipment. It would not be prudent, however, to add or oversize equipment substantially or increase capacity where no positive benefit can be shown for accident management.

4.2. RECOVERY PLANNING

The period addressed by this TECDOC begins after the emergency response to an accident has been conducted. The plant is shut down, cooled down, the reactor is under control, decay heat removal is in progress in a stable manner, and conditions are changing slowly. This could take from one day to several weeks after the event, depending on the specific conditions. During this time planning must begin to focus on recovery.

Following the operational response and while establishing long-term stability, management will have many new and unusual areas to deal with. Immediate short term planning must concentrate on many subjects in parallel which are indicated by the titles of the sections that follow. As with outage planning, recovery project planning and execution addresses activities, schedule, resources, costs, and restraints. However, a fundamental difference between outage planning and planning recovery from fuel damage is that not all activities can be known in advance. More of a "plan as you go" approach may be required where activities, schedule, etc. must await detailed characterization information and feedback from operations before future steps can be planned.

The only near-term planning certainty is that conditions will be like no one would have predicted. Despite the uncertainties, it is important to establish a plan early which addresses first regaining access to plant areas for long-term operation and/or to gather information needed to proceed.

The long-term planning horizon is when fuel and abnormal wastes are packaged either for interim storage or final disposal and activities are in place to either restore the plant to service or establish a safe state from which decommissioning planning can start. When sufficient information is available, planning should establish a long-term goal. However, depending on the severity of the accident, the needed technical information may not be available for weeks, months, or even a year or so. For example, early intentions after the TMI-2 accident did not exclude a plant restart. Also, establishing long-term objectives may be influenced by factors outside the direct effects of the event, for example, financial, need for power, national policy, etc.

If fuel damage is substantial, many special operations and tasks will be required. In such cases, it is important to derive and communicate the overall programme, both within the recovery organization and externally, so that objectives and technical issues are well understood by all involved. For this purpose, consideration should be given to formulating a "strategic plan" for the recovery. This plan will provide top level direction and policy guidance for subject areas that are not normally addressed at an operating plant. As the programme evolves, the actual conduct of the recovery may be different from the initial plan. However, if realistically conceived with the aid of experienced advisors, the overall strategic approach should need infrequent modification.

The strategic plan should establish definition of the phases of the recovery. The recovery strategy can be viewed as a phased programme in which each of several stages is defined by the type of activities that are conducted. Phases must be defined to fit the specific situation; Table III provides an example. (An "X" in a column in this table only indicates when certain activities are emphasized. Many of the activities will be conducted over several phases.) Phase definition is only a mechanism for describing the plan logic and it is unnecessary to establish a clear division or precise completion date for each phase. The plan should define the objectives for each phase of recovery as specifically as possible.

TABLE III. EXAMPLE OF PHASES OF RECOVERY PROGRAMME

Recovery activities	**Recovery phases**			
	Stabilize	**Primary cleanup**	**Restore and operate**	**Final cleanup**
Reactor control	X			
Decay heat removal	X			
Gain access	X			
Plant condition assessment	X			
Fuel condition assessment	X			
Water storage	X			
Gas processing and release	X			
Water processing		X		
Decontamination for access		X		
Damaged fuel removal		X		
Damaged fuel storage			X	
Decontamination for operation			X	
Return to operation			X	
Waste storage			X	
Decontamination for cleanup			X	
Fuel on-site storage & shipping				X
Waste shipping & disposal				X

The strategy should establish project or task groups within the organization according to the objectives of the recovery phase. As each phase's objectives are being achieved, the project organization is adjusted for the next phase. For example, if the stabilization phase requires a project group to put in place shielded access corridors, once they are established, the individuals in the project group can be assigned to other tasks.

Completion criteria for all major activities should be defined, and updated as progress is achieved. Planning should establish detailed "end points" which will serve as goals for residual contamination and fuel removal. End points should be quantitative, where possible, but realize that they may need to be adjusted for what can be realistically achieved as the recovery progresses. By specifying explicit completion targets, engineers, technicians, and other skilled workers will better be able to establish a clear idea of how to proceed with their work.

Strategic planning will need to address a wide variety of management policies, which provide guidance for mid-level management. For example:

- Consultations and directives from regulatory organizations are a given. However, it must be understood that prescriptive types of regulations are derived for standard conditions that may not be the case for many recovery situations. A process needs to be established with the Regulatory Authority for diverging from established rules and regulations that do not cover the existing physical and operational circumstances.
- Factors that are not under the control of the plant owner can affect the recovery decisions. For example, where and how to dispose of damaged fuel and abnormal waste may have an influence on conditioning methods.
- Decide the degree to which physical and administrative separation is needed for safety and operation of adjacent and connected units without the damaged fuel. This is especially important where operations and maintenance share personnel, systems, rooms, facilities, and resources.

Strategic planning can also provide technical direction for operations, maintenance, facilities needed, concept development, procurement, etc. For example:

- Special requirements for ensuring the reactor remains under control and a plan for monitoring to ensure this control.
- Methods for short term and long term decay heat removal.
- Guidance as to types of activities that can be indefinitely deferred to the future; for example, maintenance on equipment that may never be used again.
- Selection of methods for processing of water and gases.
- Requirements for conditioning of solid waste based on disposal constraints.
- An overall approach to fuel removal, detailed to the degree that fuel condition is understood.
- Develop a listing and brief function of systems and facilities thought to be needed. This includes special requirements (such as mobile laboratories) plus the use of existing plant facilities, systems, and equipment in ways not originally intended by the designers.
- Special safety, safeguards, and security measures.
- Special considerations for personnel, public and environment protection.
- How to strengthen barriers where necessary to reduce spread of fuel and waste to unwanted areas.
- Criteria for the conditions and timing when complex techniques such as robotics application and chemical decontamination should be considered.

These examples are only a few that have proven to be important in the past. The staff assigned to planning must be organized in parallel with the major types of activities and work directly with the engineering and operations organizations that carry out the activities. As a starting point, it is suggested that the management consider a planning staff assigned into subgroups responsible for:

- Data management and analysis
- damaged fuel removal

- decontamination
- water and waste management
- schedules and cost estimates.

5. DATA MANAGEMENT AND ANALYSIS

All nuclear power plants use a multitude of measurement, analysis, and other characterization techniques. However, in a fuel damage situation, data management and analysis can take on a much greater measure of significance because of the extreme difficulty of physical access and the need for information unique to the circumstances. Thus, there is created need for many techniques that are not usual for the plant. These can include, for example: sampling, radio-chemical sample analysis, chemical analysis, radio-spectrometric analysis, calculational analysis, and facilities and software for these activities. Data management and analysis as used here applies to:

- Data acquisition - planning, creating the tools, and making a wide variety of measurement observations and measurements;
- Data processing - computer systems to maintain data and convert it to useful formats and display;
- Data analysis - computer software, not necessarily complex, used to evaluate and present the results of information derived from data.

