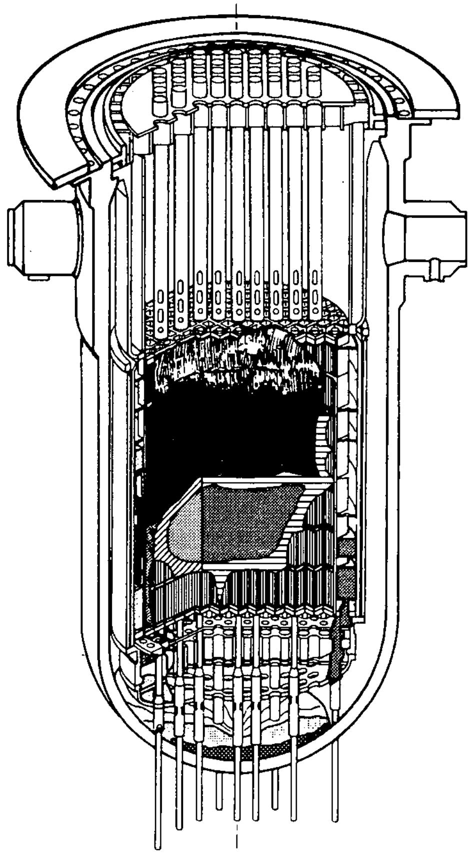

TECHNICAL REPORTS SERIES No. 321

Management of Severely Damaged Nuclear Fuel and Related Waste

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1991

The cover picture shows the known end state conditions in the Three Mile Island TMI-2 reactor vessel. By courtesy of the Electric Power Research Institute (EPRI), Palo Alto, California, United States of America.

MANGEMENT
OF SEVERELY DAMAGED
NUCLEAR FUEL
AND RELATED WASTE

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INTERNATIONAL ATOMIC ENERGY AGENCY
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FOREWORD

The on-site, post-accident activities at nuclear power plants that have experienced significant fuel damage have consumed substantial resources. However, a comprehensive review of management insights and principles has never been published. This Technical Report provides such a review. Member States who wish to complement their emergency response procedures and off-site plans with knowledge of on-site experience will find this publication useful for such a purpose. The Report will also provide a reference text on the requirements that arise after the critical phase of emergency response.

An Advisory Group on the Main Principles of Safe Removal, Conditioning, Transportation and Storage/Disposal of Severely Damaged Nuclear Fuel and Other Accident Generated Waste, convened in December 1988, reviewed available information and advised on the provisional content. Consultants from Czechoslovakia, the Federal Republic of Germany, the United Kingdom, the United States of America and the Union of Soviet Socialist Republics prepared a draft report. In the course of preparation of the document, the consultants had meetings in Leningrad and Chernobyl with specialists who participated in the cleanup of the consequences of the Chernobyl accident. A technical tour in Chernobyl included a visit to the damaged reactor, the surrounding area and the town of Pripyat. Much information of use to the consultants was obtained. The text was finalized by an Advisory Group in November 1989.

The IAEA wishes to express its gratitude to those who took part in the preparation of this publication, and in particular to C.A. Negin (USA) who chaired the meetings. Important material was provided also by I.L. Rybalchenko, E. Hladký, H. Knaab, J.M. Jones and G. Hultqvist.

The IAEA officer responsible for this publication was Yu. Martynov of the Division of Nuclear Fuel Cycle and Waste Management.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

The future use of nuclear energy depends on the safe and reliable operation of nuclear power plants. The nuclear community spares no effort to prevent accidents. Nevertheless, they do happen, and several accidents which have led to severe damage to nuclear fuel have been experienced. Such accidents, exceeding design limits, can result, and have resulted in major consequences, substantial economic loss and contamination of the environment. The experience gained from these accidents must not be forgotten; careful analysis and information about the various actions taken must be provided to all interested parties. For this reason, the IAEA has initiated the preparation of a series of technical publications summarizing the experience to date in managing these accidents.

Member States have requested that the IAEA develop recommendations for on-site management of post-accident conditions of damaged nuclear fuel and related waste from an accident at a nuclear power plant. This request is in accordance with Article 5 of the Convention on Assistance in Case of a Nuclear Accident, which establishes that the IAEA will collect and disseminate information among its Member States related to accident recovery.

The events listed in Table I comprise the major fuel damage accidents. The source material for the present report is taken primarily from Chernobyl, Three Mile Island (TMI) and studies conducted in Sweden.

An annex provides previously unpublished information on the A-1 reactor accident in Czechoslovakia. A bibliography is also included for references that apply in general to the whole report.

1.2. PURPOSE

This work addresses on-site, post-accident management leading to a stable condition with respect to gaining absolute control over damaged fuel and related waste and to ensuring there is no longer the potential for uncontrolled release to the environment. It provides information for use by:

(a) Managers of a possible future event resulting in substantial fuel damage;
(b) Those who wish to gain a better understanding of past events.

Managers responsible for the safe operation of nuclear power plants should acquire an overview of the principles involved for establishing control of damaged fuel, abnormal waste and the plant itself. Bringing to light major cleanup issues arising from past accidents can be of benefit in providing insights on planning or preparedness.

TABLE I. CASES OF SEVERE CORE DAMAGE

Plant (year)	Location	Primary cause	Brief description
NRX (1952), water cooled, heavy water moderated	Canada	Design, operator error	A reactor runaway from a combination of design flaws and operator error resulted in damage of fuel and leakage of moderator water, flooding the building [1]
Windscale (1957), gas cooled graphite pile	UK	Lack of information for operators	Uncontrolled release of Wigner energy, fire and destruction of substantial portion of air cooled core, some fission products released to environment [2]
SL-1 (1961), small prototype PWR	USA	Design and maintenance	Prompt criticality while shut down with head off, reconnecting control rod to drive mechanism, destruction of core, substantially contained within building
Fermi 1 (1968), sodium cooled plant	USA	Design	Core splitter plates vibrated loose and blocked fuel channels, causing melting of several assemblies, contained within primary system
Lucens (1969), experimental gas cooled, heavy water moderated	Switzerland	Suspected fuel element failure	Coolant leakage, followed by moderator tank rupture and severe damage to a single fuel assembly [3]
A-1 (1977), gas cooled, heavy water moderated	Czechoslovakia	Blocked fuel channel, operator confusion	Rupture of fuel cladding and decladding of fuel occurred in the upper 30–100 cm of fuel elements; 148 assemblies affected
TMI (1979), PWR	USA	Operator confusion	Failure to keep core covered with water, destruction of core with large fraction melted, fuel contained within systems, fission product gas released to environment
Chernobyl (1986), water cooled, graphite moderated	USSR	Violation of operator rules	Prompt criticality caused destruction of the reactor building with substantial distribution of fuel outside the primary envelope and fission products released to environment

1.3. SCOPE

This report is concerned primarily with severe fuel damage accidents in large electric power producing reactors such as those in the TMI and Chernobyl plants. It does include, as appropriate, knowledge gained from accidents in other power, research and military reactors. It is believed that the conclusions and recommendations apply to a large extent to severe fuel damage accidents in all types of reactors.

The period considered in this publication begins after the initial crisis of an accident has been brought under control. (This initial crisis could be from one day to several weeks after the event, depending on the specific conditions.) Accordingly, it is assumed that the plant is shut down, the reactor is under control and decay heat removal is in progress in a stable manner so that attention must be given to cleanup. This report addresses the principles involved in planning, engineering, construction, operation and other activities to characterize, clean up and dispose of the fuel and related waste. The end of the period under consideration is when the fuel and abnormal wastes are packaged either for interim storage or final disposal and activities are started either to restore the plant to service or to establish a safe state from which decommissioning planning can start.

The main focus is on accidents involving 'severe fuel damage'. For present purposes, 'severe fuel damage' may range from one assembly with gross cladding failure, to major damage of a large number of assemblies in the core, leading to substantial release of fission products and requiring special equipment for dealing with the fuel and wastes. Included is the case where the core geometry is significantly altered and fuel substantially melted. In cases of severe fuel damage, it is likely that significant quantities of fission products are released to the containment building, which provides an effective barrier against release to the environment. Release of fuel outside of the primary circuit is generally considered to be limited to small quantities of particulates. In a case in which a substantial amount of the core material is released outside of the reactor building, the main initial task is the minimization of the spread of radioactive material. No experience exists as yet on fuel removal, conditioning and transport for this case.

'Fuel failure', which is not within the scope of this report, concerns the loss of cladding integrity that is within the design limits for normal plant operational response and cleanup. Handling of failed fuel assemblies is done with standard tools available in the plant and does not lead to fission product contamination beyond the capability of the installed cleanup systems.

The cleanup of bulk contamination and normal waste management, decontamination and decommissioning are certainly of relevance to post-accident management. However, as they are dealt with extensively elsewhere, they are not addressed here.

The methods used for the disposal of high activity or fuel bearing wastes and damaged fuel will depend on the exact regulations in Member States. There is no existing base of experience. Final disposal of damaged fuel is therefore not addressed.

2. STRATEGIC PLANNING

The degree to which the strategy of post-accident recovery is applicable to future situations will depend on the individual circumstances. However, the principles and subjects discussed here will generally apply to most situations.

2.1. PHASES OF POST-ACCIDENT OPERATIONS

For long term strategic planning, recovery and cleanup after a fuel damage event can be viewed as a three phase chronological sequence, as illustrated in Fig. 1. The phases vary in the emphasis that is placed on the various activities which are being conducted. It is recognized that in most, if not all, cases there is no clear division between these phases and no precise time duration for each can be determined. The phases are:

I. Stabilize, assess, prepare access to and confine fuel

This phase covers the period from the time when an accident sequence has been safely terminated to the time when control of decay heat removal is no longer a

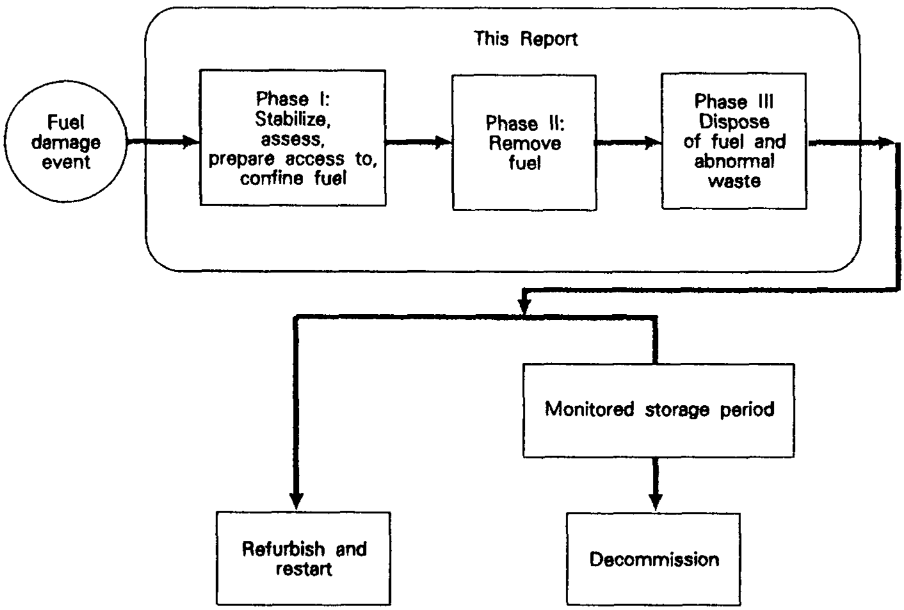

FIG. 1. Post-accident recovery.

TABLE II. ON-SITE OPERATIONS RELATED TO POST-ACCIDENT PHASES

Dominant operations	Phase I: stabilize, assess, prepare access to, confine fuel	Phase II: remove fuel	Phase III: dispose of fuel and related waste
Reactor control	×		
Decay heat removal	×		
Fission product release prevention	×	×	
Water storage[a]	×	×	
Data management and analysis	×	×	×
Water processing[a]	×	×	
Decontamination for access	×	×	
Waste storage	×	×	
Waste disposal	×	×	×
Fuel removal		×	
Interim fuel storage		on-site	off-site
Decontamination for cleanup			×
Fuel shipping			×
Waste transport			×

[a] May not be applicable for certain types of reactors such as gas cooled reactors; could include heavy water in PHWRs.

dominant issue and sufficient information has been assembled to create an overall strategy of how to proceed with the cleanup of damaged fuel and related waste. This phase is also characterized by efforts to gain control over gross contamination situations, in terms of either sufficient cleanup or isolation to make it possible to proceed with fuel removal as a primary objective. This stage also includes the safe confinement of fuel at the plant before preparations for eventual transport to other facilities. Analyses of system operability for long term use are performed in this phase.

TABLE III. PHASE TIME DURATIONS

Accident	Accident response	I	II	III
A-1	2 weeks	1 year	4 years	10 years
Chernobyl	4 weeks	3 years		
TMI	2 weeks	2 years	8 years	20 years
Windscale	2 weeks	30 years		

II. Remove fuel

The removal of damaged fuel and capture in primary containers as a prelude to the preparation for ultimate disposition is the phase that effectively eliminates the possibility of an inadvertent criticality and uncontrolled release to the environment.

III. Dispose of fuel and related waste

This phase marks the preparation of fuel and other abnormal waste for either permanent local entombment or transport to an ultimate or interim location. During this phase decisions regarding ultimate plant disposition can be made for either return to service or decommissioning.

The types of operations of importance for each of these phases are shown in Table II. It is re-emphasized that, at best, it is possible to give only a general definition of when one phase has ended and another has started. For example, there are likely to be aspects of waste management that are constantly present until ultimate plant decommissioning or restart.

All these on-site operations are required to achieve the overall objective of gaining absolute control of damaged fuel and related waste.

Examples of the range of time durations typical of the phases are shown in Table III.

2.2. ESTABLISHING A PROGRAMME STRATEGY

At the top level of the hierarchy of directives for a post-accident programme will be policy guidance and strategic planning, providing direction to the project and task managers. This section addresses only this top level because the next level will be very dependent on the specific consequences of the accident.

A strategy should be established at an early stage to provide policies and broad guidance to the post-accident organization. These strategic policies should provide a concise overview for corporate and programme management and provide a vehicle for communicating the programme to individuals and agencies which are not directly involved but must be kept informed.

The programme strategic policies should identify and provide guidance for:

(a) Programme goals.
(b) A logical, operationally focused sequence of projects and major tasks based on the specific circumstances, conditions and resources available.
(c) Short term and long term plan for decay heat removal.
(d) Policy and guidance on personnel dose management.
(e) Plant status assessment as determined from the best available data.
(f) Completion criteria (quantitative, where possible) for residual contamination and fuel removal.
(g) Priorities and strategic planning concerning waste management, decontamination, and fuel removal, fuel disposition and waste disposal activities.
(h) Operation and maintenance of nearby units, especially where the units share systems/resources.
(i) Resources needed for disposal of all kinds of waste from the accident.
(j) Consultations and acceptance of directives from regulatory organizations, and also instructions on where to depart from established rules and regulations which do not cover the existing physical and operational circumstances.
(k) Guidance on where technological innovation is necessary and what institutions or agencies will sponsor and manage the developments.
(l) Guidance on institutional issues which will impede technical progress (such as the lack of a disposal method for damaged fuel and abnormal waste).
(m) Guidance as to what should be indefinitely deferred (for example, maintenance on equipment that may never be used again).

