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FOREWORD

Remote systems technology has been extensively applied to a variety of work in spent fuel management facilities with such benefits as dose reduction to workers, enhancement of operational performance or reliability, saving of labor costs, etc. Remote systems are an integral part of facilities for work to be carried out inside shielding and/or containment enclosures engineered to protect workers and the environment from hostile radioactive sources like spent nuclear fuel or radioactive wastes.

In recognition of the essential role of remote technology in spent fuel management, the IAEA has extended since a decade an effort to provide the Member States with information on the state-of-the-art developments and practices of remote technology in the area of spent fuel management, the importance of which, has been constantly growing in the IAEA programme agenda. Several technical documents have been published with information on various technical experiences in remote technology applications to spent fuel management. The first of this series, Remote Technology Related to the Handling, Storage and Disposal of Spent Fuel, IAEA-TECDOC-842, was based on the proceedings of a technical committee meeting held in Albuquerque, New Mexico, 5–8 December 1994. Another publication, Remote Technology in Spent Fuel Management, IAEA-TECDOC-1061 was issued in 1999 based on the proceedings of an advisory group meeting held in Vienna, 22–25 September 1997. As a result of the continuing effort, this present TECDOC intends to provide an overview of remote technology applications to spent fuel management by compiling the information collected from a series of consultancies held between 1998–2000 and other related information collected thereafter through other sources.

Looking at the global status and trends, the applications of remote systems technology in the nuclear sector has been well stabilized in the past years with the limited demand and supply market. The bulk of spent fuel inventories around the world are still stored at reactor pools with little progress in the implementation of end-point options. Nonetheless, there has been increasing need and new installations with dry storage systems for additional storage, which is currently the most expansive area for remote technology applications. Attention is given nonetheless to the roles remote technology is to play in the longer term prospective of spent fuel management, in particular for the applications to innovative nuclear systems, which have been attracting a growing interest in the context of sustainable development of nuclear energy. The innovative fuel cycles to be developed, as anticipated by the recent international initiatives, may require extensive involvement of remote systems technology for industrial implementations in the longer term.

Although this publication addresses remote technology applications mainly in spent fuel management from power reactors, there would be little difference in terms of technical features with that of spent fuel from research reactors. Both current industrial practices and some future perspectives are given in this publication.

The contributions as well as participation in the meeting of the experts are greatly appreciated. The IAEA officers responsible for the meetings and this publication were P. Dyck and J.S. Lee of the Division of Nuclear Fuel Cycle and Waste Management.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

What is considered ‘remote technology’ in nuclear applications was initiated in the 1950s with the development of through-the-wall manipulators for small hot cells for handling of radioactive sources, such as examination of irradiated materials and separation of radioisotopes, and has evolved through the years into much more sophisticated systems for a variety of nuclear applications. The remote technology in this sense can be roughly defined as a functional system for safe handling of highly radioactive materials inside shielding and/or containment.

The need for hot cell operation and maintenance in the early development of nuclear power has played a significant role in the elaboration and maturing of remote handling technology by means of manipulator, among others, which evolved later to tele-robotics by merging with industrial robotics for non-nuclear applications, as well as for nuclear use. Tele-robotic systems have been developed in modular form allowing flexibility in the design and construction of systems. Reconfiguration of the equipment is possible when one task has been completed which permits reuse of the expensive components or parts. New technologies are also being developed which will facilitate reconfiguration of the remote hardware and supporting software systems.

Remote systems technology currently covers much more than a manipulator technology with high degrees of freedom. A large variety of remote systems with simpler mechanisms have also been developed and widely used for specific applications. It is also to be noted that there has been a trend in the recent evolution of remote technology toward a fusion in technical applications between nuclear and non-nuclear areas. These trends appear to have been driven by the shrinking market in the nuclear sector, especially in the fuel cycle area, on the one hand, and the expanding applications of advanced technologies in robotics, communications, informatics, etc. on the other. Applications of these high-tech variants of tele-operations to nuclear work have nevertheless been very limited up to now, due to contamination and some technical problems associated with applications in high radiation fields.

Spent fuel management has become a prospective area for application of remote technology in recent years with a steadily growing inventory of spent fuel arising from nuclear power production. A remark that could be made from the review of technical information collected from the IAEA meetings was that remote technology in spent fuel management has matured well through the past decades of industrial experiences. Various remote technologies have been developed and applied in the past for facility operation and maintenance work in spent fuel examination, storage, transportation, reprocessing and radioactive waste treatment, among others, with significant accomplishments in dose reduction to workers, enhancement of reliability, etc. While some developmental activities are continuing for more advanced applications, industrial practices have made use of simple and robust designs for most of the remote systems technology applications to spent fuel management. In the current state of affairs, equipment and services in remote technology are available in the market for applications to most of the projects in spent fuel management [1, 2, 3]. It can be concluded that the issue of critical importance in remote systems engineering is to make an optimal selection of technology and equipment that would best satisfy the as low as reasonably achievable (ALARA) requirements in terms of relevant criteria like dose reduction, reliability, costs, etc. In fact, good selection methodology is the key to efficient implementation of remote systems applications in the modern globalized market.

As for the future perspective, the increasing amount of spent fuel accumulation in the world will make it inevitable to require additional storage facilities for significant periods of time into the future. Such perspective implies the continued applications of remote technologies for handling of large amounts of spent fuel storage on the one hand, and for spent fuel packaging and disposal for much longer terms, on the other hand, as well as the conventional reprocessing operations as currently being performed in several countries. It is foreseen that another major application will emerge mainly from the need for decommissioning of old nuclear power stations where spent fuel inventories have to be removed first for decommissioning, as well as the decommissioning of spent fuel management facilities themselves. In this respect, remote technology will also be applicable to spent fuel management from research reactors.

Extensive applications of remote systems technology might also be possible in the long term future for innovative nuclear systems that have recently been attracting growing interest in the context of sustainable development of nuclear energy. With the recognition of the new realities emerged in the nineties from globalization of market economy which brought a great impact to nuclear sector as well, some new initiatives addressing future requirements for sustainable utilization of nuclear energy have recently been launched on international framework. A common goal set in those initiatives is to develop innovative nuclear systems that could satisfy the sustainability criteria in such terms as safety, economics, proliferation resistance, etc. In the current evaluation of those advanced nuclear systems, the novel processes to be used for the treatment of spent fuel would require extensive applications of remote systems technology due to the higher burnup of spent fuel and bulk radioactivity involved in some of those innovative fuel cycle processes. A representative example would be the spent fuel treatment by dry processing technology that is being developed in some Member States as a technical base for further operations like transmutation of minor actinides.

This TECDOC gives a review of the current status of remote technology applications for spent fuel management, based on country reports from some Member States presented at the consultancy meetings, of which updated reports are attached in the annex. The scope of the review covers the series of spent fuel handling operations involved in spent fuel management, from discharge from reactor to reprocessing or packaging for disposal, depending on the options chosen for spent fuel management. Because of the predominant amount of work required for spent fuel storage in the current and foreseeable future requirements for spent fuel management, more details are described on remote technology associated with storage of spent fuel. Some information on the application methodology of remote systems technology is provided with discussions on the basic principles that seem to be applicable in the development and application of remote technologies for all aspects of spent fuel handling. In addition, some practical guidance is provided on the selection of appropriate technology for implementation of a system. Finally, presented are some advanced technologies that would find applications in the longer term including the innovative fuel cycle concepts now in early stage of developments by some international initiatives like Gen IV of the USA and INPRO of the IAEA [4].