Reliable data is a most important, and often lacking, ingredient in planning cleanup operations. Data must be systematically collected, tracked, and organized to avoid false starts and overly optimistic or conservative assumptions. The importance of data specific to the cleanup and to recovery from any accident cannot be overemphasized. Furthermore, direct measurements, samples, and observations are needed to assure that decisions being made are based to the maximum degree on actual field conditions, versus assumptions or postulates.

5.1. METHODS AND TECHNIQUES

5.1.1. Direct observation and visualization

A variety of methods are required for obtaining samples and measurements, and making observations. Specific considerations include:

- The ability to visualize physical conditions is very important because many will be different from those expected by previous experience. Pictures are invaluable, whether in the direct form of photographs, video, or with the use of devices such as infrared and ultraviolet viewers, or computer imaging of the physical situation that cannot be photographed in a large view.
- Remote viewing techniques - Observation of geometric structures and surfaces, for example in situ viewing of the damaged fuel, may provide the most important information on which to base decisions for any programme of work. Equipment is available today that will function under water or in high radiation levels to provide close-up views of the items of interest. There are available endoscopes, glass fibre optics, and closed circuit radiation-hardened TV systems which are small in outer dimensions. These can provide access to concealed objects, even through curved or offset centerline pathways.
- Quality and reliability of visual information depend mainly on the precise manipulation of the visual systems to ensure the correct reference points of the observations. Optical viewing is fully dependent on adequate lighting and, for underwater application, on the clarity of the water.
- Neutron and gamma measurements can be used to locate distributed fuel material. Whether with existing or new instruments, this information can be used to find relocated fuel nondestructively in the pressure vessel, in primary circuit piping, or attached piping systems.
- Gamma spectroscopy can be used to map fission product concentration in contaminated systems and rooms.

- Methods are available to make penetrations through heavy reinforced concrete walls and steel piping material into areas which may be under positive pressures and contain radioactive water or gases. Sometimes this will be the only feasible way to sample or insert cameras and other instruments to obtain the needed information.
- A variety of robots are in use at nuclear power plants. Some or similar machines should be considered for data gathering. Past success has been achieved with a mobile platform (carrier) that can be fitted with different survey and sampling devices. Experience has shown that in procuring such machines:

    - Specify only after sufficient information is available to define what the device is supposed to do.
    - Operational personnel must participate in development.
    - Insist on mock-ups for qualification and practice.
    - Ability to decontaminate the robot is important.
    - Electronics and communication hardware must be radiation tolerant for the expected environment.
    - Avoid becoming overly dependent on costly robots that cannot be sacrificed; for example, if they cannot be retrieved for repair.

Visualization refers to the presentation of information in a format so that it can be readily understood using visual comprehension. A variety of methods are available such as video recording and editing, photographs, computer graphics, computer three dimensional modelling, and physical models. Often, information and data will have to be prepared in one of these forms so the decisions makers are provided with a clear understanding of conditions. The data management and analysis organization will need the resources and capability to do such preparation. Reference [11] contains a comprehensive Catalogue of tools and techniques to be used in case of a fuel damage event.

5.1.2. Sampling and analyses with high radioactivity

Because samples are likely to be more radioactive than usual, beta and alpha emitters can be present, a large number of analyses may be needed, and the types of analytical procedures are likely to be different from those normally used in power plants, special analysis facilities that are not available in the plant may be necessary. The types of capabilities required are shielded wet chemistry stations and gamma spectrometers. Reference counting standards for high and low energy photons should be available to calibrate radiation analyzers.

The need for fast results will mean that radiochemical capability should be established on-site or in close proximity. Such facilities can be established in existing buildings or can be provided in custom built mobile or transportable trailers.

Detailed information on the physical and chemical status of fuel or structural components may be obtained via collecting samples and by use of probing tools. Physical properties may be judged by the forces needed to collect a sample. Analyzing fuel samples of any size will require heavily shielded facilities with remote manipulators. These types of analyses will require a hot cell which does not normally exist at a power plant. To conduct off-site analyses special shipping containers will be required to bring the materials to the hot cell. Since this is likely to require several weeks after a sample has been obtained, the number of such analyses required to support decision making should be kept to the minimum necessary.

5.1.3. Computational analyses and evaluations

Capability will be required for various computational analyses. The tools and expertise for most such needs probably exists within the company. Almost all will require computers and software, again, much of which probably exist within the company. Much analytical computer software is available from libraries maintained by various international agencies. Examples of data management and computational analyses tasks include:

- Radiation calculations - dose assessments for purposes of temporary shielding design and personnel exposure assessments;
- Sample tracking by maintaining a data base of samples and analysis results;
- Waste inventory management to include tracking and reporting liquid, gas, and solid waste quantities by volume and radionuclide content;
- Spectrographic analysis - gamma scan evaluations for determining locations of fuel and evaluation of fission product spread;
- Source calculation - analyses to assess the relative amounts of fission products as they decay with time;
- Dose rate tracking by maintaining data base of area dose rates, surface contamination, and airborne activity;
- Simulators for reconstructing the event sequence and changes since the event, including material, radiation, and thermal conditions;
- 3-D visualization software is used to show the progress of activities, specifically fuel removal, but also temporary location of equipment and waste within the containment;
- 2-D drawing software is used for tasks such as design of special fixtures and components, and flow path elevation analyses for decontamination flush flow path evaluation.

5.2. FUEL CHARACTERIZATION

Before a fuel removal strategy can be defined, together with the resulting programme of work including the design of any tool or equipment packages, it is necessary to establish a reliable data base and model of the damaged reactor core. Information needed is the extent of the damage, the condition of the fuel, and its location. A related high priority action is to establish a scenario of the accident.

These will be difficult, but necessary tasks. As the ultimate fuel removal programme commences, further information is used to update the model and scenario, eventually converging on the actual condition of the fuel and accident transient. From the experience of fuel damage events that have occurred, it is essential that before embarking upon elaborate plans for fuel removal and the design of any necessary tooling, as much information as possible must be gathered on the state of the reactor core. A critical management action is to determine when information is sufficiently accurate to decide to proceed with detailed plans, procurement, and staffing for fuel removal.

In order to predict the state of the reactor core a number of techniques need to be considered. Capability for and conduct of several types of fuel evaluations and analyses are required. These include:

- Putting in place methods to directly or remotely view the damaged fuel as soon as possible is essential.
- Neutron flux, core temperature, presence of neutron moderator when combined with a loss or redistribution of neutron control and poison material can potentially create a new situation of criticality. This concern is most important while fuel movement is possible, whether it is caused by flow forces or human removal activities. While criticality may be unlikely, nevertheless, it is extremely important that the possibility for criticality be frequently evaluated.
- Details of the core operational history prior to the event are important for knowledge of fission product, fissile, and transuranic isotope inventories.
- An assessment of the state of the fuel can be made with knowledge of the fission products released during the accident. A number of computer-based models exist which can be used for the determination of the state of the fuel based upon fission product release.
- Maintaining an accounting of fuel material is required because there are national and international requirements to do so even where the question of diversion may not be an issue. Second, it is important to the cleanup effort to understand how much fuel might be distributed to other parts of the primary circuit. If there are extremes of fuel damage, normal identification and counting

methods may not be practical. In such cases, a special effort may be necessary to determine how much fuel is unaccounted for after removal of that which is accessible.