A strategy plan, which is a document to direct and implement this policy guidance, with an overview of key activities and resources required, should be provided. The plan must necessarily allow for flexibility in its implementation. In addition to the statements of policy on the subjects listed above, the contents can include specific implementation directives, for example:

— A basis for ensuring the reactor will remain under control and a monitoring plan to ensure this control.
— Guidance on how to strengthen barriers where necessary to reduce the spread of fuel and waste to unwanted areas.
— An overall approach to defuelling, detailed only to the extent that the fuel condition is understood.
— Plans for processing gaseous, liquid and solid wastes.

- A brief listing of the function of systems and facilities thought to be needed. This should include the use of existing plant facilities, systems and equipment in ways not originally intended by the designers.
- Methods for personnel, public and environmental protection.

As the programme evolves, many aspects will come to differ from the initial strategy plan. However, if realistically conceived with the aid of experienced advisors, the overall plan should remain valid. It will also be invaluable for communicating the programme both within the recovery organization and externally.

2.3. ORGANIZATION

The functional needs of an organization in a less severe case of fuel damage may be handled substantially by the plant staff but in the most severe cases will require a large additional organization. Almost any incidence of fuel damage will require outside expertise and additional personnel. The organization must be flexible and should respond quickly to the need for change in cases when the actual requirements and priorities of the project must be modified.

2.3.1. Approach to organization

Any post-accident scenario is unpredictable and will require a programme which includes continuous investigation and development. Conventional operating plant and utility management and architect–engineers, turnkey suppliers and responsible constructors must be prepared to work in an unconventional manner required by projects which engender an R&D type environment.

However, maintaining the existing plant operational organization and infrastructure is important as there will be many operational tasks to be conducted. The plant organization must be supplemented by executive management for the additional technical resources and skills.

A project oriented organization appears to be the best structure for a recovery and cleanup effort. It is better suited to the uncertainties of an accident or emergency situation. It is capable of being adjusted to deal with circumstances and technical needs that are continuously changing and evolving.

While redundancy in the organization is expensive and difficult to manage, some degree of redundancy is necessary until a stable condition is reached, to help ensure that a sufficient number of options are considered and potential problems are recognized.

After reactor control is gained, one of the most important initial efforts is collecting and expeditiously processing solid, liquid and gaseous wastes. A project organization group is essential for evaluating, selecting, establishing and operating waste systems.

A decontamination organization is required to gain access to operate equipment. It is extremely important that decontamination priorities be based on criteria which contribute to ALARA ('as low as reasonably achievable') conditions for accomplishing other tasks. Decontamination solely for the purpose of cleaning must be viewed as a low priority in the early stage of the programme.

In the early phases of a cleanup, a centralized high priority effort should be mounted to provide data on actual physical conditions. Visual and video observations are essential. The ability to quickly analyse radioactive samples on-site is paramount. Emphasis must be placed on obtaining reliable characterization information before planning systems and facilities.

Centralization of planning and data management and analysis within the organization is necessary to ensure sufficient resources and emphasis on the importance of reliable data and to provide for communication of the data to all elements of the organization.

Input from advisory groups should be integrated into the organizational structure. The experience of senior advisors can be invaluable for a project that is evolving as it is performed, as long as the agenda is specified by project management and the organization is committed to seriously considering the recommendations. It is important to ensure that the experience of the advisory group individuals is relevant and the make-up of the group should probably change as the type of operation changes.

Local on-site or near-site engineering staff and a special equipment fabrication capability are essential for proceeding expeditiously. Localization of skills serves to maintain project memory, which is an important asset when the project lasts for several years.

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

2.3.2. Interactions with the regulatory authorities

The normal method of interaction between safety regulators and the plant owner/operator will necessarily change because:

(a) There will be many design projects and operational activities for which the standard regulations must be modified.
(b) There will be other activities for which there is no regulation, but for which reviews by independent safety regulators are necessary.
(c) The usual administrative/procedural chain by which proposed activities are submitted, reviewed and approved by the safety authority is unsatisfactory in the expedited time frame.

(d) The safety authorities staff may not have the special expertise required to review the unique situations.

Experience at both Chernobyl and TMI indicates how these circumstances were managed. At Chernobyl, because the conditions were extremely different from normal, a special government commission took on the responsibility of initiating and imposing a new set of special requirements for the operational safety of the stabilization activities, particularly with respect to allowable worker exposure.

At TMI, the normally separate Nuclear Regulatory Commission (NRC) functions of regulatory review and approval of proposed changes and the inspection and enforcement (I&E) of operations to approved licence requirements were combined in a single group with offices physically located at the plant site in mobile facilities. In this manner, the review and approval process of proposed activities could be accomplished in a matter of days instead of months and the I&E function was applied to all the activities immediately. Special expertise was provided to the NRC by national laboratories and contractors.

2.3.3. Initial organization

The precise management structure of a post-accident organization is as dependent on the national and governmental characteristics as it is on the technical challenges. In the initial phases, the structure has ranged from predominantly plant staff with some degree of specific support (A-1 and Windscale) to a large government involvement (Chernobyl), or a predominantly ad hoc non-governmental response (TMI). Figures 2 and 3 illustrate the Chernobyl and TMI top level functional organizations, which are examples of governmental and non-governmental organizations, respectively.

At Chernobyl, an operational team headed by the President of the USSR Council of Minsters, N.I. Ryzhkov, was organized to co-ordinate the activities carried out by the ministries and other state departments. Scientific and technical institutes and the economic resources of the Soviet Union were mobilized. The programme was designed not only to conduct recovery work but also to restart operation of the neighbouring nuclear power plant units as soon as possible.

The accident recovery work at Chernobyl was an entirely new experience in world engineering practice. The scale and complexity of the problem and responsibility for the general population were unprecedented. A governmental commission was therefore formed to study the accident and to accomplish all required actions. The commission was headed by a Deputy Chairman of the Council of Ministers of the USSR. This commission included leading civil service administrators (Ministry of Energetics, State Committee on the Utilization of Atomic Energy, Ministry of Health, Ministry of Defence, Academy of Sciences, State Planning Committee, etc.).

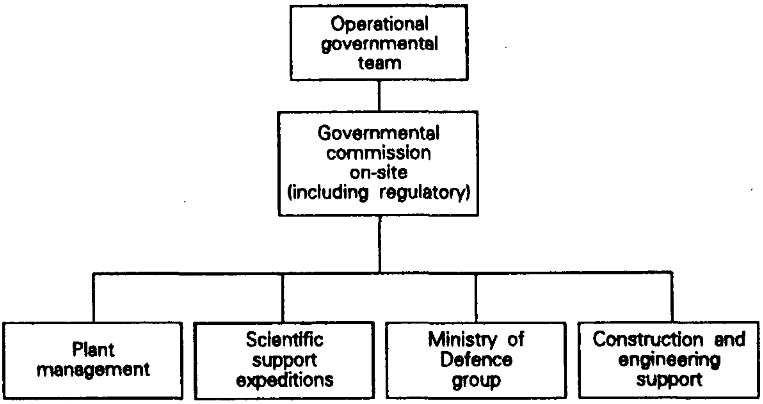

FIG. 2. Post-accident organization for Chernobyl.

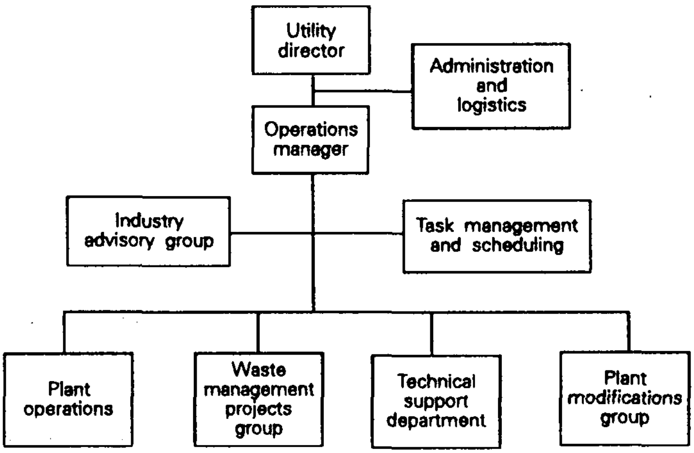

FIG. 3. Post-accident organization for TMI.

The staff of the State Committee on the Utilization of Atomic Energy co-ordinated the design and construction of the eventual enclosure as well as many other activities. Scientific support for all recovery activities was provided by the I.V. Kurchatov Institute of Atomic Energy.

A Co-ordinating Scientific Council of the Academy of Sciences was formed. Operative commissions were organized at some Ministries. Ministry of Defence groups were used for decontamination activities, the operation of special engineering equipment and the transportation of materials for the enclosure of the destroyed reactor. The Ministry of Energetics staff co-ordinated activities at and near the Chernobyl site.

For the enclosure design a special team, headed by the Director of the All-Union Project and Scientific Research Institute of Complex Power Technology, was organized. In an extremely short period of time this team produced all the required drawings and specifications for the construction. Construction groups of the Medium Machine Building Ministry carried out the enormous work of decontamination and confinement system construction.

A special industrial company 'Kombinat' was later formed with all technological facilities required for post-accident activities (decontamination, waste treatment, waste disposal, etc.).

At TMI, an on-site staff of about 2000 persons was created within three weeks. The initial organization was formed by the president of the utility. He established telephone contact with senior managers and specialists throughout the nuclear industry requesting support. The Electric Power Research Institute provided specialists. An ad hoc group of engineers, scientists and experts joined with the staff of the utility, its NSSS (nuclear steam supply system) supplier, and its architect–engineer. During this initial phase, the role of the United States Government was primarily that of providing experts from the national laboratories and setting up an off-site monitoring programme. The safety regulatory function of the NRC was continued with the normal complete independence from the utility organization.

2.3.4. Lessons learned from TMI and Chernobyl

The experience from TMI and Chernobyl has led to recommendations to create an organization with the following structure:

(a) *Overall director.* The on-site response organization is responsible to the overall director. The degree of authority vested in this director will undoubtedly depend on the degree of governmental involvement in the programme.

(b) *Plant operations director.* Continuation of operation of plant systems will be the responsibility of the normal station staff. This calls for maintaining the station organization and for additional operational organization for equipment and systems that are added or brought in. In most cases, the plant superintendent will keep overall responsibility for station operations when any system has the possibility of affecting station systems and operation. For equipment and systems which do not interact directly with the plant, operation should be given over to the independent operating group.

(c) *Waste management group.* In the early phases of a recovery, waste processing and storage issues will have a dominant influence on the ability to proceed. These challenges will be beyond the experience of the normal plant operators.

Therefore, a special project-type organization is required to manage, plan, design, construct and recommend how to operate waste systems and facilities. Waste management activities must be carried out in close co-operation with the decontamination group and those responsible for personnel protection.

(d) *Decontamination group.* Early decontamination efforts will require large numbers of people. The deployment of contractors with special skills in these fields will be advisable. In order to maintain proper priorities, management of the decontamination group should be the responsibility of the plant owner, even if contractors are used to do the work. As an example, at TMI the initial decontamination teams were volunteers from all parts of the corporation. The use of internal employees and the wide range of skills this brought to the decontamination organization were invaluable in terms of accomplishing work and maintaining morale for what is essentially 'dirty' work.

(e) *Data management and analysis.* This group co-ordinates the gathering, maintenance, analysis and distribution of technical data to support all waste management, decontamination and defuelling. Activities include arranging for on-site and off-site chemical and radiochemical analyses, investigation and procurement of special examination devices and methods, inspections to determine physical conditions, establishing databases and conducting analyses.

(f) *Engineering support.* A group of nuclear, structural, electrical and chemical engineers and designers will be required to design modifications and new equipment and systems. The availability of the as-built documentation is essential to the group's efficient activity. This group can be off-site in a classical architect–engineer or turnkey supplier situation, in which case close co-ordination will be required. However, there is a high probability that an off-site organization will tend to 'do business in the usual manner' which could impede progress, and the on-site director must not hesitate to intervene or move the group to the site if warranted.

(g) *Modifications project group.* 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 located in close proximity to the plant because there will be a continuous need for direct information.

(h) *Technical planning.* A technical planning staff to serve the director will develop strategic and technical plans, working closely with the line organization. This group should ensure that information is distributed inside and outside the organization, support the resource planning and act as the interface with the technical and safety advisory groups. This group can also be given the responsibility for arranging for outside ad hoc expertise as needed.

(i) *Independent advisory and review groups.* Two types of advisory groups should be considered: a technical advisory group (TAG) and a safety advisory group (SAG) (the first for technical critique of plans and operations and the second for review of safety practices). These two functions must be kept separate so as to ensure clear definition of purpose, although it is obvious that the technical group will consider safety aspects in their recommendations and that the safety group will be aware of the technical practicality of their recommendations. The TAG should consist of experts from a broad range of experience. The group evaluates the cleanup in terms of experience and techniques that have proven successful in other industries as well as the nuclear industry. This group will bring a depth of technical experience that will enhance the perhaps narrower experience of day-to-day engineers and managers. The SAG, on the other hand, evaluates the cleanup in terms of how the work relates to public and worker health and safety. In general, the SAG focuses on regulations, risk assessment, radiological protection, project organization, procedures, planning, public communication and conflict resolution.

3. STABILIZING THE FUEL

Cases of fuel damage can be viewed as resulting from initiating circumstances such as a flow degradation (Swedish studies, A-1), gross starvation of overall core cooling (TMI) or energetic disassembly of the core (Chernobyl). The time required to gain control of the crisis will vary depending on the specific circumstances. After the crisis resulting from an initiating event, and prior to a decision on what to do about the damaged fuel, attention must be turned to managing the first phase of stabilizing and assessing conditions. These actions will generally depend on the severity of the accident, the type of reactor and the fuel accessibility. An evaluation of the condition of the fuel and its location will be necessary as quickly as possible in order to achieve a stable state in which the fuel will be later removed.

There are three major functional principles for stabilizing fuel:

(1) Ensuring subcriticality
(2) Removing decay heat
(3) Preventing further spread of radioactive material.

In relation to technical aspects of the plant management, all operations must be based on reliable diagnostic measurements and attention concentrated on planning and executing the following activities:

(a) Stabilizing fuel by ensuring subcriticality, removing decay heat and obtaining control of flow, pressure and coolant inventory to support such removal, until such time that active systems are no longer required or normal system operations can handle the situation.

(b) Gross capture and minimization of further spread of distributed fission products and fuel and volumes of liquids and solids that contain these contaminants. This can also involve capture of fuel that may be grossly dislocated.
(c) Establishment of assessment methods and resources to gather and analyse data sufficient to support demonstration of the margins of safety, including subcriticality assurance, and to plan for cleanup with major emphasis on fuel removal.

These activities comprise the stabilization phase of on-site, post-accident management. During these operations, there will be other types of activities influencing the management of damaged fuel. Examples of these other activities include:

(i) Releasing contaminated gases and hydrogen as necessary, in a controlled manner;
(ii) Gaining access to essential operating equipment through personnel dose management, establishing radiation and contamination barriers and decontaminating where necessary;
(iii) Physically separating contiguous units with barriers, system alignment or modification, and installation of alternative systems.

A variety of systems and equipment will be required during the stabilization phase. Depending on the degree of fuel damage, this can range from almost 'nothing extraordinary' to almost 'nothing standard'. This range is best illustrated by examples, which are given below in relation to the three functional principles listed earlier.

3.1. ENSURING SUBCRITICALITY

When the reactor's normal means of shutdown is uncertain as a result of a fuel damage event, extraordinary methods for ensuring subcriticality become important. These assume the function of providing a shutdown margin, perhaps with neutron poisons, and preventing re-criticality by relocation of fuel or flooding with unborated water. Monitoring is also required.