2. OVERVIEW OF REMOTE TECHNOLOGY APPLICATIONS TO SPENT FUEL MANAGEMENT

The global statistics on spent fuel management show that some 10 000 tHM of spent fuel are discharged annually. A little more than one-third of the total amount of spent fuel discharged (225 000 tHM) in the world has been reprocessed (85 000 tHM) and a similar proportion of arising is being reprocessed annually. This means that the bulk amount of the global spent fuel inventory (amounting to 170 000 tHM) is stored in AR storage pools and increasingly in AFR storage facilities built for additional accommodation for interim storage, short of further destinations. Compared to the AR storage facilities which had largely been water pools, the AFR storage facilities, especially those recently built and to be built for additional storage of spent fuel, are predominantly of dry type and in particular modular options which have developed into a mature industry over several decades. The modular dry storage systems developed as alternative options to the classical pools are preferred by the majority of customers for additional storage of spent fuel, especially for long-term interim storage as a contingency measure for future uncertainties [5].

The accumulation of spent fuel inventory to be stored is likely to continue for the foreseeable future as more countries decide to stop reprocessing or to phase out nuclear energy option, but may begin to diminish when the planned repositories are built and begin to remove spent fuel from the AR or AFR storage. But it is unlikely to see the actual decrease of the inventory in the short-term future because of the delays in the implementation of national programmes to construct the repository due to the various problems, including siting, among others.

These other observations in the global status and trends in spent fuel management predict that the remote technology would find its most extensive applications in the handling of spent fuel assemblies and casks (or other type of modules) associated with AR storage (pool operations), interim storage and transportation activities, reprocessing, conditioning and encapsulation for disposal. The spent fuel management areas where remote technology is applied are depicted in the mass flow diagram for fuel cycle backend as shown in Fig. 1.
The options chosen by each Member State for spent fuel management can be in general categorized into three groups:

- One group pursuing closed cycle by reprocessing of spent fuel and recycle of MOX fuel
- A second group committed to direct disposal of spent fuel
- A third group having postponed decision to be taken later (‘wait and see’ position).

Some countries chose to leave the option to the decision of utilities responsible to spent fuel management.

The choice of spent fuel management option is also dependent on the type of fuel: spent LWR fuels have residual fissile content which is reusable as nuclear fuel, while fuel types using natural uranium (such as HWR and GCR) have little residual reactivity worthwhile for recycle. An exception to the latter case is spent Magnox fuel which is reprocessed in UK for reason of storage safety (i.e. magnesium cladding corrosion in water storage pool).

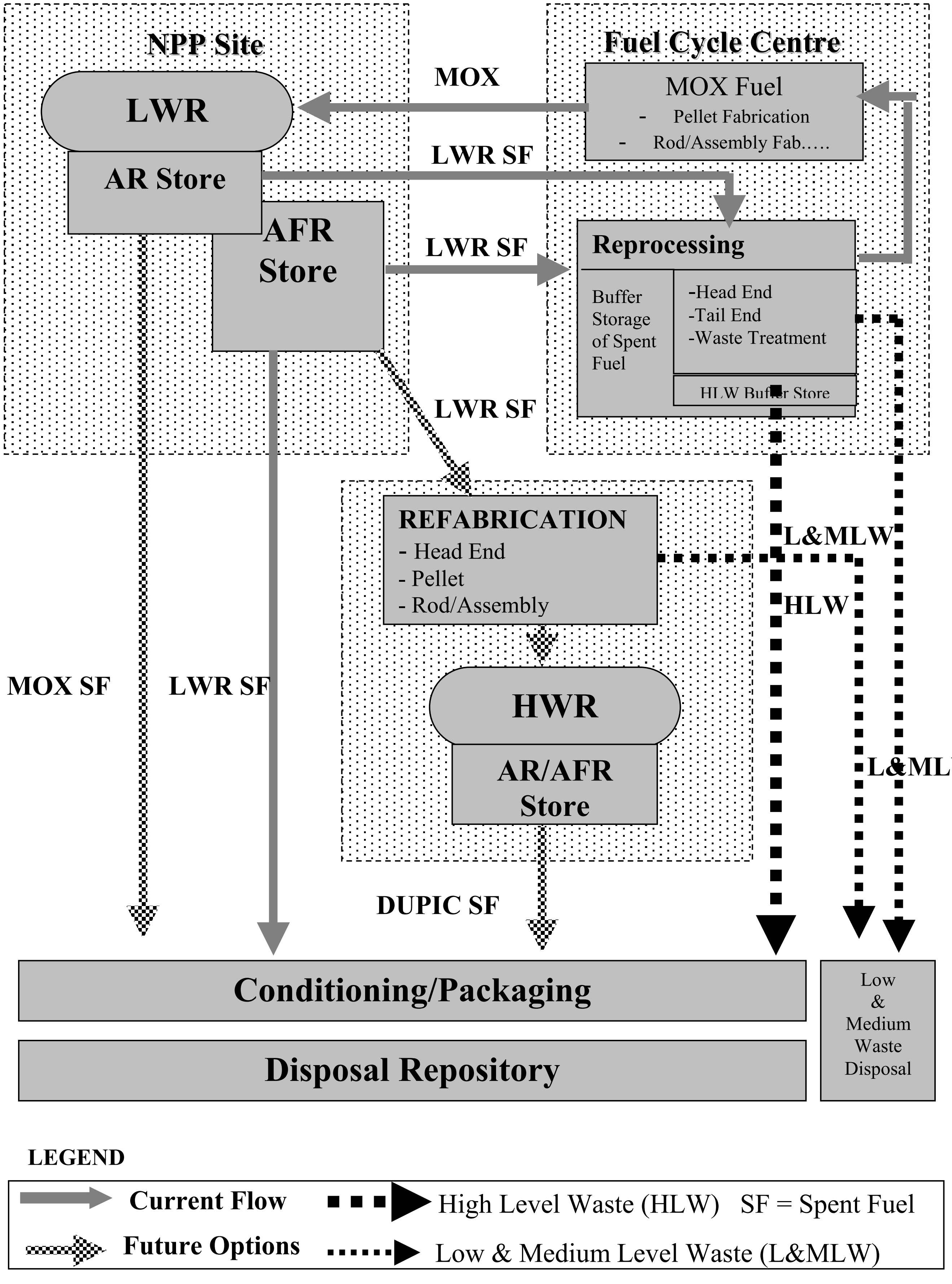


Fig. 1. Spent fuel management flow diagram with facilities for remote technology applications.

The applications of remote technology in spent fuel management are dependent on the reactor and fuel cycle, which is dependent on its turn on the type and design of fuel being adopted. Although the preponderant fuel type in current use for the majority of commercial nuclear power today is LWR, there are several other fuel types in commercial use such as HWR, GCR, RBMK, etc. The main characteristics of these fuel types and associated fuel cycle backend are summarized in Table I.