5.3. PLANT CHARACTERIZATION

Much plant characterization data will be required in support of a variety of tasks such as those listed in Table III. These include, for example:

- Surface contamination - Much of the same concern will exist as for sample analysis capability (See Section 5.1.2) resulting in a need for additional measurement capability.
- Water - In particular, management of water chemistry can be complex because of needs for criticality control, corrosion minimization and treatment to avoid biological growth and perhaps to minimize radiolytic hydrogen generation. This will necessarily be supported by frequent water chemistry analysis.
- Waste - There may be large quantities of waste and although many of the characterization techniques used are typical of the nuclear industry, the presence of levels of activity many times greater than normal at the operating plants, and the high degree of contamination by tritium, caesium, strontium, and transuranic elements may require special facilities. In addition, water contamination problems such as micro-organisms, high particulate content, and the need to maintain high concentrations of boron can contribute to the complexity of the analysis.
- Radiological health physics - During activities for decontamination and in the preparation for fuel removal, it is possible that alpha and beta particles will become airborne. This may require special instruments and analysis capability to provide timely sample results.
- Structural - Determining physical properties of radioactive materials in the form of particles or pieces of structures or equipment may require special instruments, special handling equipment, or use of off-site hot cells.

Past experience has indicated there may also be a need for very unusual data and analyses. A few examples of the more unusual characterizations include: (a) degradation of ion exchange resins (to determine if it can be removed by the existing system), (b) pyrophoricity of core materials: when exposed to air to make sure there is no possibility for ignition of metals, and (c) nature of biological growth in the water within the reactor vessel and in other storage locations. These specific analyses will not necessarily be an issue for other fuel damage recovery programmes. However, it can be expected that some type of extraordinary characterization challenge will appear.

6. STABILIZING THE CONDITIONS

Cases of fuel damage can be caused by a range of initiating circumstances. There will be an immediate operational response, the time duration of which can last from a few days to much longer. After the critical period responding to the initiating event is over, and prior to activities for dealing with the damaged fuel, the next priority is to stabilize conditions and assess the status of fuel and distribution of released fission products. For purposes here, these activities are called "stabilizing."

The activities immediately following a fuel damage event will concentrate on three types of operational activities:

(1) Assessment and gaining access,
(2) Stabilizing fuel,
(3) Prevention of further spread of radioactive material.

Conducting these activities as the initial stage of a recovery programme requires the same safety objectives as for normal operations, which are:

- criticality prevention
- heat removal
- pressure control
- leak tightness of the primary circuit
- coolant inventory management
- preserving containment integrity.

The relative complexity of the stabilization phase will depend on the severity of the fuel damage, the type of reactor, and accessibility to the fuel. In practice, and depending on the severity of the event, a variety of new or unusual methods may be required to carry out these functions if normal systems are damaged or radiation levels are excessive for access to equipment.

6.1. GAINING ACCESS

A high priority will be to establish and maintain acceptable radiological conditions to permit operational staff to carry out work associated with maintaining the reactor in a safe condition. Manually intensive methods will most likely be required for the bulk of the decontamination efforts, even with the existence of robotic and remotely operated equipment. Of course, decontamination must be consistent with ALARA principles.

Gaining some degree of human access should be achieved as soon as possible, consistent with safety and ALARA, to obtain direct measurements and samples, and to observe conditions. In particular, high priority should be placed on entering containment to expedite planning. This may be particularly complex if the event has created abnormal radiation or contamination in such areas. Considerations for access include:

- a higher than usual degree of precaution, at least for initial entries and until conditions are well understood.
- setting up a control center for management of entries. This can include video, radio, and telephone connections with critical areas.
- releasing contaminated gases and hydrogen, in a controlled manner, may be necessary.
- some degree of decontamination and exposure rate reduction may first be required.
- ventilation systems are extremely important if there is any degree of contamination spread.
- ventilation purge capability will be needed for entry into closed areas.
- use of portable shielding, protective clothing, breathing apparatus, etc.
- use of semi-remote equipment such as cameras and viewing equipment.

6.2. STABILIZING THE FUEL

The main objective of this activity is to minimize relocation of the damaged fuel and associated fission products. The most important action to take is to assure that the nuclear fuel, both damaged and undamaged parts, is stabilized in place, and that there are no opportunities for fuel displacement or movements. An important goal is to maintain at least one barrier between the damaged fuel and the environment.

Stabilizing fuel is accomplished by ensuring sub-criticality, removing decay heat, and establishing positive control of flow, pressure, and coolant inventory to support heat removal, until a time that active systems are no longer required or normal system operation is handling the situation.

Decay heat removal includes a combination of providing coolant flow, heat rejection, and keeping the core covered in the case of water reactors. When the fuel damage event prevents use of the normal systems, either as a result of damage or high radiation fields, extraordinary methods are required. The systems for reactor vessel volume and pressure control may need augmentation in the long term (months) in those cases where conditions such as high radiation prevent routine access to equipment normally used for this purpose. If conditions call for special efforts for decay heat removal, two or more parallel methods may be needed until the situation is stable. This is because time may not allow a series of trial processes. Augmentation of existing systems for removal of decay heat can be any combination of:

- install new primary side systems,
- install new secondary side systems,
- improve reliability of existing secondary side systems (for the long term, cooled down mode).

When the normal means of a nuclear shutdown are uncertain as a result of fuel damage, nonstandard methods for ensuring sub-criticality become important. Attention must be paid to maintaining shutdown margin and preventing recriticality that might result from relocation of fuel or flooding with unborated water. Other considerations are:

- Redundant capability for maintaining coolant makeup and boron concentration may also be called for if access and maintenance of the plant's systems are hindered by high radiation fields.
- Supplemental criticality control, probably as boron, may be needed. The amount and form will require special attention.

It is essential to put in place assessment methods and resources to gather and analyze data sufficient to support demonstration of the margins of safety, including sub-criticality assurance, and to plan for cleanup with major emphasis on fuel removal. As quickly as it can be accomplished, an evaluation of the status of the fuel and its location will be necessary in order to progress to a state in which the damaged fuel can be removed.

6.3. PREVENTING SPREAD OF RADIOACTIVE MATERIAL

In addition to fuel stability, several other actions must be taken within the plant to prevent further spread of radioactivity. An analysis should be conducted, followed by subsequent corrective actions, to identify any weak boundaries or barriers which could fail and release activity.