At Chernobyl, as a first step, boron was added by inclusion in the material dropped from helicopters. After the enclosure has been constructed, boreholes were made to examine the main fuel masses by taking samples, and measuring temperatures, neutron flux, photon flux and neutron multiplication. At the beginning of 1989, it was shown that the Chernobyl unit was in a deep subcritical condition.

At TMI, the boron concentration was initially increased beyond routine levels to 2000 ppm, and later, for fuel removal operations, to 3500 ppm. The normal means of neutron monitoring were used initially. When the vessel head was removed, additional instrumentation was installed. Further core disruption was avoided by limiting the flow forces and using only one reactor coolant circulating pump.

It can be seen that the use of boron in one form or another is an important consideration. However, it is necessary to take into account possible undesirable chemical reactions and effects on other reactor components (such as concrete structures).

3.2. REMOVING DECAY HEAT

Decay heat removal includes a combination of 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, 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 the presence of high radiation prevent access to equipment normally used for this purpose.

At both TMI and Chernobyl, installed decay heat removal systems were never used for their intended purposes (for different reasons). In both cases, additional systems were quickly (two months) designed and installed for contingency measures, although these were not used.

At Chernobyl, as a double insurance against the extremely low risk of the lower levels of the structure being destroyed, a heat removal system was installed beneath the foundation of the reactor building. This consisted of a plate type heat exchanger that was installed by tunnelling. The construction was completed two months after the accident.

Early activities at Chernobyl also included measuring the air flow and temperature by remote means to confirm that sufficient convective heat removal was taking place. Later, a forced air cooling system was installed, but like the plate heat exchanger, was never actually required. Natural convective flow of air is the primary method for heat removal at Chernobyl.

At TMI several concepts were defined that included short term and long term approaches. Ultimately, these concepts evolved into three general methods of implementation:

— installing new primary side systems
— installing new secondary side systems
— improving the reliability of existing secondary side systems.

The third approach was used for more than one and a half years after the accident. The primary system was then isolated from active cooling modes and the sole mode of decay heat removal became direct heat conduction to the environment. At TMI, a system was built that combined pumps and surge tanks, located in the spent fuel pool building, for pressure and volume control. This system was placed in operation when the normal make-up system failed. It operated for several years until the reactor vessel head was removed for defuelling.

3.3. PREVENTING FURTHER SPREAD OF RADIOACTIVE MATERIAL

The third principle is to prevent the further spread of radioactive material from the plant. The main objective in this regard is to minimize any relocation of the damaged fuel and associated fission products.

The most obvious action to take is to ensure that the nuclear fuel, both damaged and undamaged, is stabilized in place, and that there is no possibility of fuel displacement or movement. In addition, several other actions must be taken within the plant to prevent the further spread of radioactivity. An analysis should be conducted to identify any weak boundaries or barriers which could fail and release activity. These barriers, for example, could have been weakened during the accident.

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 could occur as a result of degradation by environmental conditions created by the accident, such as high radiation fields, heat, moisture or pressure. For example, degradation could occur in cables, lubricating oil, gaskets and other important components. If not compensated for, such failures could lead to further releases of radioactivity.

Since accidents are likely to vary so significantly from case to case, it is difficult to prescribe specifically how to implement this principle. In the Chernobyl case, the plant was stabilized through a massive effort of building an enclosure for the whole unit after the initial action of dropping materials by helicopter. At TMI, the main action taken was to ensure the continuing integrity of the reactor piping systems and the containment, neither of which was damaged to any great extent during the actual accident.

4. DATA MANAGEMENT AND ANALYSIS

Reliable data are a most important (though often lacking) component in planning cleanup operations, but they are also essential for the Phase I assessment activities as well as for planning and evaluating the Phase II and III options. Data must be systematically collected, analysed and organized to avoid false starts and overly conservative or optimistic assumptions that lead to wasted time and effort. The importance of data specific to the cleanup and to recovery from any accident cannot be overemphasized. As mentioned in Section 2, the importance of data collection and analysis must be recognized throughout the organization of the cleanup.

Nuclear power plants use a large number of measurement, analysis and other characterization techniques. However, in a fuel damage situation, data management and analysis can take on an extremely high level of significance because of the extreme difficulty of physical access and the need for information unique to the circumstances. Thus, a need is created for many techniques that are not usual for the plant. These can include, for example: sampling, radiochemical sample analysis, chemical analysis, radiospectrometric analysis and calculational analysis. Specific aspects to be considered are:

(a) *Contamination characterization.* High levels of contamination, the presence of beta and alpha emitters and the large number of analyses needed require laboratory techniques beyond those of which a normal plant is capable.
(b) *Measurements to support health protection.* During activities for decontamination and in the preparation for fuel removal, it is possible that alpha and beta particles will become airborne. This will require special instruments and analyses to provide timely sample results.
(c) *Waste characterization.* 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 10–100 times greater than those in normal 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 the presence of microorganisms or a high particulate content, and the need to maintain high concentrations of boron can contribute to the complexity of the situation. In particular, the management of water chemistry can be complex because of the need for criticality control, minimization of corrosion and treatment to prevent biological growth and perhaps to minimize radiolytic hydrogen generation. These procedures will necessarily be supported by frequent water chemistry analysis. The use of recombiners in different vessels can minimize certain problems.
(d) *Other on-site characterizations.* These cover a wide range of subjects; examples include degradation of ion exchange resins, distribution of fuel outside of the reactor vessel, airborne plutonium and pyrophoricity of core materials when exposed to air or groundwater contamination.
(e) *Longer term monitoring of off-site radioactive contamination of the environment.* At Chernobyl, TMI and Windscale, there was substantial government involvement for this purpose.
(f) *Neutron measurements.* Changes in neutron flux, temperature or amount of neutron moderator can in a secondary stage of the event create a new situation of potential criticality. It is important to accurately calculate the possibility of criticality in the damaged fuel.

Because of the number of samples, the types of analyses and the level of radioactivity, a variety of special off-site facilities (with hot cell capabilities) are needed, as is the installation of special on-site facilities.

4.1. INITIAL DATA REQUIREMENTS

Information obtained and measurements made during routine operations prior to a fuel damage event and during the transient will be very important for evaluation of the status after the event. With respect to the fuel this will include:

- The history of the fuel assemblies;
- Computerized analysis of the radionuclide content; the post-event details needed may require software not normally used for routine operations;
- Analysis of temperature, flow and neutron measurements during the fuel damaging transient as well as radiation monitoring throughout the plant.

This information will be used in the Phase I assessment work and also to provide input for Phase II planning.

It is important to collect as many data as possible and to compare diverse information to ensure that any conclusions drawn are valid. Because of the possibility of accident effects, measurements from plant instruments must be carefully reviewed and evaluated before they are used. The local post-accident conditions can have a strong effect on instruments, cables, amplifiers and power supplies. Over-ranging effects, moisture, and high temperatures and radiation levels can affect the calibration and response.

4.2. CHARACTERIZATION TO PREPARE FOR FUEL REMOVAL

From experience of fuel damage events that have occurred, it is clear that before elaborate plans for defuelling and the design of any necessary tooling are embarked upon, as much information as possible must be gathered on the state of the reactor core. It will almost certainly be necessary to revise any plans or work programmes as the defuelling proceeds and further data are acquired.

The ability to visualize physical conditions is very important. Pictures are invaluable, whether in the form of photographs or videos, or derived from the use of devices such as infrared and ultraviolet viewers or computer imaging equipment.

The details of the core operational history prior to the event are also important. Before a defuelling 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 database and a model of the damaged reactor. The necessary information includes the extent of the damage, and the condition of the fuel and its location. This is obviously a difficult task and as any ultimate defuelling programme commences, further information will be obtained which could well change the strategy and programme. In order to predict the state of the reactor a number of techniques should be considered, for example:

(a) An assessment of the state of the fuel can be made from a 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 on the basis of fission product releases. The numerical precision of the computer results, however, must be known or estimated. Judgement will be required in the assessment of any such results.
(b) Neutron and gamma measurement results can be used to non-destructively determine the distribution of relocated fuel in the pressure vessel, in piping, in concrete, etc.
(c) Techniques are available to make penetrations through containment walls and piping material into areas which are subjected to positive pressures and contain activated water. These methods should be considered because, in many instances, it will be the only way to obtain the information required.
(d) Remote viewing of geometrical structures and surfaces may provide 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 exist endoscopes, and glass fibre optics and closed circuit radiation hardened TV systems which are small in size and provide access to concealed objects even through curved or offset pathways. The quality and reliability of visual information depend mainly on the precise manipulation of the visual systems to ensure the correct reference points. Successful optical viewing depends very much on adequate lighting and, for underwater application, on the clarity of the water.
(e) Detailed information on the physical and chemical status of fuel or structural components may be obtained by the collection of samples or the use of probing tools. Shielded facilities for analysing the samples must be available.
(f) Temperature measurements (by existing or newly installed instruments) in gas cooled systems and temperature distribution data may provide information of value.

4.3. ASSESSMENT OF LATER STAGE OF CLEANUP

When the fuel removal phase is essentially complete, the status of the plant should be determined and documented in preparation for the next phase, whether it is a return to power, monitored storage or commencement of decommissioning.

A programme may be required for measuring the amount of remaining fuel. Techniques include gamma spectroscopy, solid sampling, alpha counting and neutron measurements. When it can be shown that fuel has been removed to the point that criticality is no longer possible, the cleanup programme becomes one primarily of decontamination. In addition, other types of characterizing measurements and inspections will be necessary, including, for example, monitoring of contaminations and radiation levels throughout the plant. For restart, evaluation of the readiness of equipment to operate and the requalification of the pressure boundary will require inspections and measurements.

Special nuclear material (SNM) accountability must be considered. Although the damaged fuel may in no way represent a diversion threat, which is the primary regulatory reason for SNM accountability, the requirement remains and there is a responsibility to do such accounting. A potential difficulty is that the damage may make normal means of inspection impossible. The safeguards activity may be more easily accomplished by precisely accounting for what remains after the damaged fuel has been removed.

4.4. SAMPLE ANALYSIS CAPABILITY

Because samples are likely to be more radioactive than usual, and the types of analytical procedures are likely to be different from those normally used in power plants, special analysis facilities will certainly be necessary. The need for fast results will mean that this capability should be established on the site or in close proximity to it. Such facilities can be located in existing buildings or can be provided in custom built mobile or transportable trailers. Shielded wet chemistry stations and gamma spectrometers should be included. Reference counting standards for high and low energy photons should be available for calibrating radiation analysers.

4.5. COMPUTER CAPABILITY

Computers are required for many tasks, including analysis, information management, planning and presentation.

Examples of technical applications are:

- Radiation calculations — dose assessments for purposes of temporary shielding design and personnel exposure assessments.
- Sample tracking — database of samples and analysis results.
- Waste management — managing the liquid and solid waste quantities by volume and radionuclide content.
- Spectral analysis — gamma scan evaluations for determining the locations of fuel.
- Source calculation — analyses to assess the relative amounts of fission products as they decay with time.

— Dose rate tracking — database of area dose rates, surface contamination and airborne activity.
— Three dimensional visualization — used to show the progress of activities, specifically fuel removal, but also temporary location of equipment and waste within the containment.
— Two dimensional drawing — design of special fixtures and components, flow path elevation analysis for decontamination planning and flush flow path decisions.

In addition to these, other computer applications include the preparation of presentations, report writing, action tracking and status, scheduling and budgeting.

5. INITIAL WASTE MANAGEMENT

Initial waste management deals with the early phases of work on water, gases and solids that are radioactive as a result of a fuel damage incident. These activities are to be distinguished from the later stages of preparing waste for ultimate disposal (Section 9).

A significant fuel damage incident will present a considerable challenge to the installed processing systems and shielding equipment. The reasons for this are:

(a) *Radioactivity in water.* Fuel damage can result in the release of substantial amounts of fission products, such as caesium, iodine, strontium and antimony, as well as actinides such as uranium and plutonium. These will be heavily concentrated in the primary coolant but will also be distributed throughout systems that may be exposed to primary water or steam.

(b) *Radioactivity in gases.* Gases can become distributed throughout the primary and auxiliary circuits of gas cooled plants; large amounts of the fission product 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).

(c) *Radioactivity in solids.* Fuel damage can result in heavy contamination inside the damaged plant, consisting of a variety of fission products and minor amounts of certain activated corrosion products, likely to be distributed in unexpected quantities and forms.

The quantities of water, gas and solids thus contaminated can be substantially larger than the plant's normal holding capacity.

5.1. THEORETICAL STUDIES

An appreciation of the potential magnitude of the waste volumes and the radiological hazards can be obtained from two Swedish studies [4, 5] that investigated the impacts of fuel damage beyond the design basis but at a less severe part of the accident spectrum compared with Chernobyl and TMI.

Traditionally, a fuel damage design criterion is used for normal operation of nuclear power plants, such as damage to 1% of the fuel rods resulting in the release of fission products at a corresponding rate. This criterion is used to design the radiation shields in various locations where primary and secondary systems containing fission products are located and to determine the capability of water, gas and solid processing and handling systems.

The first Swedish study [4] addressed the impact of radioactive waste from two accidents in a BWR that would result in the release of the order of 0.1% of the core inventory of noble gases, iodine and caesium. One of the cases treated was a loss of coolant accident (LOCA) resulting in 1% of the fuel rods being damaged, and the second case was the blockage of a fuel channel resulting in the meltdown of the affected fuel assembly.

The conclusions of the study include the following:

(a) During the first weeks after the incident, the access to areas where emergency cooling and controlled drainage systems are located will have to be strictly limited.

(b) Before the reactor pressure vessel is opened, the water in the pressure vessel and the containment has to be purified in order to prevent the spread of radioactivity to the reactor hall and reduce the dose rates around the reactor pool. This purification would probably only start about four weeks after the incident. A period of three to four months is estimated to be required to reach an acceptable radiation level around the reactor pool.

(c) The cleanup of the containment is a difficult job which is estimated to last some months.

In the cases studied, the conclusion was reached that there are probably no weak points in the waste treatment plants which would limit the treatment and conditioning of the radioactive waste after the postulated fuel damage. However, one utility review of the report pointed out the risk of overestimating the capacity and underestimating the technology. The study also indicates that flexibility is an important quality — difficult though it may be to define — of a waste plant and its interaction with the reactor.

In the second Swedish study [5], the fuel damage is substantially larger, reflecting a LOCA with a complete loss of all electric power for a time period adjusted to give a fuel damage corresponding to a 10% release of the core equilibrium inventory of noble gases. The resulting caesium release corresponds to

7% of the core inventory (about equal to the amount of the caesium released in TMI). Since the reactor containment is filled with water to secure long term cooling, a volume of 100 000 m^3 of highly radioactive water will have to be treated in the waste plant and the free surfaces in the containment will be radioactively contaminated.

The first waste problem encountered after the accident is the management of highly contaminated leakage water from the containment. It was concluded that the leakage water, if possible, should be directed primarily to the containment, which is a very suitable and safe storage space in this case, but other options were also recommended.

The major cleanup step is assumed to start at the earliest three months after the accident, using a feed and bleed process and the existing cleanup system in the waste plant. Owing to the high radiation doses expected in the ion exchange resins in this system, the use of zeolites is recommended. This might, however, make it necessary to connect special filter vessels for inorganic media such as zeolites in case the plant vessels are unsuitable or unavailable.