Table I. Fuel types in commercial use in the world

TYPE	DESIGN	PHYSICAL SPEC.	REMARK
LWR	PWR BWR WER	Cubic/hexagonal x-section, 4~5m long, ½ ton assembly	• Usually intact • Consolidatable • Recyclable
PHWR	CANDU	Ø 10x50 cm, 20 Kg bundle	• Handled in tray/basket • No recycle
GCR	Magnox AGR	Ø 3cm x 1.1m long slug, 24cm dia, 1m long assembly	• Need to reprocess • Dry storage possible
OTHER	RBMK	Ø 8cm x 10m long assembly (2 sect.)	• Need to cut to size • No reprocessing
	PBMR	Ø 6cm spherical form fuel element	• Canning • Possible to reprocess

Currently, the bulk amount of the global spent fuel inventory is represented by LWR type part of which is reprocessed, together with Magnox and AGR types. Other types of spent fuel are stored.

2.1. SPENT FUEL HANDLING AND STORAGE

As the classical strategy of spent fuel management had been reprocessing for plutonium recycle, earlier reactors had been built with small capacities for storage, especially in the case of LWR type reactors, in anticipation for removal to reprocessing after short period of cooling. Such early anticipation turned out to be not the case, due to various reasons, causing postponement of reprocessing or even shifting of policy to direct disposal in more and more Member States, giving rise to the problem of capacity shortage for spent fuel storage. As the lack of storage capacity can cause shut down of reactor operation, securing of adequate capacity for spent fuel storage had become an urgent issue at many AR sites. Much of the capacity shortage problem could have been mitigated by storage density increase such as re-racking the storage in pool. Having recognized such problem, later reactors have been built with larger capacities of spent fuel storage, in many plants to lifetime operation.

While re-racking method could mitigate the problems of shortage in spent fuel storage capacity at a number of older reactors, such easy methods having been nearly used up, and demands have begun to grow for additional storage capacities by away-from-reactor (AFR) type facilities that have been built in most cases at the reactor sites. As the long term storage has becoming a progressive reality to the majority of Member States, the interim storage at AFR facilities is likely to become a fallback option for managing spent fuel inventory worldwide, until removal to further destinations.

Compared to AR storage that is an integral part of the reactor operation, the AFR storage system is functionally independent from the reactor and for this reason it is sometimes called independent storage. The AFR facility can be located at the reactor site (RS) or off the site (OS). The majority of storage facilities being built for additional capacities are of AFR (RS) because of the infrastructural advantages, among others, while most of the AFR(OS) facilities built up to now are for buffer storage pools at reprocessing plants. After the AR storage or interim storage at AFR facilities, spent fuel can be sent to reprocessing plants or, as a future alternative, to a geological repository for direct disposal with appropriate packaging. The connections between these steps in the fuel cycle backend are mostly done either by spent fuel movement systems within the boundary of facility sites or by shielded casks for transportation between distant facilities.

The fundamental safety function in spent fuel handling and storage is to ensure maintaining sub criticality of the fuel, removal of residual heat from spent fuel, and confinement of radioactive substances. The integrity and properties of the fuel in handling and storage should be ensured all times during the handling and storage while radiation protection should be ensured with application of ALARA principle. Based on these requirements, remote systems have to be applied with appropriate considerations in the design and operation of relevant facilities.

One of the operational safety issues associated with spent fuel handling is the possibility of dropping fuel (or any other weight load being moved like canister, basket or cask) that may result in damage to the fuel integrity and therefore releases of radioactivity. An essential device for the movement of spent fuel assemblies and canisters in most facilities is bridge crane adapted to special safety features. Some of these safety provisions give rise to restriction to vertical and horizontal movement to prevent damage to the fuel assembly or loss of cooling/shielding function. An important consideration for fuel movement by crane is dropping of fuel during movement, for which single failure proof mode is integrated. Protection of the fuel during movement against contact with obstacles is another safety consideration in the design of the handling system and the facility. The fuel assemblies can be moved and stored both in vertical or horizontal position, depending on the system design of the facility. The handling machine moves the fuel assemblies individually or in groups within a basket for positioning in the storage racks or loading/unloading for cask operations. Facilities are normally equipped with another crane for heavy weight (usually over a hundred ton capacity) for cask handling, also with safety features in similar fashion to the fuel handling system [6].

2.1.1. At reactor operations

A variety of nuclear reactor models have been evolved in the global history of the nuclear industry and different approaches for fuel handling systems have been conceived according to the design and operation of reactors. One major difference is the mode of refueling; while some reactor types are refueled during full power operation, others are refueled during shutdown. Likewise, fuel may be stored in a dry (air) environment at some reactor types while wet storage underwater is adopted for others.

The predominant majority of spent fuel operations at reactor sites make use of water pool for cooling and shielding of spent fuel discharged from reactor core. Most pools are lined with stainless steel in order to enhance containment and to facilitate decontamination. They are built with necessary operational systems required for spent fuel handling, storage and shipping in addition to those process functions as heat exchange and water purification.

Stainless steel is widely used for lining inside surface of pool and for construction of equipment to minimize corrosion problems to the enhancement of reliability and reduction of maintenance time.

(1) Spent fuel handling and storage

The spent fuel handling systems are dependent on the design of reactor types, but in general make extensive use of remotely controlled crane motion. As a basic requirement, almost all nuclear power reactors in the world are provided with a handling system with a crane for spent fuel handling and storage, cask loading or unloading. The loading and unloading of spent fuel into and out of cask for storage are major operations to be performed at AR storage pools. Such operations are in general performed in the manual or automatic mode, sometimes assisted by auxiliary devices. The safety guide on the design of fuel handling and storage systems at reactor stations are provided in Ref. [7].

Summaries of fuel handling systems at different types of nuclear power plants are as follows.

- Light water reactors (LWRs)

LWR reactors (PWR, BWR, WWER) use the batch mode of refueling normally performed during annual outages during which various other activities associated with plant maintenance are conducted as well. The interval between refueling which has been traditionally 12 months is being extended to 15 to 18 months in an increasing number of LWRs around the world with the tendency toward higher burn up of fuel. Depending on the plant size, some 20 to 40 tons of fuel are replaced in the core.

Regarding the remote systems technology applied to refueling operations, LWR power plants are provided in the containment with a fuel handling system dedicated to the refueling operation of fresh fuel loading in the core and spent fuel discharge out of the reactor core, which is performed underwater during the outage period. The machine consists of a bridge, traveling across the reactor and a cross travel trolley on the bridge. Controls are provided on the trolley for positioning the machine over the desired handling location and for controlling movement of the hoist. The trolley is equipped with a grapple mechanism and hoist that at the lower end holds different tools for various work (Fig. 2).

The majority of LWRs have a spent fuel storage pool outside of the containment in an adjacent building in which case a separate handling system for spent fuel storage pool operation is provided. The spent fuel assemblies removed from the core are transferred to the spent fuel pool by means of a horizontal transfer mechanism through connecting canal(s) between the two buildings. In a few nuclear power plants as in Germany and in Switzerland (Gösgen) which have spent fuel storage pool inside reactor containment, the fuel handing system is used for both refueling and storage operations inside the containment.