As part of this effort, plant operators also need to carefully examine the risks that certain vital equipment may be or may become inoperable. This can be caused by degradation in the environmental conditions created by the accident, such as high radiation field, heat, moisture, pressure, etc. For example, degradation could occur in cables, electronic equipment, lubricating oil, gaskets and other important components. If not compensated for, failures in such components could lead to further releases of radioactivity.

A variety of systems and equipment may be required to control the spread of radioactivity during stabilization. Depending on the degree of fuel damage, this can range from almost "nothing extraordinary" to almost "nothing standard".

Examples of issues to be addressed to prevent spread of radioactive material to low radiation and clean areas include:

- Will the normal decay heat removal systems circulate highly contaminated water in systems outside of containment? If so, it may create accessibility problems.
- Primary water may be highly loaded with radioactive caesium & iodine. Its removal may be required before the head can be removed.
- Water storage may be critical early. A key issue will be where to put excess amounts of contaminated water. Highly contaminated water should be kept inside the containment until the systems needed for processing are ready.
- Radioactivity in gases. These could become distributed throughout the plant systems. Large amounts of fission gases such as krypton and xenon can also be present in cover gas systems of primary water and in tanks containing off-gases (it is likely that any gas released to personnel operating areas will have been purged during accident stabilization).

7. WATER AND GAS MANAGEMENT

7.1. WATER MANAGEMENT

After a fuel damage event, there may be large quantities of water contaminated with fission products or fuel particles. The plant's normal systems may not be designed to operate for the level of radionuclide concentration or solids. Human access to operate and maintain equipment may be restricted because of radiation levels from within the process systems. It is important that managers understand that storing, processing, and releasing excess water may be an immediate challenge that will demand much attention. Table IV lists some details of this challenge.

TABLE IV. WATER MANAGEMENT CHALLENGES

Need	Problem	Options
Gaining access to fuel and systems.	• Full tanks & sumps • Flooded floors • Contaminated systems	• In-plant systems • Temporary tanks • Containment sump • Mobile ion exchange systems • Filtration units
Establishing and maintaining working conditions for damaged fuel removal or repairs may first require water processing to lower area radiation levels.	• Reduce area radiation fields from pipes and sumps • Fission products may continue to be released • Contamination in water	• All the above plus low flow cleanup system for removing high concentrations of radioisotopes • High flow cleanup system with filters and ion exchangers for removing low concentrations of radioisotopes
Storage of processed water	• May not be able to release to the environment, even if within permitted limits	• Use existing tanks and sumps • Use storage tanks not normally used for radioactive water • Build additional storage tanks
Release of excess water after processing	• Greater quantities than normally released • Trace radionuclides different and greater than normal release • New flow path may be needed	• Repeated processing • Temporary revision to release limits • Additional control and monitoring equipment

Following the emergency response and while achieving stabilization, a high priority should be attention to water management. General considerations include the following:

- In any fuel damage incident, water management will consume much resources (planning, design, etc.) and attention throughout all recovery phases.
- Initial challenge will be on where to put contaminated water and materials.
- Immediate access should be arranged for experts on ion exchange, chemistry of processing, and filtration.
- Maintaining water clarity may be a challenge, for example if underwater machining is needed or if there are a lot of fine suspended particles.
- Maintaining water chemistry will be a major consideration and may vary considerably from normal conditions (for example, high boron concentration to avoid criticality).

The unanticipated spread of contaminated water during accidents has made necessary installing temporary processing systems specifically designed for the unique accident generated water. Two examples are:

- The breakdown of primary circuit integrity has resulted in contamination of auxiliary and secondary circuits. These circuits are typically not contaminated and may contain chemicals (for example, secondary cooling water cooling systems) that create unique demands on the processing systems. Issues like how and where to install the temporary processing system must be carefully considered.
- Management and control of large volumes of water during an accident have resulted in storage of contaminated water in plant systems and tanks not normally containing radioactivity. Radiological concerns in proximity to transfer pipes and the storage tanks must be considered. Transfer of contaminated water into these systems must be carefully controlled to avoid further spread of contamination.

Experience with the technical details of accident-related water management indicates that when designing and operating water processing systems, the following considerations are important:

- Separate systems may be required to separately process inventories of contaminated water that have varied chemistry and/or levels of contamination.
- Ion exchange & filtration will play a major role in water cleanups. These types of systems are generally easier to set up and operate than evaporation-based systems.
- Subject to specific chemistry, the following is a starting point for assumptions:
  - caesium-137 will be the greatest dose contributor, but is removable with zeolite or cation exchange resins;
  - radioactive iodine species will have decayed substantially, if not completely;
  - strontium-90 will be more difficult to remove;
  - there may be very little fuel or transuranic elements in suspension or solution.
- Fuel particles are not readily transported in water systems beyond the primary circuit because of their high density. Very little, if any, fuel particles should be anticipated in the water or distributed beyond the primary circuit.
- It may be necessary to deal with relatively small quantities of unusual contaminated sludges and particles in water.
- Sampling and analyses to support processing will be intensive and possibly schedule controlling.
- There is a significant potential for biological growth if stagnant, warm, aerated conditions exist. If allowed to occur, substantial delays can result while determining how to eliminate the problem.
- Storage for high activity water prior to its processing can be a major radiological health hazard.
- Storage of filters and ion exchange media after their use in processing should be considered early.
- Ultimate waste disposal must be considered in the front-end decisions for water processing for such subjects as vessel size, radiation levels, and concentrations of radioactive species.
- Processing campaigns should not be held up if shipping for disposal will not be immediately available. On-site storage may be necessary for processing vessels containing expended ion exchange media.

7.2. GAS MANAGEMENT

A variety of challenges are related to gases and airborne radioactivity. There are few processing options other than filtration. The following are typical concerns:

- Ambient air contamination in open and closed rooms requires effort for radiological controls for human exposure.
- Fission product gases within systems. These must be purged and released in order to proceed with opening the reactor vessel as well as for other fluid systems.
- The potential presence of combustible gases such as hydrogen is an important consideration. Sources of hydrogen include primary circuit chemistry, cover gases in vessels, accident generated

metal-water reactions, and radiolytic decomposition of water. Provisions must be taken to avoid over-pressure or spreading of radioactivity by combustion. For hydrogen within piping systems and rooms, purging and/or venting resulting in release must be done.

- Hydrogen that is captive inside containment is also a hazard. For accidents involving moderate levels of hydrogen ($<5\%$ inside the containment), external recombiners can be used.
- Other combustible gases such as breakdown of organic ion exchange media from radiolytic decomposition. Again, venting or purging is required to avoid the potential for burning.

Plant areas may have significant surface contamination resulting from leaks or releases from primary, secondary, and auxiliary circuits. This can cause airborne contamination higher than normal in areas of the plant that are normally not contaminated. Considerations include:

- HVAC systems may become contaminated at levels higher than is typical. This would require radiological assessment of HEPA and charcoal filter components.
- Once an area has been decontaminated, careful consideration must be given to avoiding changes in HVAC system configuration or transients which can recontaminate the area. For example, opening of doors may have to be closely controlled.
- HVAC systems servicing typically clean areas may not be designed to maintain a sub-atmospheric pressure in the building. If it becomes contaminated, assessment of potential releases, and how to prevent them, should be conducted.