Cement is recommended as the solidification matrix for many reasons; one is that this is the technique normally used in solidification systems and hence existing equipment can be employed. However, owing to the limited capacity at the early stages of the cleanup process, it is also recommended that a mobile solidification unit be used. As a conservative estimate, the entire water cleanup procedure produces about 800 concrete moulds, assuming that zeolites are used in the major step.

As a main conclusion of the second Swedish study it appears that core damage corresponding to a release of 10% of the noble gas inventory could be managed in the reference reactor with modifications in the waste treatment plant after the event. Many of the findings and recommendations are generally applicable, but individual characteristics at different nuclear power plants make the detailed results of the study reactor specific.

5.2. EXPERIENCE FROM TMI AND CHERNOBYL

The technical history of the TMI accident provides the following insights into initial waste management:

(a) From the day of the accident until the end of the cleanup, the GPU Nuclear Corporation (GPU) was forced to manage radioactive wastes on a scale and of a type without precedent in the nuclear power industry. For several years after the accident, everything seemed related to waste management. By far the most demanding challenge was the highly contaminated water and its related solid wastes.

(b) Fission products escaped from the reactor vessel core, reactor coolant system and related systems during the accident. The activity was in the form of radioactive gases, contaminated water, and particulates and fuel particles carried with the water. Cleaning up produced enormous quantities of contaminated equipment and trash, hundreds of processing vessels loaded with varying concentrations of radionuclides, and about 15 000 m^3 of mildly radioactive water. In addition to managing this waste in a manner that demanded worker and public protection and the shortest possible schedule, GPU also had to address a state of transition of national and state regulations regarding waste disposal which in many cases had not previously considered accident wastes.

(c) Most radioactive trash and solid decontamination wastes were handled in ways similar to those used at other nuclear power plants, but on a much larger scale. The control of radioactive gases was a substantial issue until 1600 TBq of krypton gas were vented from the containment in 1980.

(d) The water was initially distributed in the containment basement, reactor coolant system, auxiliary building sumps and tanks, and over the lower elevation floor of the auxiliary building. The water, with the associated high radiation fields, prevented system maintenance and hindered cleanup work. The existing plant systems were unable to process any of this water, which contained ^{137}Cs concentrations initially of several TBq/m^3. Consequently, over the first few years, a major portion of GPU's resources were spent on water management.

Experience at Chernobyl has shown that when the areas surrounding the damaged reactor are contaminated the use of motor vehicles can significantly affect the spread of the contamination. In order to reduce this effect, motor vehicle washing facilities were installed and in order to minimize the quantity of secondary waste produced a spent liquid treatment plant was also set up.

The motor vehicles were decontaminated by washing with a sulphanol and sodium polyphosphate solution. The spent contaminated solution was collected and then passed through a purification process including:

— sand filter to remove large particulate material
— coagulants to maximize the release of radionuclides in solution
— an inorganic zeolite filter for the selective removal of caesium and strontium nuclides.

The decontaminated waste was collected for reuse in the production of decontamination fluids.

5.3. INITIAL WASTE MANAGEMENT PRIORITIES

The technological details of processing abnormal waste are covered in other IAEA publications (see, for example, Ref. [6]). The aim here is to provide management insights on various issues. The discussion that follows is based on a rather severe situation, typified by Chernobyl and TMI.

It would be imprudent to attempt to anticipate all fuel damage scenarios and then install systems in anticipation of the waste processing that would be needed. The selection and design of a process will depend on subtle and unpredictable circumstances as well as those that might be foreseen. Thus, the prudent approach is to consider what might be necessary to cope with the immediate crisis and rely on the managers of any situation to make specific selections for processing based on the conditions that actually exist.

In general, the order of urgency for managing waste will be:

(1) Venting of gases, taking into consideration the inventories of fission products, radioactive particulates and possibly hydrogen;

(2) Containment of the water in tanks, sumps, primary containment buildings and basements (emergency release to the environment would be used as a last resort, with all relevant standards observed);

(3) Processing of water in systems and areas where human access is necessary for operational control — this processing is for gross capture primarily of radioactive caesium and radioactive corrosion products in order to reduce area radiation levels as quickly as possible;

(4) Shielded storage of the secondary wastes resulting from water processing (filters, ion exchange media, containers, evaporator bottoms, directly solidified water, etc.);

(5) Recycling of processed water to minimize the amount of fresh water likely to be contaminated;

(6) Final decontamination of the water as a requirement for discharge.

New waste processing systems may provide better results for liquid waste cleanup than in-plant systems for highly contaminated water. Such means were employed at both Chernobyl and TMI. In the TMI case, three additional water processing systems were installed at various stages. At Chernobyl, a large water processing unit was constructed. As Chernobyl activities continue, the need will undoubtedly arise for additional systems.

5.4. ON-SITE STORAGE OF ABNORMAL WASTE

On-site storage may be necessary for abnormal wastes for the following reasons:

— to remove radioactive material away from a working area
— to provide buffer storage because of the abnormally large volume
— to await the provision of special treatment systems.

In principle, existing storage facilities may be used for abnormal radioactive wastes. As a temporary measure, it may be necessary to use existing buildings until special purpose facilities can be built, or until the wastes are transported off the site. Since the activity levels of abnormal wastes may be higher than those normally encountered, consideration of remotely operated handling systems and of special shielding and/or personnel access control may be required.

On-site storage of unconditioned wastes should only be undertaken on a temporary basis, pending the provision of a suitable conditioning process. In this case greater attention must be given to the need for shielding and prevention of the spread of contamination. The experience with waste storage at TMI and Chernobyl is of interest.

At TMI, such storage was utilized in two separate facilities. The submerged demineralizer vessels, about 1.3 m in length and 0.7 m in diameter, contained zeolite that had captured hundreds of terabecquerels of radioactivity per vessel. These were stored under water in one of the spent fuel pools that also contained the system itself. The second storage facility consisted of 120 vertical cylindrical cells in a reinforced concrete monolith. Each cell was 5 m high and 2 m in diameter. A special 'transporter' consisting of a flat bed truck with a concrete shield cylinder was used to bring the cylinders (about 20 Sv/h on contact) to the storage facility.

At the conclusion of defuelling at TMI in 1990, there will be considerable abnormal waste remaining in the containment. This will be mainly core internals but also the concrete structural material in the containment basement, which is contaminated with ^{137}Cs. The containment thus acts as an indefinite storage location for this material until a method of removal and disposal is determined.

At Chernobyl, the intermediate and low level wastes were buried in a repository of special in-ground trenches of 15 000 m^3 capacity. The trenches are 136 m long, 52 m wide and 4 m deep and have a 1 in 12 slope. The trench floor and walls are covered with a 1 m waterproof layer of locally procured clay and a protective 0.6 m layer of earth. The filled trenches were smoothed out with a 0.6 m earth layer, covered with 1 m thick layers of clay and earth respectively, and then grassed.

The storage facility at Chernobyl includes: a network of access roads, a parking place, a decontamination and radiation control post at the repository inlet, a system of ducts around each trench and the whole repository to draw off rainwater, control and observation holes around the perimeter of each trench and the repository site, fencing and illumination.

More than 800 containers with high level wastes (having surface dose rates >3 mSv/h) were transported and placed into the space between the walls of the destroyed unit and the enclosure wall, and then grouted.

Other high level wastes are stored in a facility with the walls built of concrete blocks, and the base floor made of road slabs, placed in a pad of watertight material. The facility was designed as a system of concrete compartments. The free space in the compartments was concreted to fill voids and a protective layer of 800 mm thickness was provided under the containers. The compartments were then covered with an asphalt layer. (The facility design provides for multitiered storage.) The whole complex will be covered with earth and a watertight layer, and grassed.

The possibility of future retrieval of these wastes and their permanent disposal in a repository is not excluded.

5.5. OTHER TYPES OF WASTE FACILITIES

Much miscellaneous contaminated material, and some activated components, will have to be handled. Several types of facilities can contribute to minimizing the amount of waste created from this material. Examples include:

- Tool decontamination — there are many methods available for decontaminating hand tools, parts and miscellaneous pieces of metal which would otherwise become waste.
- Laundry — large amounts of protective clothing can be laundered and monitored prior to reuse.
- Face mask cleaning — a large number of face masks, breathing apparatus and other personal protection materials will be used. A separate cleaning facility will not only expedite turnaround on their use but will reduce the number that are discarded in low level waste bins.
- Waste segregation and packaging — a capability for segregating waste may be of value for minimizing the amount of uncontaminated material that would otherwise be disposed of as radioactive and for combing wastes to meet low level waste regulatory requirements. Establishment of a separate or combined facility on the site, either as temporary trailers or permanent buildings, will prove to be time saving and cost effective compared with reliance on off-site services.

6. INITIAL DECONTAMINATION

Fuel damage situations may require a decontamination programme, the extent of which will depend on the specific circumstances. The first priority will be to establish and maintain acceptable radiological conditions to permit operational staff to carry out any work associated with maintaining the reactor in a safe condition and/or conducting defuelling operations. Thus the objective will be to reduce general area radiation levels, airborne contamination, and particulate and surface contamination using the ALARA principle. In order to carry out decontamination to the required levels, the determination of contamination levels needs to be carried out with great detail and accuracy. Therefore, it will be necessary to establish a programme of work to accurately define conditions within the buildings using standard techniques of water and airborne sampling and surface smears. The programme of work also has to consider the requirements for access to different buildings or parts of buildings. In this connection, it has to be remembered that the building layouts of different reactor types are conceptually different, which has a strong influence on the access requirements. For example, the containment of a BWR is located inside an outer building, the reactor building, while for a PWR the containment building can be considered as equivalent to the reactor building.

It will probably be necessary to carry out decontamination in several stages with an assessment of the prevailing conditions following completion of each stage. The first stage of gross decontamination will commence once entry to the buildings or parts of the buildings is possible. If the containment has to be entered, the use of remote techniques such as water or steam jetting — with or without the inclusion of detergents — may still be necessary to reduce the radiological consequences to the personnel employed. If access is necessary to a room outside the containment where parts of a system containing highly radioactive water are installed (as the situation may be in a BWR), it is primarily necessary to decontaminate the components. This can be performed by first isolating the relevant parts of the system and then draining them. An actual decontamination of floors and walls is only necessary if a component leakage has occurred.

6.1. OVERALL STRATEGY

It is very important that the planning of the decontamination operations is included in the programme strategy as outlined in Section 2. Initial waste management (Section 5) is also related to the initial decontamination, since decontamination sometimes has to be based on an initial cleanup of highly radioactive water and the decontamination processes themselves may create a substantial amount of waste. Generally, the programme strategy should include the decontamination objectives, i.e. the end point criteria consisting of surface contamination levels appropriate for restart or long term storage of the reactor.

The choice of decontamination procedures and techniques depends on whether the plant is to be restarted. If it is, the decontamination methodologies should be as similar as possible to those used during normal operational conditions. This means, for example, that the procedures and techniques used must as much as possible reduce the recontamination of decontaminated surfaces without destroying them.

If dismantling or decommissioning is chosen, the main priority is usually to obtain the most effective decontamination, without regard to damage to the decontaminated object. Therefore, more aggressive reagents or more 'destructive' techniques can be used.

A key element when there is significant area contamination is the operation of ventilation systems. Special attention must be given to preventing recontamination of areas that have been cleaned, or cross-contamination of different areas. An action as simple as opening or closing doors in combination can cause transport of radioactive dust. Consideration should be given to creating a 'ventilation' committee to investigate in detail what precautions should be taken.

The containment decontamination is of special interest since it involves a large operation and is a prerequisite for defuelling the reactor. Essentially, containment decontamination may be accomplished in four stages:

(1) Characterization of the containment to determine the current and evolving radiological and physical conditions;
(2) Gross decontamination to remove the bulk of the relatively loose and soluble contaminants;
(3) Hands-on decontamination to aggressively remove tightly adhering deposits and reduce radiation levels to those suitable for defuelling;
(4) Further decontamination to reduce radiation levels to those consistent with normal conditions — if this is considered appropriate — and/or to establish a stable and safe condition.

It may be necessary between stages 2 and 3 to reassess the contamination levels before implementing a new decontamination programme. In order to eliminate potential radiological hazards, it may be necessary, following the decontamination procedures, to dismantle or replace some items of equipment to reduce area dose rates.

6.1.1. Decontamination methods

Owing to the wide variety of conditions that might be envisaged and the unpredictable sequences of fuel damage accidents, it does not seem useful to devote limited manpower and resources to the development of decontamination techniques specifically addressed to accidents. In many cases, methods used for more normal conditions may be used, possibly after some adaptation. Other methods can be developed for special decontamination operations after an accident with severely damaged fuel. Assessment of the wide range of decontamination techniques available is unnecessary here as they have been adequately addressed elsewhere [7–13].

In general, the selection of an appropriate decontamination process should consider the following factors:

— planned future usage of decontaminated system;
— effectiveness of the decontamination process;
— operational requirements for the process (time, temperature, concentration, etc.);
— inherent hazards associated with the use of the process (fire, chemical attack, etc.);
— impact of the process on waste management;
— impact of the process on the accumulated radiation dose to workers;
— overall system cost.

6.2. TMI EXPERIENCE

TMI experience reinforced the lesson that decontamination is labour intensive and that people are the most important element, regardless of what technology is available. Specific observations from the immediate cleanup effort to gain access to operating equipment in the auxiliary buildings include the following:

(a) An initial decontamination was conducted by existing staff with a mixture of skills. Direct supervision by the utility manager contributed to a high state of morale and a range of skills that worked very effectively.
(b) Planning and tasks had to proceed in small increments. While long term goals could be established, the task planning horizon was one to two weeks, with changes occurring almost daily on the basis of the previous day's progress and events.
(c) Support facilities were in very short supply. On-site laundry and respirator cleaning facilities were needed immediately.

Waste disposal regulations that have been established since the accident — which prescribe considerable analysis and conditioning before shipment — created a need immediately to establish facilities or locations for interim storage of waste in order to avoid impeding decontamination.

Hands-on decontamination of the operating levels was assumed to be a prerequisite for defuelling. When the initial containment entries in 1980 revealed that background radiation was significantly lower than expected, an expedited decontamination schedule was established to make up for the growing slippage in the overall cleanup schedule.

In 1984, the overall programme strategy was clarified and a revised approach to decontamination was established. The shift was manifested by changing the approach from:

(1) Gross contamination/flushing
(2) Hands-on decontamination
(3) Maintenance decontamination

to

(1) Gross decontamination/flushing
(2) Dose reduction to support defuelling
(3) Decontamination to establish a stable and secure condition.

The programme strategy contained the end point criteria consisting of allowable levels of surface contamination for long term storage. The strategy also included a statement that the cleanup was to be conducted without regard to the ultimate disposition of the plant (restart was later precluded). By defining the decontamination objectives and parameters in this way, the utility GPU could decide on priorities for its decontamination work and allocate resources as needed.

More details about the decontamination experience are presented in Refs [14–16].

6.3. CHERNOBYL EXPERIENCE

The Chernobyl accident has resulted in a significant contamination of not only the reactor building and service rooms at the unit concerned, but also at units 1–3, the whole plant site and large external territories.

The initial stage of decontamination included the collection of highly radioactive materials of different sizes dispersed around the damaged reactor in various rooms, on the roof of buildings and on the near-by territory. Collected materials (parts of fuel elements, graphite and pieces of reactor structural materials) were disposed near the damaged reactor.

6.3.1. Interior decontamination

For the decontamination of equipment and rooms inside the units, classical two-bath methods using oxidation–reduction solutions were not effective owing to the chemical inertness of the contaminants. Experience shows that it is advisable to use methods involving the application of surface active substances. Intensification of decontamination processes was achieved by means of physical and mechanical action on contaminated surface using cloths, brushes, vacuum cleaners, and jet and spray devices.