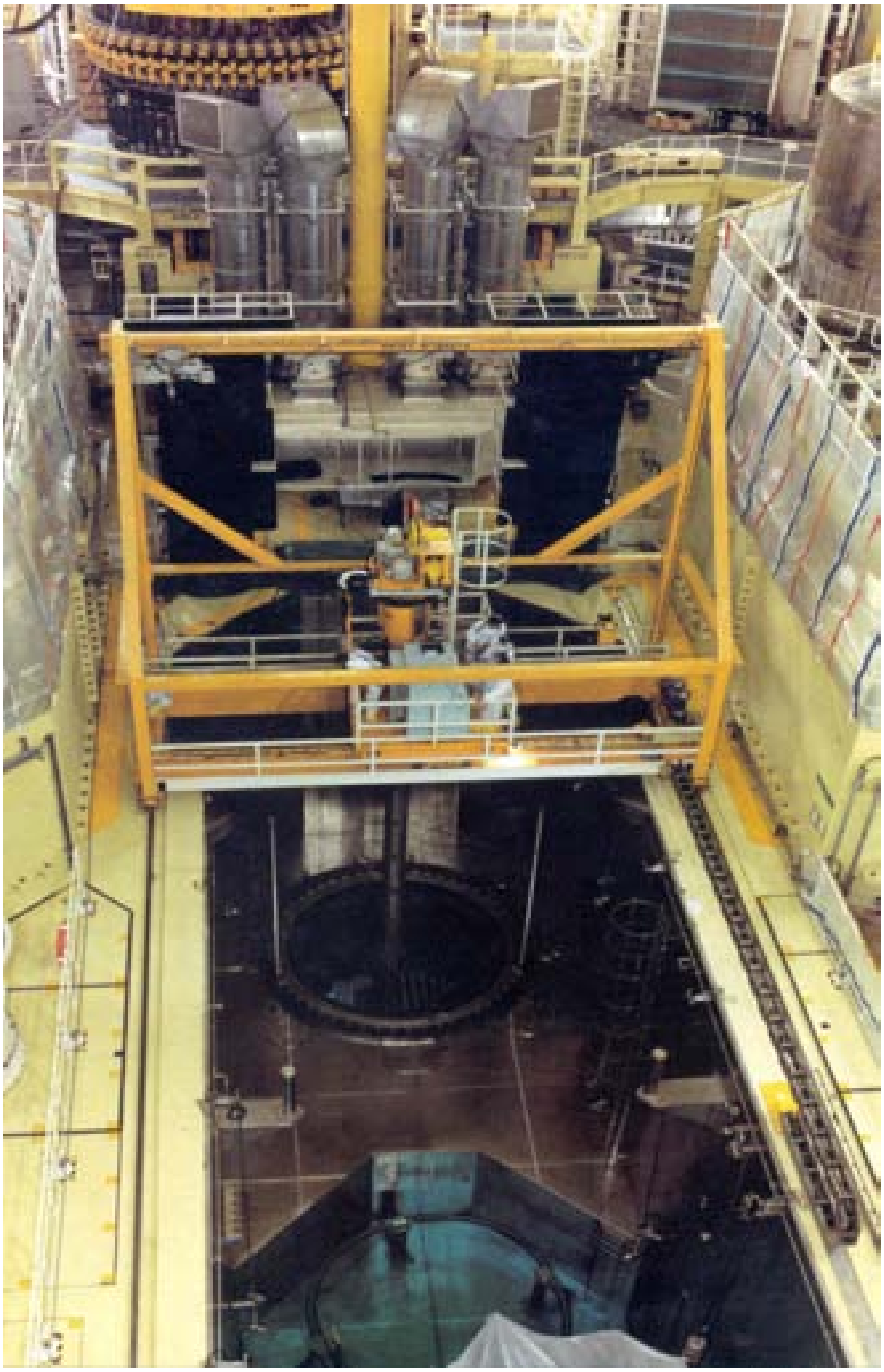


FIG. 2. Fuel handling machine on reactor core.

- Pressurized heavy water reactors (PHWRs)

In contrast to the batch mode refueling at LWRs, a continual mode of refueling is used for CANDU reactors designed with horizontal calandria housing several hundreds of pressure tubes, each containing a stack of a dozen fuel bundles. The pressure tubes with fuel elements can be charged and discharged almost daily, one independently from others, during the on-power operation of the reactor. Refueling is accomplished by means of a pair of mobile fueling machines attached by locking to opposite ends of a pressure tube.

The refueling machine is a bulky piece of device with a ram mechanism to move fuel bundles in and out of the magazine. Either machine may serve as a charger or discharger of fuel bundles, remotely operated from the control room. A stack of fresh fuel bundles (4 to 8) is inserted into the channel by one refueling machine by pushing out the same number of spent fuel bundles to the other side of the channel into another refueling machine that receives them into a magazine. The refueling machine, which takes over the spent fuel bundles, takes them to a ladle to move them into the storage pool.

- Gas cooled reactors (GCRs)

Continuous mode of refueling is also used for most gas-cooled reactors (GCR) including Magnox and AGR types that have a vertical core to which fuel standpipes are positioned on the concrete shielding floor with plugs on each of the fuel standpipes. This is a technical feature that is similar to the PHWR in terms of operating mode.

Access to individual fuel channels is provided by the locations of penetrations through the gas baffle dome in line with the standpipes. A fuel handling machine moves fuel elements and control rods to be loaded and discharged from the core through the standpipes. As the spent fuel (or irradiated materials) is handled out of the shielded floor, the fuel-handling machine must have the functional requirement of shielding, containment, as required for a transportation cask.

- Water cooled, graphite-moderated pressurized tube reactors (RBMK)

(2) Spent fuel inspection

Although the major applications of remote technology at the reactor involves refueling operations including movement of assemblies from the reactor core to a storage pool, a number of inspection devices, deployed remotely, have been developed and used to identify defective fuel assemblies and failed fuel rods for which special measures have to be taken in addition to the normal procedure of fuel handling.

The test methods used on spent fuel assemblies or rods include: visual examination, dimensional measurements, gamma scan, eddy current test, ultrasonic testing and sipping. Some examples were reported at IAEA meetings [8].

- Visual inspection

Some primary methods of spent fuel inspection are visual ones: the most widely used being an underwater camera that can be mounted on a X-Y table or pan-tilt fixture suspended from a handrail pole. Recent products are offered with high tech electronics and computer analysis systems.

An example of fuel inspection (and reconstitution) performed underwater at the reactor site was reported by Germany for instance Multi-Inspection and Ultravision systems that were developed by Siemens and has been used at a number of reactor sites. Extensive systems for spent fuel inspection and repair services have also been reported by Framatome and BNFL/Westinghouse. Remote inspection is preformed via sensors and under water video cameras where the oxide layer thickness on fuel rod can be measured using the Inoxis system. The data from the sample measurements are immediately evaluated and displayed on a screen.

Another device is a Multi-Inspection system, which allows for the visual inspection of an assembly in a receptacle located in the spent fuel pool, releasing the refueling bridge for other purposes. A third measuring system allows repeated measurements on irradiated flow channels on BWR fuel assemblies.

- Ultrasonic / eddy current method

In addition to the visual method, several techniques are available for checking the integrity of fuel cladding, including ultrasonic and eddy current methods.

Eddy current can be used for detecting defects in the cladding, while ultrasonic technique is conveniently used for presence of water in fuel rods by making use of the attenuation of an echo signal from those containing water for which the attenuation is much faster than intact ones containing only gas. The Ultratest of Siemens makes use of computer-controlled probes on each side of the 4 sides of fuel assembly to enhance speed.