8. DAMAGED FUEL REMOVAL

Core damage may range from damage of one to several fuel assemblies in a limited core region to a full core having passed through a loss-of-coolant thermal transient. Fuel removal actions for such a variety of conditions will vary from a minimum, using available standard equipment and tools, to the maximum requiring specially designed handling and cutting equipment, including system modifications around and near the reactor. It may be necessary to use destructive methods for removal of fuel or on the reactor's internals to gain access to damaged fuel. While there will be many important decisions for fuel removal, deciding that destructive methods are required will be very important for all the subjects in this section.

8.1. PREPARATION AND PREREQUISITES

Management planning must be flexible in its approach to fuel removal. In many cases, there will be insufficient early information to support a complete and detailed plan before commencing removal operations. Therefore, it may be necessary to establish an overall fuel removal plan that defines the overall major steps, is detailed for the near-time steps, and proceeds incrementally for later details as circumstances become clear.

Information management - before consideration can be given to the methods to be employed for fuel recovery, it is essential that data bases are established to provide clear and understandable models of the reactor, detailing the radioactivity/fuel inventory, fuel physical condition and location, and any structural or component damage. Depending on the severity of the accident this may involve significant work using a number of techniques ranging from direct samples, video surveys, ultrasonics, etc. Creating a realistic model of the physical situation prior to giving consideration to any fuel recovery is very important; specifically:

- get direct evidence of fuel and core conditions as early as possible and continue to update,
- immediately establish and continue to maintain data base of fuel status,
- photographs and video are essential; they should be frequently updated,
- the physical state of the reactor core should be well understood before making elaborate fuel removal plans,

- the core operational history prior to the event is important to establish fission product and transuranic levels and fissile material distributions.

During preparation for later fuel removal, alteration of its geometric arrangement which could lead to inadvertent criticality should be anticipated and precluded. Monitoring and control of the reactor will have to be continued to ensure that the reactor remains in a safe state and that any recovery operations will not cause recriticality. The methods to prevent recriticality during removal operations must be established. They should consider:

- From the data assembled on the fuel, its quantity, position and condition, together with data on the transuranics present, a criticality assessment can be undertaken using known computational methods. The results of this analysis will need to be considered in the light of the possibility of any conceivable configuration giving rise to criticality, noting in particular the presence of any moderating material.
- If criticality cannot be excluded by analysis, then measures are necessary to avoid it. This will most likely include the addition of neutron absorbers to the core such as boron or other neutron poison. The form will depend on the state and type of fuel.

Further, any operation that may lead to movement or relocation of the fuel within the pressure vessel must be anticipated. The procedures and steps of opening the pressure vessel will have to be defined according to a prior assessment of the extent of damage. Continuous surveillance of the core conditions will necessarily accompany all steps during fuel removal.

Testing for operability, maintenance and personnel training is vital for successful operation in a hostile environment. New tools must be qualified prior to their actual use by testing them on a mock-up. Final testing must include procedures for mounting, operation, maintenance and dismounting of each tool. The operating environment should be simulated in all important aspects during testing. Set up a test tank, spent fuel pool, or refuelling canal for tool development, testing and training. Use of a full vertical range of operations is very important, while the lateral area needed is only as necessary for the operations being practiced. Full capability testing is also the appropriate method for training the operators in the use of tools in order to gain the necessary skills for high efficiency before they use the tools for actual fuel removal.

8.2. PERSONNEL CONSIDERATIONS

Before starting fuel removal operations, acceptable working conditions will have to be established with regard to the radiological and environmental conditions by:

- establishing limits for the working period of personnel for exposure and fatigue;
- providing the appropriate protective clothing for radiological and other hazards;
- providing breathing air supply;
- insuring body cooling (for example, by means of ice vests, forced air) until a sufficient ventilation capability for cooling, filtering and controlling humidity is available;
- setting up equipment for monitoring the working environment for conditions such as radiation fields; temperature, humidity, radiological and chemical composition of the air, and presence of hot particles;
- keeping records of personnel exposures and health conditions.

The need for the amount of decontamination of the working area within the containment has to be defined applying ALARA principles. The objective is to restore, with reasonable time or effort, as near normal working conditions as possible for the fuel recovery operations realizing that normality may be not totally achievable in terms of contamination, radiation levels, or area within containment.

The use of robotics for handling fuel or operations in contaminated plant areas needs to be carefully considered. Robotic devices primarily offer the advantage of being able to be placed in areas where humans should not go. (The other primary feature of robotics of doing repetitive tasks is not an issue here.) However, a fall-back plan is needed in the event the device does not perform as required, or fails in service. It does no good to depend on a mobile device that in itself cannot be retrieved in some way if it has a problem.

Fuel removal can be a long-term and demanding job for the workers. Depending on conditions, manual operations may be very difficult. Some considerations for easing the workers' effort are:

- To the extent practical, establish conditions such that no heavy protective suits are required and normal working shift periods are possible.
- Manual tools will probably be preferable because of the basic simplicity; however, the working environment for use of such tools must be acceptable and in accordance with the ALARA principle.
- Consider the maximum depth of water in which it is reasonable to use manual tools. For example, if manual tools must be manipulated at the bottom of the core, it will be much more difficult than normal fuel handling.
- Place high emphasis on establishing and maintaining water clarity and lighting so that visibility for tool manipulation and fuel placement is at the maximum.
- Define the need for special equipment for sampling, measuring, local controls, and other manually operated equipment that is in addition to that for the reactor and fuel.
- Rely heavily on simple methods - automation cannot be avoided, however, do not permit methods that are complex and will take a long time to put in place.

8.3. PLANT MODIFICATIONS TO SUPPORT FUEL REMOVAL

Plant managers should be aware that coping with the task of removing damaged fuel may require modifications of existing plant installations, adding new equipment, and developing new procedures and processes. For example:

- During stabilization, removal of decay heat and cleanup of any required systems will necessarily have been established. However, if the operations mode was set up as an interim configuration, long term, reliable operating systems should be available to ensure the continued safety of the reactor system.
- The availability of services such as electricity & lighting, compressed air, ventilation, and lifting will have been reestablished. If such systems are damaged then replacement may be necessary.

Depending on the severity and the extent of fuel damage, special installations may be needed around the reactor vessel and fuel transfer/storage pools with the aim of:

- Providing radiation shielding for workers as there will be a requirement for long duration of operations in close proximity to the damaged fuel.
- Providing a special work platform above the reactor to accommodate the special tools and equipment that will be necessary.
- Containing highly contaminated water in the reactor vessel to avoid spreading into large water volumes. It is much more efficient in time and cost to process smaller volumes with concentrated contamination. Special water processing systems may be required, as discussed in Section 7.
- Enabling on-site transport and intermediate storage of fuel canisters. In almost all cases of fuel damage, additional special design canisters and handling containers will be necessary.