Decontamination of the concrete floor was carried out by removal of 2–3 mm top layer with a mosaic floor grinding machine. To achieve the required dose rate levels, a 100–150 mm thick concrete coating was necessary. In some places, lead sheets were laid under the concrete.

An important problem was decontamination of the ventilation systems. These were contaminated during the first two days after the accident since they were not isolated from unit 4 at once. As the first step of decontamination, the so-called 'dust trap' air ducts were dismantled. The rest of the air ducts were decontaminated by a 'back blast' technique.

6.3.2. Decontamination of the site

The contaminated area was divided into zones with different levels of contamination to reduce exposure to the personnel:

- a zone with a special regime, which included the damaged unit and the rest of the nuclear power plant installations;
- a zone with rigid regime, having a radius of 10 km;
- a zone with a general regime, having a radius of 30 km.

Each zone is characterized by a specific mode of decontamination; the common approach was to divide the territory into sections, depending on the contamination level, and then to start cleaning from the cleanest area to the dirtiest one. This practice excluded the possibility of secondary contamination and reduced the workload.

The next steps were to build a temporary facility for cleaning the cars which operated within the zones or left the 30 km zone, and to install a special department for cleaning small or dismantled units and components using a wide spectrum of cleaning techniques.

Cleanup operation on the site area included disposal of radioactive objects from the site, removal of contaminated topsoil, laying reinforced concrete slabs or using a concrete mix. Removal of 10 cm topsoil provided a decontamination factor of 10. Subsequent laying of reinforced concrete slabs on the clean ground plots allowed a reduction in radiation levels from the ground by a factor of 20–30.

More details about the decontamination experience are presented in Ref. [17].

7. FUEL REMOVAL

As previously stated, the core damage may range from one to several fuel assemblies affected in a limited core region to a full core having passed through a loss of coolant thermal transient. Fuel removal actions will vary from the use of available standard equipment and tools to the application of specially designed handling and cutting equipment and system modifications around and near the reactor. The procedures and steps involved in opening the pressure vessel will have to be defined according to a prior assessment of the extent of the damage. Continuous surveillance of the core conditions will necessarily accompany all steps during defuelling.

The discussion below is based on the case of a partial melt such as that which occurred at TMI. In the case of Chernobyl no effort has yet been made to remove fuel from its original location.

7.1. PRE-CONDITIONS

It is assumed that radioactive material has been released from the reactor primary circuit into the containment building during the accident and deposited on equipment surfaces, walls, floors and ceilings. Investigations performed during the prior assessment phase provide the initial characterization of the radiological and physical conditions inside the containment.

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

- limiting the working period for personnel to reduce exposure and fatigue;
- providing appropriate protective clothing against radiological and other hazards;
- providing a breathing air supply;
- providing means of body cooling (e.g. ice packs or forced air) until a sufficient ventilation capability for cooling, filtering and controlling humidity is available.

During the stabilization phase, removal of the decay heat and cleanup of any required systems will necessarily have been carried out. However, if the operations were of a provisional nature, long term, reliable operating systems should be made available to ensure the continued safety of the reactor system.

The availability of services such as electricity and lighting, compressed air, ventilation and lifting power will have been re-established. If such systems are damaged then replacement may be necessary.

The necessary monitoring and control will have to be continued to ensure that the reactor remains in a safe state and that any recovery operations will not cause recriticality or other potential hazards such as dryout leading to overheating or dusting.

Equipment for monitoring the physical status of the working environment (radiation fields, aerosols, temperature, humidity and chemical composition of the air) should be provided and records should be kept.

Before consideration can be given to the methodology to be employed for fuel recovery it is essential that a database be established to provide a clear and understandable model of the reactor, detailing in particular the radioactivity/fuel inventory, the physical condition and location of the fuel, and any structural or component damage. Depending on the severity of the accident, this may involve significant work employing a number of techniques (direct sampling, video surveys, sonic ranging, etc.). Creating a realistic model of the physical situation prior to fuel recovery is of the utmost importance.

The required amount of decontamination of the working area within the containment has to be defined on the basis of the ALARA principle with the objective of providing as near normal working conditions as possible for the fuel recovery operations, though this may not be totally achievable either in terms of the conditions or the area within the reactor building.

7.2. TOOLS FOR FUEL REMOVAL

The tools needed for the removal of fuel are considered in the light of the physical conditions of the fuel and the available access to it. One of the greatest challenges is deciding the trade-offs between power assisted and manual tools for various operations. It should also be realized that the situation will continually evolve as new conditions are discovered or as specific designs prove to be inadequate. Flexibility is paramount as defuelling proceeds and the ability to establish a capability to respond to needs is more important than attempting to pre-define all possible situations that might arise.

7.2.1. Types of tools

In addition to the standard tools for fuel handling available in the plant, many specialized tools are required. The need for special manipulating tools starts during the lifting of the upper core structures (i.e. PWR upper core grid, BWR steam/water separator), when parts of damaged fuel assemblies may be connected and possibly raised along with the structure. Some specialized tools can be prepared in advance to help prevent the spread of fissile and highly radioactive material outside the reactor vessel. It is important to prepare certain general purpose tools, i.e. grippers, pliers, vacuum systems and canisters to collect unexpected loose pieces of any material. Vacuum systems (suction pump with particle sieve and filter unit) are useful for collecting small pieces of particle debris for pumping into a canister and for creating a pressure differential at the nozzle to hold larger pieces for transfer to a canister. Such systems have been successful in many applications.

Specially designed fuel transport 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.

Tools may be required for the 'destruction' of material. Molten fuel may solidify in very large lumps, which according to TMI experience are very hard but show brittle behaviour. These lumps will have to be subdivided for collecting into storage or disposal canisters. The mechanical drilling of holes to prevent breaking up of pieces by the application of high hydraulic stresses is one possible approach. Metal structures can be cut mechanically in many ways. Plasma arc cutting and electric discharge machining (EDM) have been successfully applied for underwater tasks. In the USSR the contact arc cutting technique is widely applied for various tasks in the nuclear industry. This cutting process is similar to EDM using the thermal effect of a high energy electric arc discharge, but requires less sophisticated electronic means of control. Methods for both handling and breakup of fuel will have to be optimized to produce the smallest amount of fine particles since the solidified fuel still has a high radioactivity concentration requiring elaborate collection and immobilization techniques.

7.2.2. Tool design and fabrication

Experience has shown that the design of tooling for defuelling a damaged core must proceed along with increased knowledge on the status of the damaged core. This means that experienced tool designers and manufacturing workshops must be available 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. Direct access from the reactor building without the need for shielded transport is to be preferred.

As a general principle, fuel handling tools should be designed to be simple. They should be optimized to serve only one purpose rather than being universally applicable. Whenever environmental conditions (radiation, temperature, etc.) allow manual operation, long handled tools are preferred to remotely controlled ones. To facilitate use, hand operated tools should either be lightweight or have a means for weight support without restricting their mobility during use. Remote operation of tools requires sturdy structures for support and sensitive motion control. The advantage of remote operation is a high degree of freedom in placing the operator and the control panel in the best environment.

Adequate sensors, including TV viewing aids, are a means of ensuring the safe operation of some tools. The energy supply to the tool head may be electrical, pneumatic or hydraulic, depending on the specific task. Modular construction of tools will facilitate maintenance. The design and fabrication must minimize trapping of contamination in order to limit radiation during maintenance.

7.2.3. Testing and mock-ups

Testing for operability and maintenance and personnel training are vital for any successful operation in a hostile environment. New tools must be qualified prior to their actual use by testing on a mock-up. Final testing must include procedures for the mounting, operation, maintenance and dismounting of each tool. The operating environment should be simulated in all important aspects during testing. Full testing is also the appropriate method for training operators in the use of tools in order to gain the necessary skills for high efficiency before they work with the tools on the reactor.

7.3. PREVENTION OF RECRITICALITY AND REHEATING

Damaged fuel is kept in a safe subcritical condition as discussed in Section 3. During preparation for fuel removal, alterations in geometric arrangements which could lead to an inadvertent criticality should be anticipated and precluded. From the data collected 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 configurations giving rise to criticality taking into account the presence of any moderating material.

If criticality cannot be excluded by this analysis, then measures are necessary to prevent it. These methods can include:

- The addition of neutron absorbers such as boron to the core, with the form depending on the state and type of fuel;
- The use in some gas cooled reactors of the nitrogen tertiary shutdown system to reduce reactivity.

Defuelling operations should be aimed at further reducing the possibility of criticality occurring. This aim can be achieved by dilution or by controlling the geometry of the remaining fuel. Adequate measures to sustain the removal of decay heat during fuel removal operations and to eliminate the possibility of fuel reheating should be provided.

7.4. PLANT MODIFICATIONS TO SUPPORT FUEL REMOVAL

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:

(a) Containing highly contaminated water in the reactor vessel to prevent mixing into large water volumes. It is much more efficient in terms of time and cost to process smaller volumes with concentrated contamination. Special purification systems (units) which are normally not available at nuclear power plants may be required.

(b) Providing radiation shielding for workers in view of the fact that long duration operations will have to be carried out in close proximity to the damaged fuel.

(c) Providing a work platform above the reactor to accommodate the special tools and equipment that will be necessary.

(d) Enabling the transport and intermediate storage of fuel canisters. In almost all cases of damaged fuel, additional specially designed containers and shipping casks will be necessary.

The defuelling concept chosen at TMI [18] left the refuelling canal dry so that the highly contaminated water was limited to the volume inside the reactor vessel. Another important consideration in this 'dry transfer' decision was that manual defuelling methods would be necessary for much of the operation and that filling the refuelling canal would result in tool handling from about 15–20 m above the work area. Such remote manual operations are impossible for all practical purposes.

Water for shielding damaged fuel was also used in the fuel storage pool outside the containment and in the deep end of the refuelling canal where the gate to the external pool is situated. This necessitated a dam at the deep end of the canal to keep the water level sufficiently high for shielding of fuel canisters in pool racks. In addition, the deep end provided a location for storing the upper internals assembly from the reactor vessel, thus avoiding the need to fabricate a specially shielded container elsewhere within the containment.

Special filtration and ion exchange systems were installed, partially within and partially outside the containment, to operate continuously to maintain water clarity and control the activity content.

A rotatable, shielded work platform was mounted on top of the reactor vessel, permitting the use of long handled tools. The fuel handling bridges were equipped with shielding flasks for the transfer of fuel canisters in the dry condition from the reactor vessel to the fuel transfer canal and within the fuel storage pool. In addition, jib cranes were installed at the reactor cavity to provide flexibility. The existing polar crane was partially refurbished and used extensively throughout the defuelling.

Two of the most significant types of machine provided at TMI were:

(1) An oil rig type vertical drilling device, specially designed and developed for boring into the fuel, and

(2) Underwater plasma arc cutting devices.

These provided the primary means of delivering cutting energy to the resolidified mass and reactor internals so as to subdivide the materials into sizes small enough for manual and hydraulic (vacuum, water lift) removal.

The modifications necessary to support TMI defuelling continually evolved. The basic concepts were decided after careful consideration of various alternatives. This approach provided the necessary flexibility. Ultimately, the preferred technique was manual defuelling, supplemented by the use of special mechanized devices, many of which were developed as the need arose.

7.5. FUEL CANISTERS

Fuel canisters serve as a safe envelope for the damaged fuel. With regard to the 'defence-in-depth' concept, while in storage or shipping, canisters replace the function of the fuel clad, which is now damaged, as a barrier between fission products and the environment. Canisters should be designed to:

— accept all types of fuel geometries encountered during defuelling
— provide easy and safe handling, specifically for opening and closing the lid and during interim on-site storage
— comply with transport requirements.

At TMI, one standard external canister design (0.36 m diameter, 3.8 m long) was used with three different internal configurations. These were:

(1) As a debris canister, capable of containing large pieces up to a full size assembly. This design used an open inside.
(2) A 'knock out' canister which was used in the vacuum and water cleanup processes as a density settling volume prior to filtration. The internals were configured for liquid–solid separation.
(3) A filter canister to capture fine and coarse particles in the vacuum and water cleanup processes. Sintered metal filters were used, with a pre-coat medium to prevent rapid clogging of the filters.

Factors that might effect limitations in canister design include criticality safety, the possibility of radiolytic decomposition of water to create hydrogen and oxygen gas, the loading capacity and geometric constraints of the fuel transfer system, and the nature of the shipping casks used for transport off the site.

At TMI, boral shrouds were a feature of criticality control. Catalytic recombination media were built into the canisters to control gas accumulation during intermediate storage and transport. For long term storage, the content of the canisters was dried and controlled venting provided.

One of the lessons learned from TMI was the limitation involved in accommodating a full size fuel assembly and constraining all three canister types to the same external envelope. A larger diameter canister with a small length would have been more useful. However, at TMI the design had to be established well before the core situation was completely known and before it became clear that there was no need to accommodate full length fuel. This illustrates the potential conflict between maintaining flexibility to redesign as conditions become clear and the lead time required for design and safety assessment.

7.6. DEFUELLING OPERATIONS

The first steps involved in gaining access to the fuel in the core are more or less identical to the normal refuelling activities. In LWRs, heavy components such as concrete missile shields above the reactor vault, the vessel head and the vessel upper internals have to be removed with the containment crane. Lifting the vessel head and the upper internals must be done carefully in order to minimize radiological hazards to personnel and prevent undue spread of contamination.

These actions are the first after long term stabilization of the decay heat removal which have the potential to alter the core geometry. Thus, they should be accompanied by appropriate safety and contingency plans. Special consideration must be given to the conditions of the accident that might affect the ability to use normal handling equipment. For example, at TMI the possible effects of the high temperature on the upper internals during the accident was a major element in planning. To the extent possible, inspection of components is necessary before plans are established.

Fuel removal activities should be based on the actual fuel conditions established by direct visual inspection. The tools and equipment used should depend on the extent of the fuel damage.

8. FUEL CONDITIONING, TRANSPORT AND INTERIM STORAGE

Transportation and storage of irradiated fuel as an interim step in nuclear fuel management constitute a well established technology in many countries. It normally includes such operations as:

— discharge of irradiated fuel from the reactor by the refuelling machine;
— placing the fuel in an at-reactor water filled pond for interim storage or in a dry canister when water cooling is no longer essential;
— transportation of the fuel from an at-reactor pond to a centralized away-from-reactor storage site (which can be wet or dry);
— reprocessing of spent fuel or disposal in a repository.

Transportation of irradiated nuclear fuel is performed in special transport casks provided with the required cooling and shielding in accordance with national and international standards and regulations [19]. Existing storage and transportation practices are described in a number of IAEA publications [20–22]. These practices are used for normal fuel without damage or with only small cladding defects.

The degree of fuel damage depends on the severity of the accident. In an accident with minor loss of cladding integrity or small change of fuel dimensions, damaged fuel is placed in special sealed canisters using standard tools and equipment and then stored in storage pools. In the case of severe damage with massive destruction of the fuel elements or fuel melting, when the standard defuelling technique is no longer applicable, special measures must be taken for removal of the damaged fuel from the reactor and for its transportation and storage.

If any damage occurs to the irradiated fuel in the storage pools, the fuel should be managed and conditioned in a way similar to damaged reactor fuel. It also may be desirable to ship any undamaged fresh fuel stored near the damaged reactor off the plant site.

Depending on the severity of the damage to the fuel, different management options are possible:

— conditioning of the damaged fuel for transportation to off-site storage or disposal
— conditioning of the damaged fuel for storage on the site before shipment to reprocessing or off-site storage and disposal.