- Sipping test

In addition to the spent fuel inspection activities in AR pools, some mechanical operations on the spent fuel can also be performed in AR pools by application of remote technology. A requirement for spent fuel acceptance at downstream stages, especially at interim storage is to ensure integrity of fuel rods for handling, storage, and any eventual retrieval. Sipping is a simple method of detecting gas leakage from fuel rods. One of these devices developed by Siemens (now Framatome-ANP) is for the rapid detection of leakage from an assembly (Mast Sipping) of spent fuel (or of core components) while the assembly is being removed from the core rather than in the fuel pool. The Siemens systems use a man-in-the-loop (tele-operation) to perform most of the operations rather than automation or tele-robotics. Both the Multi-Inspection system and the Mast Sipping system can be used in either BWR or PWR plants and are available in several different versions so that either can be tailored to the facilities needs.

(3) Fuel reconstitution, repair, and rod consolidation

An example is reconstitution of fuel assembly by replacement of some fuel rods with fresh ones to boost the depleted reactivity or to remove fuel rods with some other technical problems. Segregation and canning of defective spent fuel, is another example of spent fuel handing operations in AR pools, which is applied to defective fuel elements where the rate of occurrence is a function of the fuel performance of the NPP.

Spent fuel rod consolidation is a more recent development of utilizing the pool facility for underwater operation to remove structural components of spent fuel assemblies for consolidation of fuel rods to 2:1 compaction ratio compared to the intact fuel assembly, as a method to extend the capacity of existing pools. The technical operation of reconstitution can be extended to rod consolidation in that both techniques involve extraction of fuel rods from the assembly and insertion of fuel rods into either a fuel assembly or a canister.

The remote technology applications to the fuel reconstitution or consolidation are quite challenging because of the relative complexity of the mechanical process operations to be performed and the associated maintenance work, as well as the additional chore required for disposing of structural wastes left over from the consolidation operation. These technical features are part of the main reasons for the stalemate of progress nowadays in the applications of the rod consolidation technologies at AR and AFR storage facilities.

(4) Handling of defective fuel

An example of remote operation at reactor storage is encapsulation of failed fuel at AR pools. Even though the rate of defect fuel arising is usually insignificant, but taking appropriate measure to contain radioactivity is an important issue from a safety point of view. In order to encapsulate a defective fuel assembly into a canister, a series of remote operations are called for, together with relevant provisions in the facility including encapsulation equipment and storage location.

(5) Spent fuel cleaning

In some cases of fuel operation in the reactor core, corrosion product deposits (so-called crud) need to be removed from reloaded fuel surfaces by suitable cleaning techniques with a view to enhance fuel utilization and reduce dose rate to the workers. The trend toward extended burn up can increase the buildup of corrosion product deposits, shifting the power profile toward the bottom of the core (Axial Offset Anomaly), which can call for derating of a plant late in the fuel cycle to maintain a safe shutdown margin. The crud can also cause problems in the later stages of the fuel cycle backend by the spallation of surface deposits resulting contamination of spent fuel handling processes such as reconstitution or rod consolidation. It is also well known that the insoluble crud entrained in the separation process of reprocessing operations is a problem due to the difficulty of removal. Because of the need to remove the crud deposits several techniques have been developed and used for cleaning of the spent fuel surface.

- The chemical decontamination, which has been extensively used in nuclear industry, is also used for cleaning of metallic surface by dissolvent. A system developed by Framatome ANP is HP/CORD to wash the spent fuel surface of corrosion products (Fe, Cr, Ni, among others) by flushing in a tank [9].

- Ultrasonic technique for application in the US to the cleaning of spent fuel has been published [10, 11].

- Ice particle abrasion: a new decon technique called ICEDEC , developed by Westinghouse was reported to have been used at Ringhals #1 NPP in Sweden [12].

Due to the highly radioactive processes involved in the cleaning, remote technologies are required for the cleaning operations. The design of the cleaning system needs careful incorporation of safety provisions for the cleaning operations to be conducted safely.

2.1.2. AFR storage facilities

After the AR pool operation, the next phase may involve AFR storage whose significance continues to be amplified due to the growing demand for additional storage of an increasing cumulative inventory of spent fuel worldwide. In consideration of the global perspective on spent fuel management, the importance of AFR storage of spent fuel is likely to grow in the future with an implication in remote technology required for operation and maintenance involved in related work. It is therefore propitious to elaborate some more aspects associated with interim storage of spent fuel focusing on AFR storage technology.

AFR facilities can be located either at the reactor site (most of the current AFR facilities) or at a distant site (such centralized storage facilities as Gorleben in Germany). The technical features of remote system technology applied at AFR spent fuel storage facilities are similar to those of AR storage facilities.

(1) Technical options for AFR storage

The technologies currently available for spent fuel storage fall into two categories, wet and dry, distinguished according to the cooling medium. For a long period, the wet storage of spent fuel using water pools was the predominant storage method. As an established practice since the early days of nuclear power, water filled pools have been used almost exclusively for initial shielding and cooling of spent fuel discharged from reactors not only for temporary storage at reactor site but also for AFR storage at reprocessing plants. Since the eighties, however, dry storage options began to be developed and used at an increasing number of new builds especially with cask type storage systems.

- Water pool

Water pools are the most common option for storage of spent fuel immediately upon discharge from reactors, since they provide excellent heat transfer, which is essential in the early phase of cooling. At the nuclear plants, these pools are generally integrated with the plant design and spent fuel management in these pools is part of the plant operation. Water pool storage is however also being considered for AFR storage facilities by virtue of the large amount of experience available with this technology, in addition to some inherent merits of water as a medium for spent fuel storage. Water pool storage, however, requires active process systems to ensure satisfactory performance and continuous attention to preserve water purity. Most of the smaller scale AFR storage facilities of water pool type have been built nearby the reactor sites in consideration of various factors including sharing of infrastructure available from the reactor sites. The interim storage facility CLAB in Sweden is a unique case of a stand-alone water pool storage facility for handling and storing large amounts of spent fuel (5 000 tHM which is being increased to 8 000 tHM capacity) to be extended to direct disposal.

A view of large AFR storage pool at the Sellafield reprocessing plant is shown in Fig. 3.

Because of the large inventory of radioactivity under a relatively vulnerable shielding protection against external hazards (earthquake, tornado, flooding, aircraft crash, etc.), wet storage has been subject to scrutiny with a variety of safety issues in addition to other criteria like economics, safeguards, etc.