8.4. TOOLS AND FIXTURES

Fuel removal activities should be performed based upon the actual fuel conditions established by direct visual inspection and measurement. Selection and design of tools and equipment depend on the extent of fuel damage. Mostly standard handling equipment might be in order for fuel damage in the range of partial loss of mechanical integrity of a few assemblies.

At the other extreme of a complete change of physical state of the major parts of the core, a variety of new and different equipment may be required. Methods for damaged fuel removal can range from using hand-operated long-handled tools to remotely controlled one. Some general management approaches to follow in these cases are:

- Avoid too much early tool planning. Experience has shown that designs of tooling for defuelling a damaged core must proceed along with increased knowledge on the status of the damaged core. Tool needs and designs will continually evolve as new conditions are discovered or as specific designs prove to be inadequate.

- Question all designs of special equipment that are based on assumption. Direct evidence of fuel conditions is essential for such designs.

- A very limited number of general purpose hardware (such as grippers, pliers, vacuum systems, canisters) can be prepared before fuel removal operations.

- Flexibility for development as fuel removal proceeds is most important, and the ability to establish capability to respond to needs is more important than attempting to pre-define all possible situations that will arise. This means experienced tool designers and manufacturing workshops must be available on short notice during the entire fuel handling period.

- A "hot machine shop" equipped with decontamination facilities and the main types of mechanical machine tools will be needed to perform modification and maintenance work on contaminated tools and devices. Provide the least possible restrictions for moving contaminated tools to and from the containment, preferably without a need for shielded transport.

The possible need for special manipulating tools begins with operations of lifting of the upper core structures (i.e. PWR upper core grid; BWR steam/water separator). It is possible that parts of damaged fuel assemblies are connected and possibly raised along with the structure.

As a principle, fuel handling and removal tools should be designed to be simple. The concept of "simplicity" means:

- Robust processes work best.
- Requirements for precision placement should be avoided.
- Tools should be optimized to serve only one purpose rather than being universally applicable.
- To ease the use of hand-operated tools they either should be lightweight or have a means for weight support, without restricting their mobility during use. Design and fabrication must minimize trapping of contamination in order to limit radiation during maintenance.

Tools for removal of fuel are selected based on the physical conditions of the fuel assemblies, fuel material, and accessibility from work platforms. One of the most challenging considerations is deciding the tradeoffs between power assisted and manual tools for various operations. Considerations include:

- Designing automatic tools for conditions that are not well known and have a high probability of being outside the range for which a tool is designed is difficult. In such cases, some type of manual alternate should be available.
- Remotely operated tools allow placement of an operating station and control panels in a preferred environment for its location. The tradeoff is that remotely operated tools require sturdy structures for support and sensitive motion control, increasing the bulk and complexity of the equipment for the selected task.
- Specially designed fuel lifting tools are required if during the accident the designed load bearing components of fuel assemblies (i.e. PWR control rod guide tubes; BWR tie rods or fuel channels) were damaged. In such cases the standard grippers for fuel transport have to be supplemented with custom-made devices which support the fuel assemblies at the lower end and provide lateral guidance.
- Energy supply to the tool head may be electrical, pneumatic or hydraulic, depending on the specific task. Modular construction of tools will enhance maintenance during application.

- Adequate sensors, including viewing aids by television, are means to ensure the safe operation of some tools.

Tools may be required for "destruction" of material and removal of particulate material. Molten fuel may solidify in very large lumps which experience shows have high hardness and are brittle. These lumps will have to be subdivided for collecting into storage or disposal containers. Considerations include:

- Methods for both handling and breakup of fuel should produce the smallest reasonable amount of fine materials since fuel bearing particles still have a high radioactivity concentration requiring elaborate collection and immobilization techniques.
- Mechanical drilling of holes to enable breaking by applying high stresses via hydraulic pressurization inside the holes.
- Metal structures can be cut mechanically in many ways. Plasma arc cutting and electro-discharge machining (EDM) have been successfully applied for underwater tasks. Contact-arc cutting technique is used for various tasks in the nuclear industry. This cutting process is similar to EDM using the thermal effect of electric arc discharge with high energy, but requires less sophisticated electronic controls.
- At TMI, a "drilling rig" was placed atop the reactor vessel and used to grind up the mixture of fuel and metal and to drill holes for access below the core support structure. Development of special drill heads was required to be useful for both ceramic and metallic materials.
- Vacuum systems (suction pump with particle sieve and filter unit) are useful to 1) collect small particle debris for pumping into a canister, and 2) use the pressure differential at the nozzle to hold larger pieces for transfer to a canister. Such systems have been successful in many applications.

8.5. FUEL REMOVAL OPERATIONS

The first steps to gain access to the fuel in the core are mainly identical to the normal refuelling activities. In LWRs, heavy components such as concrete missile shields above the reactor vault, the vessels head, and the vessel upper internals have to be removed with the overhead crane. Special considerations are needed regarding the conditions of the accident that might affect the ability to use normal handling equipment. For example, if the event involved higher than normal temperatures, distortion of the upper internals is a possibility. If the upper internals are damaged, then special methods such as cutting may be required.

Lifting the vessel head and the upper internals must be conducted carefully to minimize radiological hazards to personnel and to avoid undue spread of contamination. These actions are the first ones with the potential to alter the core geometry after a long term period of stabilization. Thus, they should be accompanied by appropriate safety and contingency plans.

From this point, the fuel in the reactor core location is removed. The complexity of the effort and schedule will be determined by the physical conditions of the fuel, discussed above with respect to fuel tooling considerations.

The fuel damage event, and subsequent fuel removal activities from within the reactor's normal core envelope may result in particles and small fragments being distributed to:

- The bottom of the vessel. This creates the fundamental question of whether the fuel can be removed without removing core basket and lower core support.
- Outside the reactor vessel but within the primary circuit, especially at low points or volume expansions such as the pressurizer, steam generator plenum, or within pump casings.
- Outside the primary circuit such as in the purification and decay heat systems, safety and relief valve receiving tanks, or the containment or suppression pool floor if there has been flow to these areas.

After removal of the damaged fuel from within the core region extraordinary effort may be required to remove such redistributed material. Information needs and planning for this effort should not wait until the core region is defuelled.

8.6. DAMAGED FUEL CANISTERS

In a fuel damage event with only loss of cladding integrity and/or small change of fuel dimensions, damaged fuel is placed in special canisters using standard tools and equipment and then stored in storage pools.

In case of severe damage with massive destruction of the fuel elements, fuel melting, or any situation when fuel assemblies no longer have their normal envelope, then standard refuelling techniques are no longer applicable. Special measures must be taken during and after removal of damaged fuel from the reactor for its on-site storage prior to transportation and disposal. In particular, fuel canisters serve as a safe envelope for the damaged fuel and perform primary functions of:

- Structural strength; without external support, the forces of handling could cause further breakage.
- Retention of fuel material and fission products; while in storage canisters will minimize contamination of pools and reduce the need for water processing. During shipping, canisters replace the function of the damaged fuel clad as a barrier between fission products and the environment.