8.1. CONDITIONING OF DAMAGED FUEL

Conditioning of damaged fuel before its transportation and storage or disposal is an additional interim procedure that is used to prevent criticality and improve radiological safety, to provide for heat removal, to eliminate possible chemical reactions with the environment and to prevent the release of radioactivity.

The conditioning and packaging will depend on the management option chosen. In most cases the development of special canisters will be necessary (see also Section 7.5).

Conditioning of damaged fuel may include such operations as:

— provision of an inert atmosphere within the canister
— provision of additional neutron absorbing material if necessary
— provision of or checking for proper operation of a catalyst recombiner
— sealing canisters for leaktightness.

The damaged fuel should be conditioned in such a way as to meet, as far as possible, the requirements of the relevant safety standards and transport regulations and to be compatible with the existing handling and transport systems and storage facilities. Development of special handling equipment or conditioning systems may be required.

In a real situation, damaged fuel can differ significantly — both chemically and physically — from the original state (because of melting, fragmentation, reaction with other materials, etc.). In cases where proper conditioning of damaged fuel for its safe disposal cannot for some reason be achieved, consideration should be given to the possibility of additional treatment for the recovery of fission products and actinides to help reduce the hazard of the damaged fuel.

Various hydrometallurgical, pyroplasma and laser chemical processes may be considered for this purpose, but additional R&D work in this direction is required. The timing of such recovery operations will depend upon the availability of the technology as well as economic, environmental and other considerations.

In the TMI case, the following operations took place after canisters were filled with fuel debris:

— dewatering by pressurizing with argon gas and/or vacuum drying
— measurement of external dose rate, checking canister leaktightness and verification of the performance of the catalytic recombiner
— mass measurement [23, 24].

Before transport, gas samples from canisters were taken and analysed and the gas pressure was measured to verify that the buildup of combustible gases was below the established limits. Canisters with fuel debris were stored initially in the spent fuel storage pool prior to shipment and were then transported to a water pool at the Idaho National Engineering Laboratory for long term storage.

The conditioning of damaged fuel at Chernobyl differs significantly from TMI experience. What has been done at Chernobyl so far can be considered mostly as a stabilization phase. The initial stages of conditioning included the operations of fuel fragment collection at the plant site and the loading of them into the damaged reactor building. The construction of the reactor enclosure was a temporary measure of damaged fuel and highly radioactive material disposal. Further long term measures for conditioning and disposal are required. The research programme now being implemented is directed towards the solution of this problem.

8.2. TRANSPORT OF DAMAGED FUEL

The transport system will depend on the option chosen. Existing packaging and means of transport should be used as far as practicable. In some cases, adaptations of existing packaging or development of new package designs will be required.

The following aspects must be considered:

- physical and chemical state (conditioned or not)
- criticality safety
- radiological safety
- heat removal
- consequences of radiolysis.

All relevant (national and international) transport regulations [19] should be complied with as far as possible.

The transportation of damaged fuel requires heavy shielded casks. Although standard spent fuel transport casks can be considered, modification for specific cases may be required.

In the TMI case, a decision was made to design, license and fabricate new casks for fuel debris transport rather than modify existing casks. Shipment by rail instead of truck was chosen in order to minimize transport operations. Fewer shipments reduce the probability of transport accidents, minimize radiation exposure to workers and are less costly.

Casks with two safety barriers were built. The NuPac 125B rail cask consists of two separate containment vessels, one inside the other. The TMI fuel canister itself was actually a third barrier for preventing the release of material during transport [23]. Three rail shipping casks were manufactured and used for debris transport.

In the Chernobyl case no transportation of damaged fuel off the site has been carried out so far.

8.3. STORAGE AND DISPOSAL OF DAMAGED FUEL

Storage of damaged nuclear fuel is an interim step before final disposal in order to reduce the level of radioactivity and heat release and provide time for making further decisions and constructing a disposal facility. For interim storage of damaged fuel existing spent fuel or highly radioactive waste storage facilities are likely to be used or new ones can be constructed when necessary.

The storage of properly conditioned damaged fuel does not need special requirements in addition to those applicable to normal spent fuel which are laid down in national and international regulations [20]. This storage will need to meet all technical and safety criteria which guarantee reliable operation, nuclear and radiation safety and the minimum release of radioactivity into the environment. At this stage storage can be wet or dry.

In the TMI case an existing water pool at the Idaho Nuclear Engineering Laboratory (INEL) Hot Shop was selected as a storage site. In preparation, equipment was refurbished and modified. This work included reconditioning the crane system, cleaning the water pit and rebuilding remotely controlled manipulators [24].

At the INEL site, the cask was transferred from rail car to truck transporter. All operations at the storage building involving manipulations of canisters were conducted remotely behind shielded barriers. Canisters withdrawn from the cask were loaded into a storage module, which can hold six canisters. Each canister in the module was vented and filled with demineralized water (to prevent the accumulation of radiolytic gas.)

The TMI experience demonstrated that damaged fuel can be safely handled and stored in a practical and effective manner. In the Chernobyl case the entombment facility serves as an interim storage for damaged reactor fuel. The research programme now being conducted is directed towards the development of a final disposal technology which can be either a modification of the entombment to a permanent storage facility or transfer of the damaged fuel to another location.

9. ABNORMAL WASTE: CONDITIONING TO DISPOSAL

In this section, waste is said to be 'abnormal' when it has physical, chemical or radiochemical characteristics which are unusual with regard to customary or existing processing capabilities and disposal requirements.

The stabilization and cleanup of solids, liquids and gases from fuel damage incidents will result in a variety of solid waste forms that are substantially different from those that are produced by normal plant operation. Examples of these wastes, prior to preparation for disposal, include concentrates from liquid processing, unusually contaminated dry active waste, core structure components (contaminated or activated metal), damaged or very highly contaminated resins, and sediments or sludges that have been gathered and stabilized.

In fuel damage situations, these wastes are 'abnormal', usually because of the following conditions [6]:

(a) The radioactivity is greater than, or substantially different in isotopic composition from, the normal solid waste. The type and level of radioactivity are important aspects that affect the selection of both waste treatment and conditioning and the appropriate protection for the site personnel and the environment.

(b) The 'form' of the waste may be substantially different from that normally processed for packaging and disposal. Examples include sludges, zeolite media and substances with high polymeric or organic material content. This may necessitate the installation of special conditioning systems.

(c) The chemistry may be different because of the use of decontamination agents or because the events resulted in mixing or transformation to unusual constituents.
(d) The volume of solids may be larger than the installed plant can handle in a reasonable time or can be disposed of without impact on the disposal facility.

Examples of abnormal wastes and their classification are given in Table IV. In the light of the abnormal nature of the waste, management considerations unique to fuel damage situations might include:

(1) The total amount of waste and its effects on the cleanup work at the plant and on near-by operating plants make it necessary to ensure that the waste conditioning programme is handled in an optimized manner. Various strategies can be chosen depending on the length of time the conditioning may take.
(2) Special processes or encapsulation methods must be used to render the waste technically adequate for ultimate isolation as 'normal' low level or high level waste (LLW or HLW).
(3) Decisions must be taken — with supporting cost-benefit studies — to either concentrate the waste to the limits of handling and shipping, or dilute it as part of the conditioning and packaging process, in order to render it equivalent to LLW. It is unlikely that the latter option will be available for HLW.
(4) There must be considerable interaction with government agencies that regulate disposal and with the operators of disposal sites. This can often take the form of requests for special waivers or variances to allow the disposal of some of the waste at LLW sites. Special analyses may be required to support such requests to show that the environmental and health effects are acceptable.

9.1. CHERNOBYL AND TMI EXAMPLES

To illustrate the challenge to management of abnormal waste forms the following TMI and Chernobyl examples are given:

(a) *Medium activity demineralizer wastes.* For the more highly loaded vessels from the medium activity processing system, the United States Department of Energy (DOE) developed a high integrity container that allowed commercial land burial. Characterization work was performed on one or more of the vessels.
(b) *High activity demineralizer wastes.* For the 19 highly loaded submerged demineralizer system (SDS) vessels, the DOE conducted a waste immobilization R&D and testing programme, including monitored retrievable burial.
(c) *Transuranic (TRU) contaminated waste.* TRU waste that could not be qualified for commercial burial was considered by the DOE on a case-by-case basis for either generic R&D or cost-reimbursable storage or disposal.

TABLE IV. EXAMPLES OF ABNORMAL WASTE TYPES AND THEIR CLASSIFICATION

Waste type and origin	Physical form	Chemical properties	Radiochemical characteristics and specific activity
Core components which are primary accident wastes	Dry 'solid' wastes; non-compactable	Metallic	Neutron activated components; high level of radioactivity, possibly contaminated with fuel and transuranics
Special tools for handling of damaged fuel during removal	Dry 'solid' wastes; non-compactable	Metallic	Surface contamination; intermediate level wastes, possibly contaminated with fuel and transuranics
Contaminated soils resulting from accident	Dry 'solid' wastes	Chemically inactive material	Surface contamination
Spent ion exchange materials and evaporation concentrates from from water processing	Wet 'solid' wastes	Possibility of combustible gas generation from radiolysis; corrosive, presence of chelating agents	Intermediate and high activity, contaminated with fission products; presence of transuranic nuclides may be substantial
Slurries from water processing and decontamination	Wet 'solid' wastes	Chemical compounds with various properties	Intermediate level wastes, possibly contaminated with transuranics
Used protective clothing, cleaning materials from cleanup and fuel removal activities	Dry 'solid' wastes; combustible, compactible	Various plastics, textiles, rags, paper, PVC, etc.	Large volumes of low level radioactive waste, possibly contaminated with transuranics
Spent filters from ventilation systems resulting from waste processing during accident	Dry 'solid' wastes; combustible, compactible plastics	Charcoal, wooden frames, halogenated plastics	Intermediate level wastes, possibly contaminated with fuel and transuranics

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TABLE IV. (cont.)

Waste type and origin	Physical form	Chemical properties	Radiochemical characteristics and specific activity
Reagents from chemical decontamination processes	Concentrated liquids	May contain variety of organics and inorganic chemicals, such as citric acid, permanganate, nitric acid	High activity waste

(d) *Make-up and purification system resins and filters.* These were treated in the same way as TRU wastes.

(e) *Make-up and purification resins.* These were eluted for caesium removal and subsequently solidified by cementation and shipped to the LLW disposal site.

(f) *Other solid radioactive wastes.* These were wastes associated with decontamination and maintenance (e.g. some ion exchange media, trash, sediment, clothing) and were disposed of at commercial burial sites. They actually constituted about 98% of the non-fuel-related waste shipped off the site.

(g) *Secondary radioactive wastes.* The secondary wastes resulting from cleaning up the Chernobyl site consisted of contaminated soil, concrete, bricks, steel, wooden constructions, wood and other material.

(h) *High and intermediate activity wastes.* For the Chernobyl accident, these wastes were mainly pieces of ruptured construction, graphite debris, parts of equipment, etc. A substantial part of these wastes was contaminated with finely dispersed fuel.

9.2. CLASSIFICATION OF ABNORMAL WASTES

One major aspect of abnormal wastes is classification in terms of ultimate disposal. National regulations may establish the allowable concentrations or total package content for disposal as LLW, and the stability of the waste form necessary for long term residence at the disposal site. There may be very strict limits on the types of contamination. The design of ultimate repositories may not have taken into account the possibility of fuel in a damaged form.

For ultimate disposal, solid wastes require classification in terms of their physical, chemical and radiochemical characteristics. These three primary characteristics are all related to the type of isolation from the environment that will be required [25].

9.3. CONDITIONING OF ABNORMAL WASTES

Conditioning of abnormal wastes is conducted for purposes of conversion to forms acceptable for transportation, storage and disposal. Abnormal solid wastes derived from the solidification or immobilization of liquid wastes will generally not require further processing and can be considered ready for final storage or disposal. However, they may have to be specially packaged. The performance characteristics of solidification and other immobilization techniques, such as the use of high integrity containers, are well known [26–28].

Selection criteria for waste conditioning must be carefully applied.

Some abnormal wastes resulting from an accident and the resultant damaged fuel management will challenge the ability of conventional processing techniques. For this reason a detailed analysis of the final characteristics should be performed prior to the selection of the conditioning or immobilization alternative. Of particular concern for high specific activity abnormal wastes are: thermal stability, radiation resistance and combustible gas generation.

Some types (categories) of abnormal solid wastes such as evaporator concentrates, sludges, spent ion exchange resins and trash will probably require some form of pre-treatment before conditioning [29].

9.4. STORAGE OF ABNORMAL WASTES

On-site storage of abnormal wastes is considered in Section 5.

Off-site storage may be required for abnormal wastes for one or more of the following reasons:

- insufficient on-site storage capacity
- unsuitability of on-site storage facilities
- national regulations and policy.

Different types of storage facilities may be used for different wastes. More detailed information on on-site and off-site storage systems may be found in Refs [26–30].

In the TMI case, two off-site storage programmes were required. The first was for two year storage of about fifty demineralizer liners (containers). These were ultimately buried in an LLW burial ground after special high integrity containers were designed and built for each of the liners. The second is a long term programme in which a government facility pool is used to store the several hundred canisters of core material until the national repository is ready to receive them.

9.5. WASTE TRANSPORT

For on-site transport of abnormal wastes within a controlled area only, the packaging and transport requirements may not be as stringent as for transport outside the controlled area if an adequate degree of supervision is provided.

The off-site transport of radioactive wastes is governed by the regulations affecting the transport of radioactive materials. At present, most waste transport is within the confines of individual countries and in this case only national regulations are applicable. National transport regulations are usually based on recommendations published by the IAEA [19].

The methods of transport available (road, rail, inland waterway) and the type of casks that can be used or designed represent interconnected issues that must be taken into consideration.

At TMI the following particular actions were required:

— design and fabrication of special casks for truck shipping of highly loaded demineralized vessels;
— design and fabrication of special casks for rail shipment of fuel canisters;
— construction of special tipping rigs at the site to load the casks;
— development of methods to ensure that hydrogen generation caused by radiolysis of entrained water during shipping would not create a hazard; this required a special drying procedure prior to loading and the incorporation of a recombining catalyst within the vessels;
— development of techniques for decontaminating and surveying of the casks prior to shipping because of the potential danger of a high beta content in the water where they were stored.

9.6. DISPOSAL OF ABNORMAL WASTES

The disposal of radioactive wastes is governed by national regulations. The national programme gives guidance on criteria which must be applied to the waste in order for it to be acceptable for disposal.

A safety analysis of particular disposal systems has to be carried out to assess occupational doses, individual doses to members of the public and collective doses to present and future generations.

Abnormal waste must be processed in such a way that it can be disposed of in accordance with any existing national programme. However, in most cases national disposal criteria are based on 'normal' radioactive wastes. Therefore, special dispensations may be required from regulatory authorities for abnormal waste.

In cases where national disposal programmes have not been established, general criteria for waste disposal can be found in IAEA publications [30, 31].

10. PREPARATION FOR THE DECOMMISSIONING OF FUEL DAMAGED PLANTS

10.1. IMMEDIATE OR DEFERRED DISMANTLING

The decommissioning of a plant that has had severe fuel damage can involve unique issues that are not considered in the course of normal decommissioning planning for nuclear plants. This section addresses these particular aspects. The general topic of nuclear plant decommissioning has been well covered in the literature [32–36] and is not considered further here.