An advanced concept of spent fuel storage incorporates in its design some of the enhanced features with a view to ameliorate the drawbacks of wet storage system; cooling and purification systems are modularized for simple submerging in the pool (as in the Nymphea system used at the storage pool of La Hague reprocessing plant), protective concrete wall over the water basin, enhanced economics in operating costs by incorporating passive features, etc. [13]

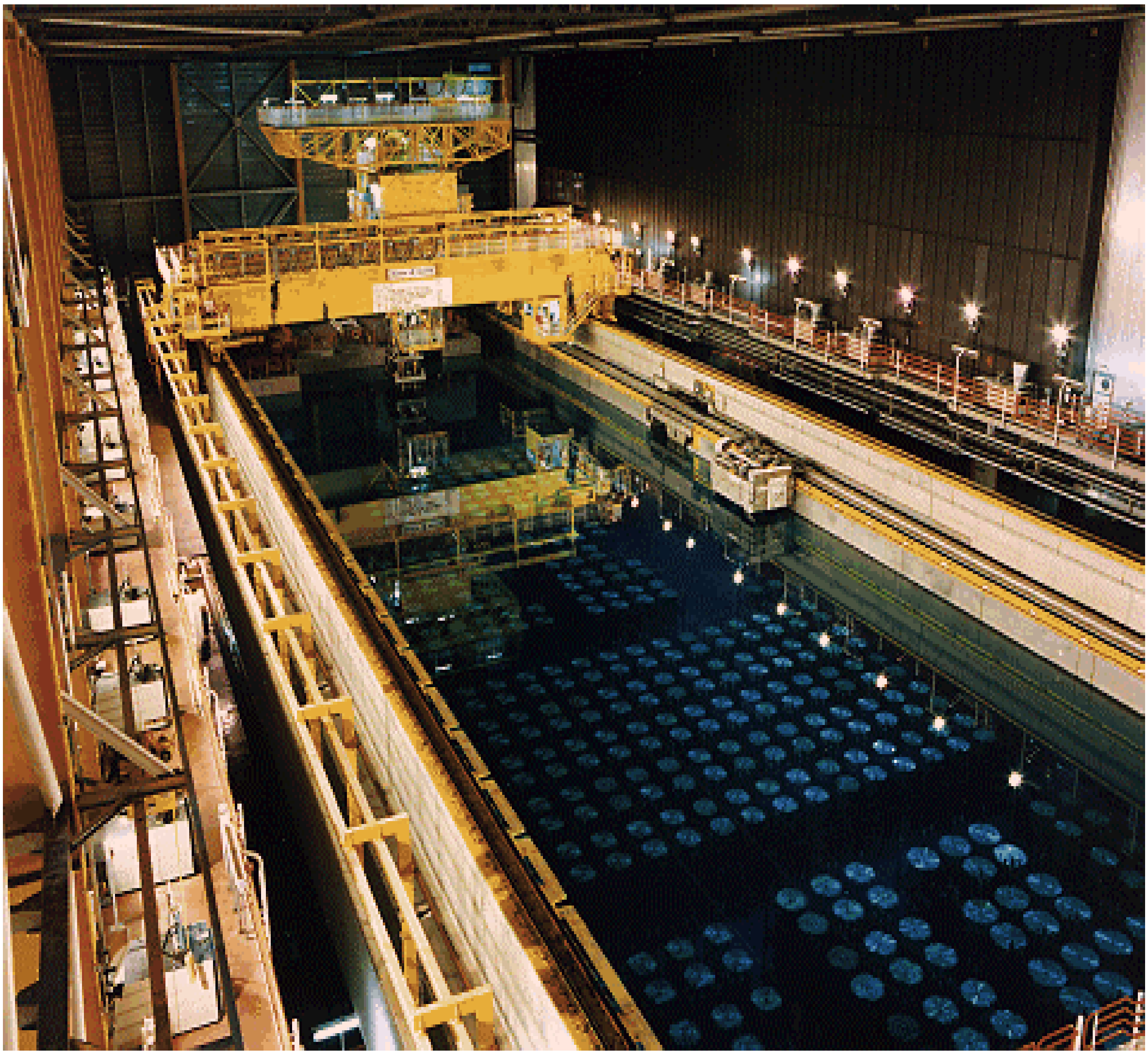


FIG. 3. Spent fuel storage pool at Thorp reprocessing plant.

- Dry storage options

The spent fuel assemblies are in general suitable for naturally cooled dry storage after a few years of initial cooling in the water pool. The minimum required time of initial cooling in pools is mainly related to the burn-up and the irradiation history. Taking into consideration the 20 to 50 years or even longer period required of storage, it is obvious that the naturally cooled dry storage options could be an attractive alternative to water pools.

A review of spent fuel storage facilities implemented during the last 10 to 20 years show that the storage in a dry environment is becoming more common. There are several generic types of these technologies available from vendors on the international market. Prominent among them are: metal casks in which spent fuel assemblies or consolidated spent fuel canisters can be accommodated in suitable basket and concrete casks in which spent fuel enclosed in canisters can be accommodated as a separable package.

There are also a large number of facility designs based on these generic technologies that are now available. These technologies differ largely in terms of materials of construction, size, modularity, spent fuel configuration, layout of the storage containers (horizontal, vertical etc) and methods for fuel handling. Multi-purpose technologies (i.e. a single canister design for storage, transportation and disposal) have also been studied in some countries. Despite the benefits expected from standardization by the multi-purpose canister (MPC) concept, the uncertainty of the final form of the disposal package has deferred any definite concept for the MPC design. Further differences could be in terms of their placement above or under the earth’s surface. An increasing number of storage facilities are coming into operation for each of these types.

Although there is no clear favorite technology worldwide, dry storage of spent fuel in casks is being particularly recognized as a flexible option with the advantages of transportability in case of future need, incremental investment as needed or the option of leasing of casks from vendors, in addition to the passive feature of dry storage.

There are several AR storage facilities where the spent fuel is handled in the dry mode called Modular Vault Dry Store system (MVDS) (Wylfa in the UK, Fort St.Vrain in the USA), which was also adopted for the AFR storage of spent fuel at Paks nuclear power plants in Hungary. This technology is being adopted at several sites in the USA for storage of canned spent fuels from non-power reactors, which requires extensive application of remote technologies for the preparatory operations [14].

A summary of the AFR storage concepts are as shown in the Table II.

Table II. Dry storage options for AFR storage of spent fuel

TYPE	OPTION	CONTAINMENT	SHIELDING	FEATURE	EXAMPLES
Wet	pool	water	water	classic option	
Dry	metal cask	cask lid	metal	dual purpose	CASTOR Series, TN Series, NAC series
	concrete cask	canister	concrete overpack	vertical	Hi-Star/Storm, CONSTOR,
	concrete module	canister	concrete module	horizontal	NUHOMS MACSTOR
	vault	canister	concrete vault	several cases	Wylfa, Paks
	drywell	canister	drywell	no commercial	