Design and fabrication of special canisters for damaged fuel may be required. This can only be reasonably undertaken after the condition of the fuel is known and the canister storage decisions have been made. Canisters can have a variety of design issues, such as:

- Ability to accept all types of fuel geometries encountered during fuel removal, ranging from distorted assemblies to fragments of fuel rods and fuel assembly structural material. As part of fuel removal, transferring the damaged fuel into the canisters may include operations such as piece-by-piece loading of large fragments, hydraulic lifts, and water vacuums, and manual movement of particles and fines.
- Criticality safety may impose geometric constraints and requirements for built-in neutron absorbers.
- Handling capability that is compatible with loading capacity and geometric constraints of the fuel transfer system. Consideration must be given to available cranes and other lifting and transport equipment; or integrating the design with specifications for such equipment to be purchased.
- Method of placement, and opening and closing the canister lid underwater requires special attention.
- The canister top must be compatible with equipment for loading and unloading the fuel.
- The overall canister size and shape must be compatibility with storage racks, existing or to be installed, for on-site interim storage.
- Possibility for use in a vacuum and water cleanup processes as a density settling volume to separate large particles prior to filtration. The internals are configured for liquids/solids separation.
- Possibility for use as a debris canister, capable of containing large pieces up to a full size assembly. The inside of this type is completely void of fittings.
- Possibility for use as a filter device to capture fine and coarse particles in the vacuum and water cleanup processes. Much attention must be paid to the filters and pre-coat media to prevent rapid clogging.
- Sealing canisters that contain heavily damaged clad or rubble for tightness.
- Venting of gases from radiolytic decomposition of water to create hydrogen and oxygen gas.

It is possible that two or three different canister configurations will be required to meet the various requirements.

9. RETURN TO OPERATION

When the fuel removal phase is essentially complete, the status of the plant must be determined and recorded in preparation to its return to power. (Or for that matter, any other disposition such as monitored storage or commencement of decommissioning.)

Especially important prerequisites for return to power are addressing the cause and consequences, i.e.:

- The cause of the event must be determined and prevented from recurring. This will most likely be a primary focus of regulators as well as the plant owner and operator and will undoubtedly receive much attention. The degree of investigation and evaluation for a fuel damage event will likely be of a high level of effort because of the potential threat represented by a recurrence.
- The effects of clean up and repair must be known in detail because subsequent operation may be: (1) directly affected by new equipment, modifications, and procedures, and (2) less directly affected, but of equal importance, by circulation of residual material within the primary circuit and connected systems.

9.1. RESIDUAL FUEL CONTAMINATION

To restart a unit that has experienced fuel damage, the residual fuel particles will have to be reduced to some practical level to minimize activation and circulating radiation. The level of decontamination needed depends on an analysis of impacts. To decontaminate to zero is not necessary. The allowable residual level of contamination should be determined according to the ALARA concept, applied to the working areas, as well as its effect on plant effluents. In cleaning up the primary circuit, its connected systems, and the reactor vessel, keep in mind that:

- A major part of the cleanup will probably be controlled manually.
- A variety of vacuuming type devices will likely be required for underwater and dry conditions.
- Remotely operated machines may also be used. However, caution is urged in specifying high technology devices where essentially manual methods are effective.

Establishing criteria for the allowable amount of remaining fuel particles can be difficult. Criteria should only be stated with a good understanding of what can be proven. Care must be taken to establish requirements that can be practically achieved and for which the ability to demonstrate is possible; that is, criteria must not be too sensitive to measure with reasonable certainty. A balance must be established between the number of measurements, samples and radiochemical analyses to be conducted versus what is required to assure that the established criteria have been met. It does no good to write requirements and then find out later that conformance cannot be shown, though acceptable conditions can be achieved.

9.2. QUALIFICATION FOR RESTART

Approval by Safety Authority will be required. A safety assessment must be conducted to evaluate any modifications and to establish if there is a need for additional safety operating constraints (operating specifications).

Plant qualification for restart can include:

- Fuel management evaluations will be necessary to compensate and substitute for fuel that was damaged.
- Evaluation of damage and affected systems. Safety equipment which could have suffered from transients must be evaluated to determine if a requalification is needed. The readiness of equipment to operate may require a start up test program substantially beyond that for normal restart.

- In addition, replacement of equipment may be called for, even if it did not fail but is sensitive to or has been exposed to high levels of radiation, temperature, humidity, or pressure.
- Reactor repair. Requalification of internals and pressure boundary may require analysis, inspections, and measurements.
- Equipment modification. There may be a need to modify systems for operation or to monitor operation after restart. Installation of special instrumentation is an example.
- If additional hardware has been installed, such as filtration devices to trap particles, mock ups to validate the design should be strongly considered.

If as a result of the fuel damage or plant modification, there are anticipated variations in operation, such as restrictions on power operations, higher radiation levels, or special monitoring procedures, personnel qualification and training will be required. Such training should use mock ups used for validation of hardware.

9.3. MONITORING AFTER RESTART

A comprehensive monitoring programme should be established after the restart and the early stages (days or weeks) of subsequent operation. Monitoring will be required to:

- detect if fuel damage is recurring;
- detect any increase of particles in the water;
- detect an increase of radiation (for example, caused by either activation of particles or relocation of internal contamination);
- assess effectiveness of modifications;
- validate requalification done by analysis and can only be demonstrated fully during operation (for example, radiation environments).

Special monitoring instruments may be required. Customary techniques for radiation effects such as gamma spectroscopy, solid sampling, alpha counting, and neutron measurement may be required at an order of magnitude greater frequency for the early stages of restart. Other types of characterizing measurements and inspections may be necessary. This can include, for example, air contamination and radiation levels throughout the plant. Special radio-chemistry procedures may be required after operation begins for tracking contaminants in the plant's water and gaseous waste systems.

10. MANAGING SOLID WASTE

Fuel damage can release substantial amounts of fission products such as caesium, iodine, and strontium, as well as actinides such as uranium and plutonium. Even events of minor consequences can present a considerable challenge for handling of this radioactivity using the plant's equipment and conditioning systems with their installed shielding. Managing of solid waste products is normally standard and routine. However, stabilization and cleanup from fuel damage can produce a variety of solid waste products that are substantially different, in both quantity and form, than normal plant operation.

This section focuses on "abnormal" solid wastes; that is, abnormal with regard to that which is ordinarily handled at a nuclear power plant. Waste can be thought of as abnormal when it has characteristics which are unusual with regard to either or both customary or existing conditioning capability and disposal requirements and capability. Table V lists some examples of abnormal wastes that can be produced in recovering from a fuel damage event.