Normally at shutdown and the start of a decommissioning programme, a nuclear power plant is defuelled using the normal operational methods. This is followed either by dismantling of the reactor, permitting the use of the site for other purposes, or, more likely, a period of long term safe storage subject to ongoing maintenance and surveillance followed at a later date by decommissioning.

If it is decided that a plant with severe fuel damage is not to be returned to normal operations, two principal options exist:

— immediate dismantling
— long term safe storage of the facility with deferred dismantling.

Deferring dismantling enables advantage to be taken of the natural decay in radiation levels; thus the ALARA principle can be used with beneficial reduction in personnel exposure. This is due primarily to the presence of ^{137}Cs with a half-life of 30 years. Deferring final decontamination and dismantling for periods of this magnitude would thus reduce dose rates by approximately one half. The consequences of beta radiation exposure and ingestion will also be reduced because ^{90}Sr has a similar half-life.

Advances in technology over the deferred period may result in methods that would also significantly reduce the exposure to personnel from both the cleanup and dismantling operations. In particular, the experience gained in the design and use of robots, not just in the nuclear industry but in other industries, will permit many operations to be carried out remotely.

Once it can be assured that fuel criticality is no longer a possibility, consideration can be given to significantly reducing the staffing levels of the plant from those specified by the licensing authority for an operating licence. Better use of resources can then be made on a task by task basis.

With a severely damaged plant, complete defuelling may not be possible or practicable without incurring either significant radiation exposure penalties to personnel or unacceptable environmental risks. Long term safe storage may thus be the only option that can be pursued. This requires a proper understanding of the condition of the fuel remaining within the plant. Indeed, this may be a prerequisite for the national regulatory authorities to agree to long term safe storage rather than immediate defuelling and/or dismantling.

In establishing a safe storage condition, a related consideration is that once a site has been used for electrical power generation, it is often desirable to continue its use for the same purpose. This is because existing sites represent locations that have requisite attributes such as the availability of cooling water, road and rail connections, transmission lines, local support industries and so on. In the case of a damaged fuel plant that remains contaminated, one choice could possibly be to reuse certain parts of the facility. This would involve removing all non-useful portions of the damaged unit except those which are contaminated, such as inside the containment or inside an environmentally stable and isolated enclosure.

10.2. LONG TERM SAFE STORAGE

The long term safe storage state is basically a passive one. The safety of the shut down plant, personnel and the environment does not rely on maintaining systems operational; for example, coolant circulation or continuous forced ventilation are not required. However, the safe storage state would be subject to regular monitoring, surveillance and maintenance. Even though the plant is in a passive state, there will be a requirement for some level of operational activity such as:

- infrequent solid and liquid waste processing, such as rainwater collection in building sumps
- maintaining equipment, for example ventilation and lighting systems, to protect personnel
- housekeeping and building maintenance
- response to natural events, for example flooding
- emergency response for fire or injury to personnel.

It will also be necessary to carry out inspection, surveillance and maintenance activities on a continuing basis including:

- periodic/regular containment entries to monitor radiological conditions
- periodic/regular verification of containment as a contamination barrier.

In addition, managers responsible for the ultimate disposition of the plant may choose to carry out some continuous decontamination, dismantling and assessment activities, working towards the final goal.

For non-damaged plants, a long term safe storage state can be met by completely defuelling the facility and emptying all liquid and gas systems. However, for a damaged facility, it may not be possible to completely defuel or to reduce contamination levels within the containment building to sufficiently low levels. In such cases, it is suggested that there are three aspects which are unique to fuel damaged plants and for which criteria must be established. These are:

- residual contamination (see Section 6)
- residual fuel (see Section 7)
- systems and facilities.

In order to establish and implement criteria it will be necessary to define specific requirements for the long term safe storage conditions of buildings, systems and facilities. In determining these requirements it will be necessary to consider the target decontamination levels, the fuel remaining, and the methods employed to give long term assurance of isolation and control.

10.3. REQUIRED SYSTEMS AND FACILITIES

As already stated, the long term safety of the facility is based upon a passive installation that will not constitute a potential threat to personnel or the environment. However, in order to maintain this isolation and to guard against potential threats, specific systems and facilities need to remain operational. These can include the following:

(a) *Plant security.* The fenced protected area is maintained, with unauthorized entry to the plant restricted by locked access doors, closed circuit TV surveillance together with regular security inspections. A security guard system will be required if access to radioactive areas is physically possible.

(b) *Fire protection.* A system for fire detection and fire suppression, possibly using the plant's main and local extinguishers, will be required. Emergency response procedures need to be defined. The degree of protection should be consistent with the appropriate insurance requirements.

(c) *Radiation monitoring.* Regular surveys of radiation levels, both internal and external to the plant, are required. Where existing monitors are used, continuation of power supplies and maintenance will be required.

(d) *Water ingress to auxiliary and fuel handling buildings.* It will be necessary to maintain systems in operation for draining process and building sumps and for the disposal of any water collected.

(e) *Ventilation systems.* Radiological and industrial safety questions relating to personnel access must be considered and a decision made whether it is necessary to maintain ventilation in operation for purging or exhausting areas as an alternative to using protective clothing with integral breathing air supplies. Ventilation systems can also be used to collect any airborne contamination, thus further reducing the risk to personnel and the environment. However, it must be remembered that one of the criteria to be satisfied for long term safe storage is that the facility must be passive.

(f) *Electricity supplies.* Electrical power will be required for monitoring and support systems as well as lighting. If decontamination or dismantling activities are planned, these will also need appropriate supplies.

(g) *Other services.* These may include communication systems for the security personnel and others within the facility, and domestic water for housekeeping. If water supplies are made available, the problem of preventing criticality must be reassessed.

In the establishment of a long term storage configuration, consideration should be given to possible future decommissioning requirements and whether there is economic and technical justification for maintaining systems for future use that are not otherwise needed for ensuring the ongoing integrity of the long term safe storage of the plant. For example, the following facilities should be considered for future use:

— ventilation and water supplies
— water cleanup system
— waste storage system
— waste handling and packaging facilities
— hot machine shop
— plant cranes.

10.4 ASSURANCE OF THE SAFETY OF LONG TERM SAFE STORAGE

Safety must be assured for a period of long term safe storage. A technical safety analysis and environmental assessment need to be made. While the fundamental approach for such evaluations may be similar to those for normal plants, the analytical methods may have to be modified to accommodate the unique conditions.

Depending on the national regulatory situation and plant ownership, demonstration of long term financial assurance may also be necessary. There will probably be some concern amongst the local population about the financing of commitments for thirty or more years into the future. This is a quite different situation from the decommissioning of a normal plant, because a fuel damaged plant that will no longer be operated does not provide any operating income to provide for future requirements. There is little existing experience or information on this subject, but it must be addressed by the plant owners.

11. CONCLUSIONS

The actions needed to recover from future fuel damage events that are beyond the normal plant design basis can to some extent be based on the experience of the past. Although any future scenario will be different, the management approach will need to address similar technical and safety issues for recovery and cleanup strategy, and in some cases for specific operations.

The Chernobyl, TMI and several other fuel damage accidents have demonstrated that post-accident operations can be effectively managed. Knowledge derived from this experience should become part of the preparedness of responsible authorities and nuclear industry managers. The conclusions below are based on this principle.

11.1. GENERAL CONCLUSIONS

11.1.1. Management training

Managers at nuclear utilities and national agencies should be trained in the thinking process required and instructed on what to expect as a result of fuel damage events. To accomplish such education, a multi-step process is required. Relevant texts should be made available and meetings should be held to promote understanding of the unique challenge posed by a fuel damage event.

11.1.2. Technology catalogue

The cleanup of fuel damaged plants has resulted in the development of new hardware and new methods. Many of these are well documented, but others are not. It would be useful in this connection to develop a 'catalogue'. Such a catalogue would include details of:

(a) *Data management and analysis*. The experience from past events will be most valuable in the measurement of various radiation energies but also for the other types of visual observations and measurements made at Chernobyl and TMI. Experience with computer software, not necessarily complex, used to evaluate and present the results of information derived from data would also be useful.

(b) *Decontamination*. To the extent that decontamination techniques and tools are different, or results challenge conventional wisdom, they should be summarized.

(c) *Fuel disassembly and removal.* Many special tools have been designed, fabricated and used for the removal and encapsulation of damaged fuel.

(d) *Remotely operated vehicles.* As with data collection methods, experience gained with remotely controlled vehicles and robots for damage fuel recovery operations should be catalogued.

(e) *Radiospectroscopic, radiochemical and chemical analyses.* Mobile laboratories and on-site/near-site facilities for radiochemistry and chemistry analyses are important and are urgently needed in the event of a fuel damage event.

(f) *Health physics and personnel protection methods.* Special personnel protection methods will be required, especially with respect to alpha and beta contamination. Heat stress control under such conditions is important.

(g) *Plant modifications to cope with damaged fuel.* With respect to hardware modifications, it is doubtful that any future event will closely pattern any of the past. It is not prudent to conduct specific physical modifications related to specific accident sequences that are not part of the design basis negotiated between owner, designer and regulator.

(h) *Prescriptive regulations for fuel damage events.* Prescriptive regulations for coping with activities for post-accident management should be avoided. Any future event will follow its own course, and the best preparation is understanding past experience. Specific rules and procedures are unlikely to be applicable to the specific sequence for recovery for a future fuel damage event. Both plant owners and regulator must necessarily adapt to the unique circumstances.

11.2. SPECIFIC CONCLUSIONS

Certain conclusions from specific sections of the present publication are now summarized.

11.2.1. Strategic planning

Recovery from any fuel damage event can in general be divided into the following phases:

I. Stabilization, assessment and safe confinement of fuel and preparation of access to it

II. Fuel removal

III. Disposal of fuel and related waste.

The types of activities and organizational functions have been identified in this report. Clearly, the degree to which any will depart from the normal plant activities and organizations will depend on the severity of the event.

11.2.2. Stabilizing the fuel

The three major safety functions for reactor stabilization that apply to fuel damage events are in principle the same as those that apply to any accident or shutdown condition. They are:

(1) Ensure subcriticality
(2) Remove decay heat
(3) Prevent further spread of radioactive material.

After the initial crisis of an event is past, these three principal goals provide the focus for initiating planning and actions to proceed to a condition from where removal of the damaged fuel can be started. In practice, depending on the severity of the event a variety of new methods may be required to carry out these functions.

11.2.3. Data management and analysis

Reliable data represent a most important requirement for planning cleanup operations. Data must be systematically tracked, analysed and organized to avoid false starts and overly optimistic or conservative assumptions. These activities must be given high priority.

A 'model' functional specification for a mobile unit that would provide the minimum amount of required analytical capability would also be useful.

11.2.4. Initial waste management

Dealing with the quantities and levels of radioactivity of waste from a fuel damage event will challenge and may exceed the capability of the plant's normal systems. It is important for managers to understand this and be trained in how to cope with the immediate problem of storing, diluting or releasing excess water and storing or purging air contaminated with radioactivity and possibly containing hydrogen.

It is generally not considered practical to install special processing systems to cope with such problems because the quantities, locations, chemical characteristics and radiochemical characteristics of the water and gas cannot be specified with sufficient precision to define a system design. However, this is not to preclude specific reviews by Member States of their reactor systems that may be deemed essential in the context of their national programmes and requirements.

11.2.5. Initial decontamination

The ordering of priorities and reliance on existing technology are amongst the most important management lessons to be learned from past events. The first 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.

Later, the decontamination priorities will shift to operations connected with fuel removal. Ultimately, decontamination will create conditions which are sufficiently clean for a return to normal operation or decommissioning.

The determination of appropriate decontamination methods will be case specific. Manually intensive techniques will likely be required for the bulk of the decontamination efforts, even if robotic and remotely operated equipment is available.

11.2.6. Fuel removal

Procedures, tools and equipment for fuel removal must be selected and designed along with the growing knowledge about the status of the damaged fuel as the fuel removal progresses. Alternative methods must be continually considered so as to retain flexibility if unexpected difficulties are encountered.

Hand operated, long handled tools are preferable to remotely controlled ones, as long as the working environment is acceptable. Since fuel removal can be a long term and tedious job, the conditions have to be such that no heavy protective suits are required and normal working shift periods are possible.

Plant managers should be aware that coping with the task of removing damaged fuel may require the modification of existing plant installations, the addition of new equipment and changes in existing rules established for normal plant operations.

11.2.7. Fuel conditioning, transport and interim storage

The main purpose of conditioning damaged fuel is to transform it into a condition which complies with the established national systems for transport, storage and disposal. The process can be rather complicated and no detailed recommendations can be made for future cases because the characteristics of the damage cannot be predicted. In any case, existing handling and transport systems and storage facilities should be used far as practicable.

As the final long term disposal requirements of highly radioactive materials are still in the development stage, and no repositories exist, all the requirements discussed in Section 8 are of a provisional character. This situation should improve as current programmes are completed.

Additional R&D work may be needed on the long term behaviour of conditioned damaged fuel with respect to chemical stability, the leaching properties of fission products and actinides and chemical treatment for their separation before final disposal.

11.2.8. Abnormal waste conditioning for disposal

For the most part, abnormal wastes can be processed by use of state of the art technologies and facilities that are used for normal waste processing. The major problem may be the insufficient capacity of these facilities, in view of the large quantities of wastes produced. On the site or off the site interim storage will therefore be important. Attention to this problem should be given in the training of managers for understanding the actions required to recover from a fuel damage event.

The conditioning and packaging of high level radioactive wastes containing significant amounts of transuranics and fuel particles represent problems that may require special technologies, tools and facilities.

Another serious problem is the disposal of abnormal wastes in compliance with national regulations, which, in all likelihood, may not deal with such wastes.

11.2.9. Preparation for the decommissioning of fuel damaged plants

Once it has been decided that the plant is not to be returned to normal operation, then the options are immediate dismantling or long term safe storage with deferred dismantling.

If the second option is chosen, the long term safe storage state should be passive, though there may be some requirements for operational activity in order to ensure personnel safety and the continued isolation of radioactive materials from the environment.

Annex A

NUCLEAR POWER PLANT A-1 (CZECHOSLOVAKIA) EXPERIENCE

A.1. INTRODUCTION

This annex is provided because the information, which is directly useful for this report, has not been previously published.

The nuclear power plant A-1 with a gas cooled (CO_2) and heavy water moderated reactor (GCHWR) was operated from 25 December 1972 up to 22 February 1977. Its average power output was approximately 100 MW(e). There were 148 fuel assemblies and 40 control rods in the core. The fuel assemblies have diameters of 102 or 114 mm and are made up of fuel elements of natural uranium with Mg–Be cladding. The length of their active part (in the core) is 4 m. The reactor vessel has diameter 5.1 m and height 20.1 m. The primary circuit consists of six loops, each with a turbocompressor and a steam generator. The moderator circuit consists of three loops, each with a circulation pump and a cooler. At the end of February 1977, an operational incident occurred. As a result of this incident, fuel cladding fracture and fuel uncladding occurred in the upper part of fuel elements over the length of 30 to 100 cm. The primary circuit (coolant) was contaminated by fission products. Some auxiliary circuits and facilities were also contaminated.

A.2. PHASE I: STABILIZATION AND CHARACTERIZATION

After reactor shutdown, the first task was cooling of the fuel elements in the reactor. This was carried out by means of the coolant circulation in the primary circuit. During this period, particular attention was given to the control of the radiation situation, including monitoring of contamination and environmental monitoring. Some fuel elements were unloaded from the reactor for visual inspection in a hot cell to obtain more detailed information about the extent of the cladding damage.