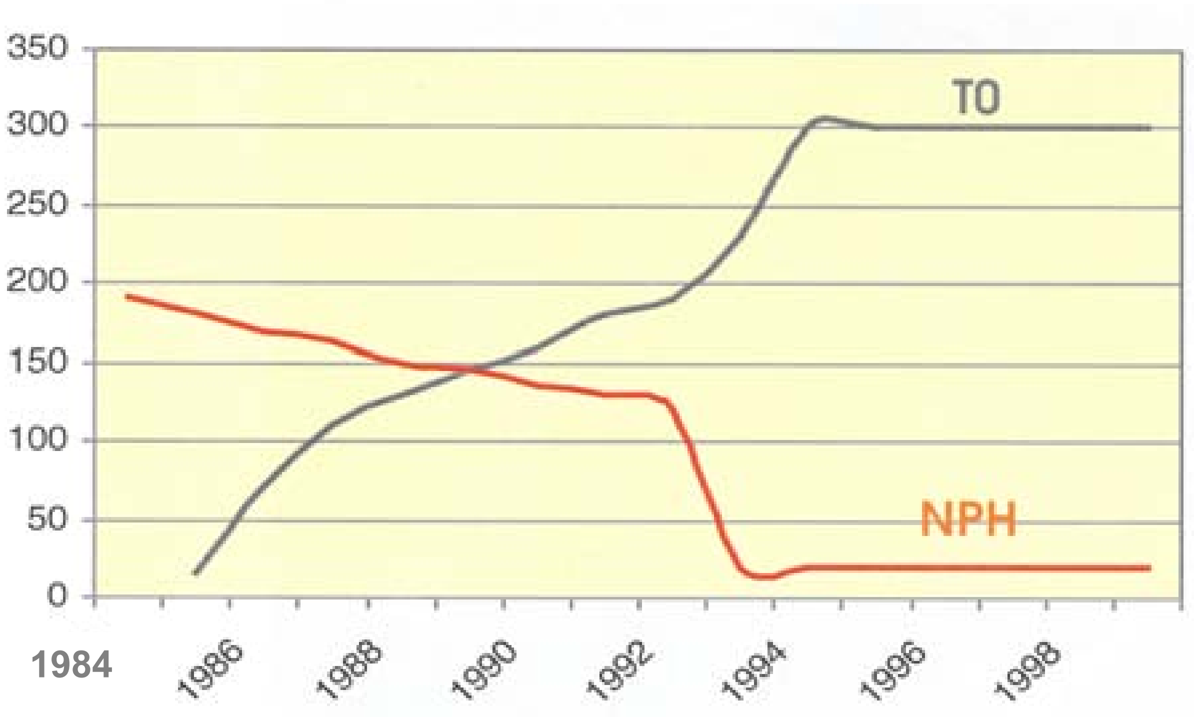
Several variants of these concepts, often by combination of existing dry storage technologies, have been developed with prospective applications in the future: by combination between canister, cask and vault (metal casks in vault), or a new variant like the twin-tunnel concept (combination of underground drywell and ventilated cask).

(2) Remote technology applications to AFR storage

The loading and unloading of spent fuel assemblies in the cask or canisters, in addition to the welding of the loaded canister, are the major operations requiring involvement of remote technology associated with AFR storage systems.

The remote technology applications in AFR pools have well been refined throughout the maturing industry of reprocessing. In the La Hague reprocessing plant, for example, the occupational dose rate has considerably decreased by remotization of much of the storage pool facility operations and furthermore by application of dry unloading technology [15].

The actual reduction in occupational dose rate achieved by remotization of operation and maintenance work at La Hague pool (NPH) facility was 6 fold, from 1.8 mSv/yr in 1984 down to 0.3 mSv/yr in 1998 (the same value as that of dry unloading work at nearby T0 facility), for an annual workload of approx 300 casks (see Fig. 4).



Year	Dose Tate (mSv)	Operation & Maintenance
1984	1.8	Operation 55% Maintenance 45%
1994	0.3	Operation 10% Maintenance 90%

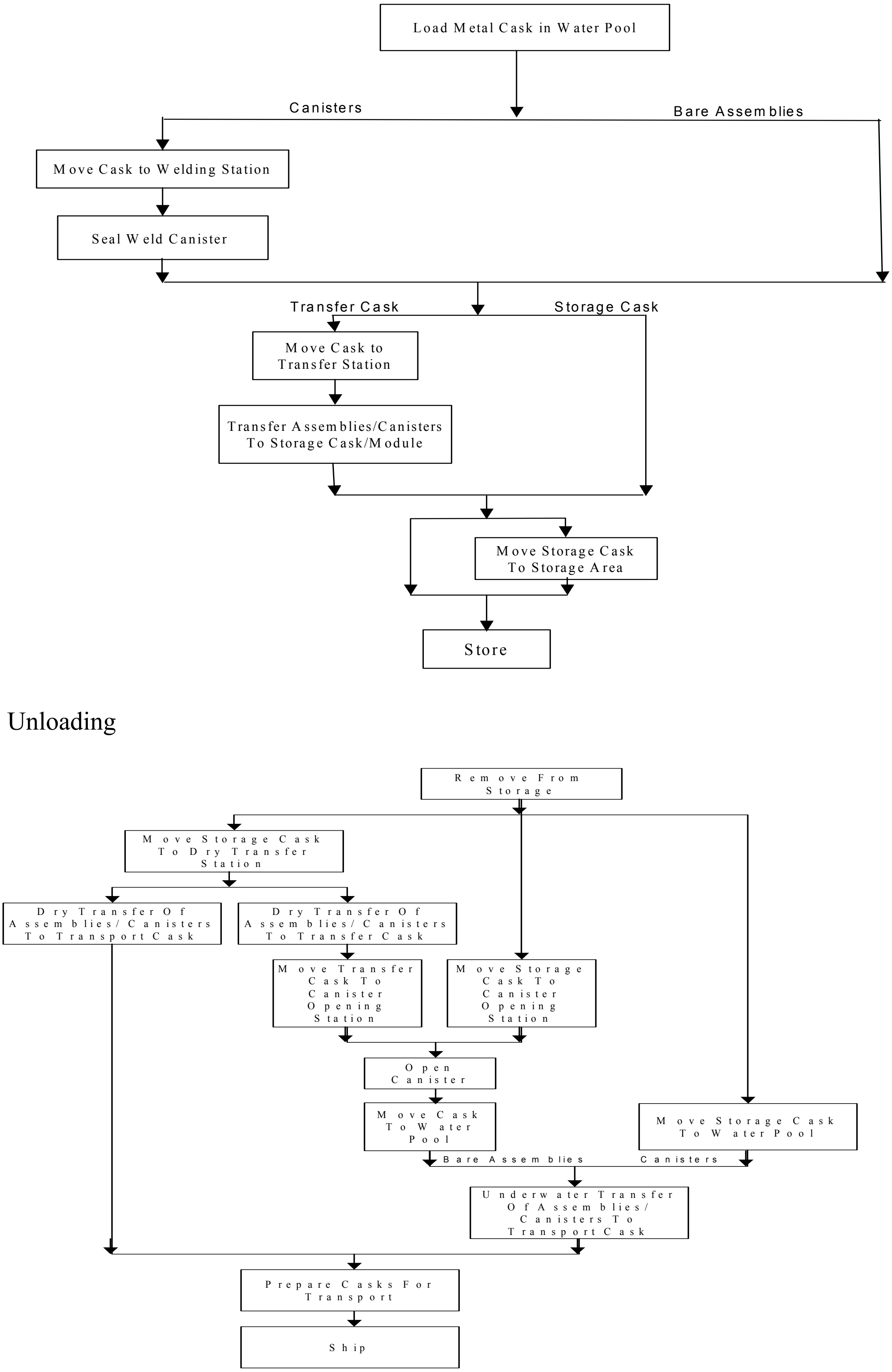
FIG. 4. Dose rate reduction by remote technology application in AFR storage at La Hague.

In the dry AFR storage systems, the remote technology can be applied to the following operations:

- Handling of spent fuel assembly/canister for loading and unloading

Most of the current AFR storage systems located at reactor sites make use of a water pool facility for unloading or loading of spent fuel assemblies, thus avoiding additional investment. The optional operations of loading and unloading as required for spent fuel storage in dry storage facilities are represented in Fig. 5.