TABLE V. ABNORMAL WASTE TYPES (EXAMPLES)

Waste type and origin	Physical form	Chemical properties	Radiochemical characteristics and specific activity
Core components which are primary accident wastes.	Dry solids; non-compactable	Metal	Neutron activated components; high level of radioactivity possibly contaminated with fuel and transuranics.
Special tools for handling of damaged fuel during removal.	Dry solids; non-compactable	Metal	Surface contamination. Intermediate level wastes; possibly contaminated with fuel and transuranics.
Spent ion exchange material materials and evaporation concentrates from water processing.	Wet solids	Organic and inorganic beads, particles, sludges - Chemistry can include ion exchange groups, dissolved minerals and salts, and inactive solids.	Intermediate and high activity contaminated with fission products. Presence of transuranic nuclides may be substantial. Possibility of combustible gas generation from radiolysis; corrosive, presence of chelating agents.
Slurries from water processing and decontamination.	Wet solids	Chemical compounds with various properties	Intermediate level wastes; possibly contaminated with transuranics.
Spent filters from water processing.	Wet or dry solids	Charcoal, metal, fabric, or paper media	Intermediate level wastes; possibly contaminated with transuranics.
Spent protective clothing, cleaning materials from cleanup and fuel removal activities.	Dry solids; combustible, compactable	Various plastics, textiles, rags, paper PVC, etc.	Large volumes of low level waste, possibly contaminated with transuranics.
Spent filters from ventilation systems operating during the event.	Dry solids; combustible, compactable	Charcoal, wooden or metal frames, paper	Intermediate level wastes; possibly contaminated with fuel and transuranics.
Rubble from surface removal.	Dry solids, non combustible, somewhat compactable	Spalled and scoured concrete,	Low activity wastes.
Reagents from chemical decontamination processes.	Concentrated liquids	May contain variety of organic and inorganic chemicals such as citric acid, permanganate, nitric acid	High activity waste.

Existence of one or more of the following conditions will contribute to making waste abnormal:

- Radioactivity is greater, or substantially different in isotopic composition than the normal solid waste (for example, contaminated with fuel or transuranic having high alpha content, or contaminated with fission products having high beta activity). The type and level of radioactivity will be important factors affecting both the selection of waste conditioning and appropriate protection for personnel and for the environment.
- Waste materials may be substantially different than is normally processed for packaging and disposal (for example, sludges, zeolite media, high polymeric or organic material content). This may require the installation of special conditioning systems.
- The chemistry may be different because of the use of decontamination agents (for example, chelating agents). Neutralization or other additional treatment may be required.
- Waste constituents may be noncustomary (for example, ash from burning). Further treatment may be required.
- The volume of solids may be larger than the installed equipment can handle in a reasonable time or can be disposed of without impact on the disposal facility. This may then require extraordinary numbers of personnel, packages and special hardware and increased cost and time to condition and package for disposal.

It is possible that waste products will be created that are substantially contaminated with or contain nuclear fuel. This may be either as fuel material particles, whole or broken pellets, or as parts of a fuel element. It may be mixed with structural parts of a fuel element. These types of products are separate from the subject of this section and should be managed as spent fuel or high level waste.

10.1. CONDITIONING OF ABNORMAL WASTES

Conditioning of abnormal wastes is conducted for purposes of waste conversion to forms acceptable for transportation, storage and disposal. Conditioning includes physical processes, chemical processes, and manual methods to prepare waste with regard to form, properties, and radionuclide concentrations.

For the most part, abnormal wastes can be processed with state-of-the-art technologies and facilities used for normal waste conditioning. The primary problem may be the insufficient capacity of these facilities, taking into account large quantities of produced wastes.

The physical/chemical capabilities and performance characteristics of solidification agents and other immobilization techniques, such as high integrity containers, are generally well known. Once solidified, products from immobilization of liquid wastes will generally not require further conditioning and can be considered ready for final storage or disposal. However, they may have to be specially packaged for transportation.

Some abnormal wastes resulting from an accident and the damaged fuel management may challenge the ability of conventional conditioning techniques. For that reason a detailed analysis of the final product's characteristics should be performed prior to the selection of the conditioning and immobilization alternative. Decisions, with supporting cost/benefit studies, to either: 1) concentrate the waste to the limits of handling and transportation, or 2) control the concentration of the waste as part of the conditioning and packaging process, in order to make it acceptable for disposal.

Conditioning and packaging of high-activity radioactive wastes containing significant amounts of transuranics and fuel particles is a specific problem that may require special technologies, tools, facilities, canisters, etc. Of particular interest for high specific activity abnormal wastes are: thermal stability, radiation resistance and combustible gas generation, as they relate to the chosen product matrix.

It is very important to package the waste product with careful consideration of how it is to be disposed. Wastes must be prepared to satisfy classification criteria that can include waste form, concentration of radionuclides, method of packaging, radiation levels, or other factors specific to the requirements of the facility where the waste is to be disposed. Processes and methods must be selected and operated to segregate and control the materials in the final waste packages to optimize among handling, transportation, and ultimate disposal. This may be difficult at times because there will be a natural preference to maximize the effectiveness of the front end of this chain. However, doing so can lead to waste packages for which shipping and disposal are very difficult, and/or costly.

Special processes or encapsulation methods may be required to make the waste technically adequate for ultimate isolation as "normal" low level waste (LLW). As a first principle, development of conditioning processes for abnormal waste should be designed to qualify the product for final disposal using the customary requirements as specified by regulations. If this cannot be accomplished with reasonable effort and costs, then requests for special waivers or variances to allow disposing of some of the waste at LLW disposal sites may be the best course of action. Such requests will require considerable interaction with government agencies that regulate disposal and with the operators of disposal sites who must adhere to strict rules for disposal. The conditions of such variances might include special conditions such as depth of burial, special packaging, etc. Special analyses may be required to support such requests to show that the environmental and health effects are acceptable.

10.2. ON-SITE WASTE STORAGE

As both normal and abnormal wastes are accumulated during recovery activities, on-site storage may be necessary. Reasons for establishing a special storage area include:

- to remove radioactive material from a working area;
- to allow decay (for example, for iodine to disappear, or for reduced handling exposure);
- to provide buffer storage because of an abnormally large volume;
- to await special conditioning or packaging systems.

In principle, existing storage facilities may be used for abnormal radioactive wastes. If these are full, or inadequate for the purpose, as a temporary measure, using existing buildings may be necessary until special purpose facilities can be built, or until the wastes are transported off-site. Since the activity level of abnormal wastes may be higher than normally encountered, considerations for storage should include:

- Remote handling by either indirect manual methods or more sophisticated "robotic" equipment.
- Adequacy of shielding; existing shielding may have to be supplemented with additional concrete, lead, steel, sand, or water.
- Personnel access control.

On-site storage of *unconditioned* wastes should only be undertaken on a temporary basis, pending the provision of a suitable conditioning process. In such cases, special attention must be given to the needs of shielding and prevention of spread of contamination.

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