In the second step, all fuel assemblies were unloaded from the reactor into the facility for interim fuel storage, which is located in the main hall. Fuel unloading was done with a special fuelling machine, used for fuel reloading during normal operation of the reactor. A spent fuel storage facility was built at A-1 for interim storage. It has been in service since the beginning of operation. Spent fuel assemblies are placed into stainless steel casings (penals) filled with cooling medium.

Dowtherm (a mixture of diphenyl and diphenyloxide) or an aqueous solution of potassium chromate are used as a cooling medium.

The event (stabilization phase) was handled by the normal plant organization and cleanup systems. However, this organization was supported by additional specialists from corresponding organizations (research laboratories, laboratories for radiation protection, design organization, producer organizations, etc.). A member of the competent authorities also took part. All activities performed for stabilizing the fuel were controlled by special staff. Special working groups were established to solve individual problems (fuel handling, assessment of the degree of fuel damage, assessment of the spread of contamination and the radiological conditions, etc.). The qualification structure of normal operating personnel was sufficient in this part of the stabilization phase. The following data were gathered:

- temperature of fuel elements in the reactor
- pressure of coolant in the primary circuit
- flow rate of coolant in the primary circuit
- temperature of cooling media in the fuel storage pool
- results of fuel inspections
- concentration of fission products in the coolant
- concentration of fission products in the cooling media used for fuel storage
- burnup of unloaded fuel elements
- radionuclide concentration in auxiliary system media
- area dose rates
- airborne activity
- results of contamination monitoring
- results of radioactive effluent control
- results of environmental monitoring.

Analyses of these data were used as the basis for estimating the results of activities and for deciding on the further course of work. During the stabilization phase, normal operational equipment was generally used. In addition there were:

- a special device for sampling the coolant from the primary circuit
- a special sampling device for airborne radioiodine control
- special laboratory techniques for plutonium measurements in various samples
- special tools for inspection of the damaged fuel in the hot cell
- equipment for airborne sampling from fuel storage casings and the hydrogen concentration control.

Persons who carried out 'critical activities' were provided with special protective clothing and respiratory protective equipment. In some cases, clothing which could be pressurized from a supply of breathing quality air were used. Special individual dosimeters were also employed. The assessment of the radiation situation used high range radiation monitoring instruments and self-powered air samplers.

A.3. PHASE II: CLEANUP OPERATIONS

After fuel unloading, the coolant cleanup was carried out directly in the primary circuit by means of suitable filters. Distillation was also used. The heavy water (moderator) was discharged from the auxiliary moderator circuit into storage tanks. Decontamination was performed only as needed. Total decontamination will be carried out as a part of decommissioning activities.

Technological decontamination procedures were developed for these purposes. At present, three basic methods are used for decontamination: chemical decontamination, chemical decontamination in connection with ultrasound, and electrochemical decontamination. Decontamination procedures based on the utilization of efficient foams have been developed for decontamination of large floors and wall surfaces in rooms. Gaseous wastes were treated during normal operation, i.e. contaminated air was collected by ventilation systems and cleaned up by means of special filter systems. Short lived noble gases were dealt with by means of four storage tanks for a maximum of 4250 kg of gas under normal operating conditions. The dominant radionuclides in the gaseous wastes were: radioisotopes of the noble gases, ^{131}I, ^{141}Ce, ^{144}Ce, ^{103}Ru, ^{106}Ru, ^{140}Ba, ^{140}La, ^{134}Cs, ^{137}Cs, ^{95}Zr and ^{95}Nb.

Liquid radioactive waste, generated during the stabilization period, was processed by using the waste management system for normal operation of the nuclear power plant. Liquid wastes were collected in two tanks, each with a capacity of 100 m^3. From there they were pumped into a gravitational tank and flowed down into a mixer-settler. After the addition of the necessary chemicals to bring about coagulation, the sludge was separated from the solution in a coagulation tank. The cleaned-up water passed through a filter bed into an evaporator.

Concentrated liquid wastes were stored in a number of storage tanks. The spent beds of the sand filters and the ion exchange filters were also discharged into the storage tank. About 300 m^3 of radioactive liquid concentrate was produced by the treatment of primary liquid wastes during the stabilization period. The average volume activity of the concentrates has been 1–10 GBq/m^3 with a salt content up to 10 kg/m^3 and pH levels of 8–9. The dominant radionuclides in the liquid wastes were ^{141}Ce, ^{103}Ru, ^{106}Ru, ^{140}La, ^{134}Cs, ^{137}Cs, ^{95}Zr, ^{95}Nb, ^{131}I and ^{60}Co. Transuranium elements were also found.

Radioactive solid wastes were taken to the interim solid waste repository on the power plant site. Soft wastes were pressed before storage.

A.4. PHASE III: CONDITIONING, TRANSPORT AND STORAGE OF DAMAGED FUEL

A.4.1. Damaged fuel management

As mentioned above, all fuel assemblies were stored in the interim storage facility.

A classification of the stored fuel was made in preparation for transport to a reprocessing plant. The classification was based on the operational history of the fuel elements, a review of fuel elements in the hot cell and control measurements in the fuel assembly casings in spent fuel storage.

On the basis of the above classification, the technology for treatment prior to transport was determined. The basic technological operation was to transfer the fuel assemblies from the storage casing into the special transport casing and then produce a sealing. The sealing has to be so good that it excludes leakage of fission products from the transported fuel element into the surroundings. Because of the requirement for hermetic sealing, it was necessary to remove moisture from the fuel elements, so that hydrogen formation during further handling and transport was not possible. For this reason, it was decided, two months prior to hermetic sealing, to transfer fuel assemblies from the Dowtherm and chromate solutions into dry casings. After two months of dry storage the formation of hydrogen decreases sufficiently and the fuel assemblies can be transferred into a sealed transport casing. The sealing of the casings with fuel elements is carried out on a so called 'sealing stand' where the lid is welded on the casing. A helium leak test is then carried out.

In total, 18 sealed casings with fuel assemblies can be placed into a cask. When the shipping cask is filled, it is placed into a special wagon (wagon-container). The shipping container is then sealed and the sealing is checked by means of helium. It is then filled up to a pressure of 0.3 Pa with a gaseous mixture containing 4–4.8% O_2, a maximum of 2% H_2 and the rest N_2.

For some cases an alternative procedure was designed. The procedure is based on the following steps:

(a) Withdrawal of the casing together with the fuel assembly from the storage pond
(b) Transfer of the casing with the fuel assembly to a drainage and cutting stand
(c) Discharge of the chromate solution from the casing and shortening of the casing to the transport length
(d) Transfer of the shortened storage casing (containing the fuel assembly) to the sealed (transport) casing
(e) Sealing of the transport casing and checking of the sealing
(f) Transfer of the transport casing into a wagon-container.

The fuel in the sealed casings is transported in special railway wagons and wagon-containers, which fulfil strict requirements for radioactive material transport. At present, the transport of spent fuel from the A-1 plant using the above technology is in progress. The experience obtained is used for modifications of the technological procedure or the equipment used.

A.4..2. Radioactive waste conditioning, transport and storage

A.4.2.1. Radioactive wastes from spent fuel storage

The cooling media (solutions of chromate and Dowtherm) represent liquid radioactive waste with specific fission products (^{134}Cs, ^{137}Cs ^{90}Sr) and certain amounts of alpha nuclides (^{238}Pu, ^{239}Pu, ^{241}Am and others). Their specific activity reaches values of 4–6 M Bq/m^3.

There is sludge in the chromate solution which mainly contains corrosion products of the fuel element cladding, chromium III, uranium in the form of oxides, metallic uranium and corresponding amounts of plutonium (depending on the stage of fuel element burnup). The Dowtherm also contains dispersed metallic uranium together with a smaller amount of corrosion products in the form of a fine dispersion.

Liquid waste from spent fuel storage is of a specific character, requiring special measures and the application of other technological procedures for its treatment and conditioning that differ from those for the processing of common liquid radioactive wastes from the plant operation. The wastes are characterized by:

— a relatively high specific activity
— the presence of plutonium and other transuranium elements
— the non-homogeneity (considerable amounts of solid particles in the form of sludge)
— the presence of an organic liquid (Dowtherm).

Chromate solution ('chrompik') will be processed (in view of its radioactivity level and chemical composition) by vitrification. At present, a technological vitrification plant project is ready, the vitrification furnace has been manufactured, together with a unit for high frequency heating, and further parts of the plant (evaporator, condenser and others) are in in the course of manufacture. The vitrification plant should process 40 m^3 of active 'chromate'. Borosilicate glass blocks will be the final product; following the cooling, they will be put into the shipping casing (six blocks per casing). Each shipping casing will be sealed and placed into a wagon-container for transport to the USSR for permanent storage.

For processing Dowtherm, fluid combustion and bituminization processes are under development or verificaton.

Combustion of Dowtherm should be carried out in a reactor with an Al_2O_3 fluid bed. Dowtherm together with oxygen and nitric acid will be sprayed on it. The combustion temperature will be 500°C. The material of the fluid bed, which will contain radionuclides from the Dowtherm, will be the resultant product. The properties of the resulting Dowtherm combustion product do not allow its direct storage at the site. One of the possibilities of conditioning prior to long term storage is cementation.

The second possible way for processing Dowtherm is utilization of standard bituminization, modified according to the properties and composition (chemical and isotopic) of the Dowtherm. Experimental results have proved that up to 5% of Dowtherm can be fixed into a bitumen matrix. The mechanical and chemical properties of the resulting bitumen product (including leachability) meet the requirements for storage in a regional storage site.

The relatively high values of cooling media activity from spent fuel storage require:

— higher radiological protection of personnel by means of suitable protective measures as well as improved work organization
— reliable equipment
— mechanization or automation of the technological processes applied.

A.4.2.2. Radioactive wastes from decontamination

The substantially higher concentrations of active components in decontamination solutions and the high content of iron in solutions after decontamination are extraordinarily demanding on the treatment of liquid wastes from decontamination. Used decontamination solutions should be collected separately from other liquid wastes. Two procedures have been tested for fixation of used decontamination solutions: cementation and bituminization. It has been shown that by using a mixture of Portland cement, $Ca(OH)_2$ and clinoptylolite, even strong decontamination solutions, containing phosphoric acid and nitric acid, can be effectively solidified. Bituminization appears less suitable, because there is a high content of iron in these wastes and the properties of the resultant product are significantly worse. In addition, the resultant deactivation solutions are in most cases of a strongly acidic nature, while bituminization requires the pH value to be kept above 6.

A.4.2.3. Solid radioactive wastes

The decommissioning of a nuclear power plant as a result of an operating accident is associated with the production of large amounts of solid wastes, varied in character (metallic wastes from equipment, concrete, some kinds of used decontamination agents and protective clothing).

The problem is not only a large amount of solid wastes and their heterogeneity, but in the case of the nuclear power plant A-1 the fact that certain parts of the solid wastes contain alpha nuclides. In addition to the utilization of standard methods for the treatment of solid wastes (combustion, pressing), considerable interest is being shown in melting. It is a procedure for metallic radioactive waste treatment leading to volume reduction and a waste form which is more suitable for permanent storage.

At present, the effect of basic parameters in the melting process in an induction furnace for A-1 metallic wastes is being experimentally verified to test the behaviour of the radionuclides present, mainly ^{60}Co and ^{137}Cs. The results show the suitability of this process for metallic waste treatment. In view of the large amount of metallic wastes from the A-1 decommissioning (estimated at about 10 600 t), other procedures for volume reduction are being studied. One of these is decontamination of low level wastes to a value of surface contamination that permits release into the environment and unrestricted reuse. On the basis of the most probable scenario for the release into the environment and subsequent reuse, limit values of 0.37 Bq/cm^2 for surface contamination and 1 Bq/g for volume activity have been proposed.

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CONTRIBUTORS TO DRAFTING AND REVIEW

Baekelandt, L.	National Agency for Radioactive Waste and Fissile Materials, Belgium
Bakunyaev, A.D.	State Committee on the Utilization of Atomic Energy, Union of Soviet Socialist Republics
Bitskij, A.A.	All Union Design and Research Institute of Complex Power Technology, Union of Soviet Socialist Republics
Bokelmann, R.	Siemens AG, Germany
Borovoj, A.A.,	I.V. Kurchatov Institute of Atomic Energy, Union of Soviet Socialist Republics
Buzulukov, Yu.P.	I.V. Kurchatov Institute of Atomic Energy, Union of Soviet Socialist Republics
Dlouhý, Z.	Nuclear Research Institute, Czechoslovakia
Dobrynin, J.L.	I.V. Kurchatov Institute of Atomic Energy, Union of Soviet Socialist Republics
Dojiri, S.	Science and Technology Agency, Japan
Elkert, J.	ABB-ATOM AB, Sweden
Filippov, E.M.	Design and Research Institute of Complex Power Technology, Union of Soviet Socialist Republics
Gago, J.A.	ENRESA, Spain
Grahn, P.H.	OKG Aktiebolaget, Sweden
Hladký, E.	Vuje Nuclear Power Plant Research Institute, Czechoslovakia
Hultqvist, G.	Swedish State Power Board, Sweden
Isaev, A.N.	I.V. Kurchatov Institute of Atomic Energy, Union of Soviet Socialist Republics
Ivanov, A.I.	I.V. Kurchatov Institute of Atomic Energy, Union of Soviet Socialist Republics

Jones, J.M.	United Kingdom Atomic Energy Authority, United Kingdom
Kheruvimov, A.N.	I.V. Kurchatov Institute of Atomic Energy, Union of Soviet Socialist Republics
Klug, N.P.	Department of Energy, United States of America
Knaab, H.	Siemens KWU Group, Germany
Krivokhatskij, A.S.	V.G. Khlopin Radium Institute, Union of Soviet Socialist Republics
Martynov, B.V.	Scientific Research Institute of Inorganic Materials, Union of Soviet Socialist Republics
Martynov, Yu.P.	International Atomic Energy Agency
Motlich, T.V.	I.V. Kurchatov Institute of Atomic Energy, Union of Soviet Socialist Republics
Muravev, V.F.	Scientific Research Institute of Mounting Technology, Union of Soviet Socialist Republics
Negin, C.A.	Grove Engineering Inc., United States of America
Nenarokomov, E.A.	Scientific Research Institute of Inorganic Materials, Union of Soviet Socialist Republics
Neumann, W.	Kerntechnischer Hilfsdienst GmbH, Germany
Ogorodnik, S.S.	I.V. Kurchatov Institute of Atomic Energy, Union of Soviet Socialist Republics
Pleskachevskij, L.A.	I.V. Kurchatov Institute of Atomic Energy, Union of Soviet Socialist Republics
Ponticq, M.	Electricité de France, France
Popov, V.D.	I.V. Kurchatov Institute of Atomic Energy, Union of Soviet Socialist Republics
Rao, P.K.M.	Ontario Hydro, Canada
Reed, J.	HM Nuclear Installations Inspectorate, United Kingdom

Renard, E.V.	Scientific Research Institute of Inorganic Materials, Union of Soviet Socialist Republics
Rybalchenko, I.L.	All Union Design and Research Institute of Complex Power Technology, Union of Soviet Socialist Republics
Sakashita, H.	Science and Technology Agency, Japan
Schmitt, R.	Department of Energy, United States of America
Soda, K.	Japan Atomic Energy Research Institute, Japan
Sorokin, V.T.	All Union Design and Research Institute of Complex Power Technology, Union of Soviet Socialist Republics
Strakhov, M.V.	All Union Design and Research Institute of Complex Power Technology, Union of Soviet Socialist Republics

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