Loading



Unloading

FIG. 5. Spent fuel loading and unloading for AFR storage.

If the existing facility cannot be used for the required operation for any reason (such as storage-only casks which cannot be moved to the pool for unloading or a pool is simply not available due to decommissioning of the plant), an additional facility would be required for the necessary operations. Such contingency is also conceivable when the casks may have to be opened at the end of the licensing period, i.e. after 20 to 40 years of storage as applicable to many countries. Currently, re-licensing of existing storage systems beyond licensed period is being sought in some countries.

A centralized dry storage facility using storage-only type casks would involve massive operations for spent fuel transfer to and from transport casks. Even if spent fuel is brought by dual-purpose casks from the plant sites, the spent fuel would have to be taken out eventually for conditioning as required for disposal. A representative case is the interim storage concepts developed in the USA in the past for monitored retrievable storage (MRS) and centralized interim storage facility (CISF), although neither has materialized for non-technical reasons.

As it is clear that the spent fuels in various types of storage have to be conditioned into disposal package before disposal, a facility is needed in conjunction with the spent fuel packaging for disposal to move out the spent fuel from a conventional top loading cask to another one or between multipurpose canisters in the shielded overpack. Such a system will enable transfer of spent fuel or canister between different capacities or functions. In a collaborative program DOE/EPRI conducted in the latter half of the nineties, a prototype for dry transfer of spent fuel called dry transfer system (DTS) was fabricated and successfully demonstrated with mockup fuel at the Idaho National Engineering and Environmental Laboratory (INEEL). The equipment of dry transfer system (DTS) is shown in Fig. 6.

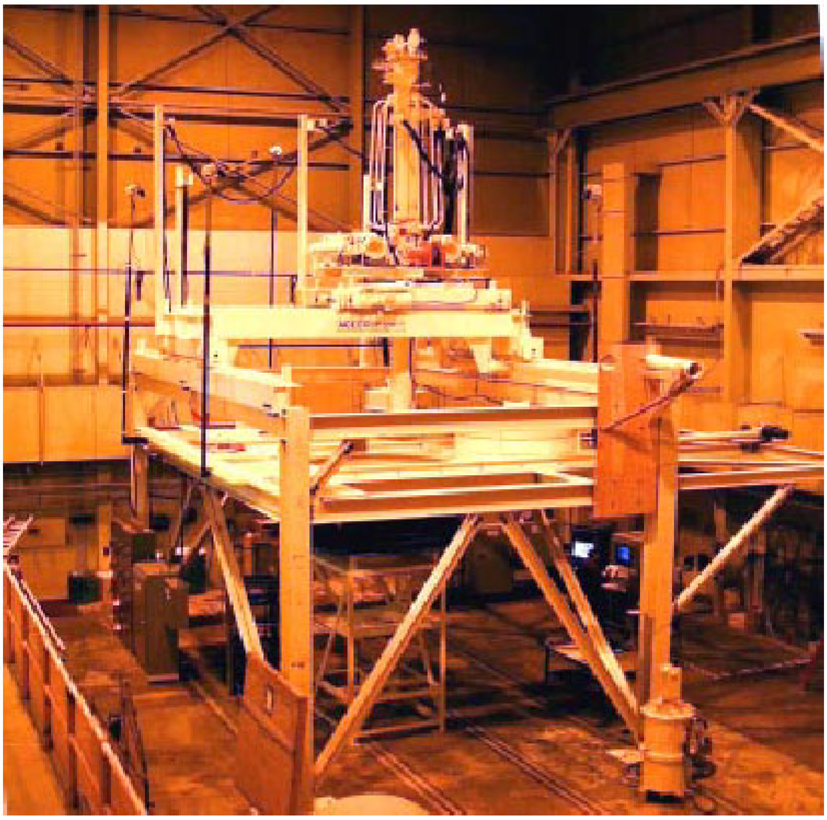


FIG. 6. Dry transfer system (DTS).

The Topical Safety Analysis Report of the DTS was submitted to the NRC in September 1996 and the NRC issued a Final Assessment Report in November 2000. The Commission concluded that the DTS was licensable and the Assessment Report includes site specific items that must be addressed by an applicant. The Revision 1 of the DTS TSAR, which incorporates the Assessment Report findings, was transmitted by DOE to the NRC in December 2002. The DTS technology is incorporated in the design of the Fuel Handling Building of the Federal Repository facility at Yucca Mountain (see ANNEX VI).

- Spent fuel handling in vault storage

In the case of MVDS, the spent fuel-handling machine has evolved from refueling machines used at GCRs. As the MVDS makes use of similar technical features as the GCRs in terms of fuel handling systems, those functional requirements of shielding, containment, cooling, and sub criticality are called for the remote operations involved in spent fuel handling and storage at MVDS facilities (see annex, UK Country Report). Aside from Wylfa in UK, the MVDS is also used for spent fuel storage in the USA at Fort St.Vrain which is a HTGR type reactor.

The application of the MVDS for storage spent fuel from commercial LWR is represented by the Paks NPP (WWER type reactor) in Hungary. A vault storage of spent LWR fuel with increase storage density is the Mega–Vault concept which make use of large size canisters (similar to the canisters used for concrete cask storage) for storage in the pits in the vault, as proposed by GEC and Toyo Engineering.

An example of dry vault storage of spent fuel non-power reactors is the Idaho Spent Fuel Storage Vault of which construction started in 2000 for repacking a total of 265 tHM and storage in dry vault of spent fuel from power reactors (Shippingport and Peach Bottom) as well as research reactors (TRIGA) that have been in various type of storage at Idaho site, with a view to start operation in 2005 [16].

- AFR storage of spent fuel from pebble-bed reactor

A uniquely different case in the method of spent fuel handling and storage is the pebble bed reactor THTR-300 located at Julich as developed in Germany. The pebble-like thorium fuel balls are drained down through an outlet to fill containers that are buffered in dry pit storage. They are taken out from the buffer storage by crane and brought subsequently to an adjacent loading station. One container equivalent to 2,100 fuel pebbles is inserted in the cask CASTOR THTR/AVR. The loaded cask is provided with a primary lid that is bolted by a manipulator and moved to a working platform where the primary lid bolt is tightened for air-tightness and where the secondary lid is also bolted and air-tightness checked. After completion of cask loading, sets of 3 casks are put on the transport wagon by a heavy load crane to ship out the casks to the Ahaus interim storage facility. Several hundreds of the casks were delivered to the Ahaus storage facility in the mid-nineties [17].

- Special preparations for spent RBMK fuel storage

For some types of spent fuel, special processes are required in preparation for AFR storage, calling for extensive application of remote technology. A good example is the preparation of casks for AFR storage of spent fuel from RBMK reactors, as being done in Lithuania, Ukraine, and Russia. The spent RBMK fuel assembly has a dimensional structure, which requires disassembly of the unusually long skeleton (10 m) into two sections of fuel rods, including the associated structural materials, in order to fit in the commercially available casks for AFR storage.

The pioneering work for packaging of spent RBMK fuel for dry storage was initiated by Luthuania for the Ignalia Nuclear Power Plant (INPP) in 1997. The spent fuel pool bay at the INPP had been refurbished for the spent operation and associated waste packaging. The long RBMK fuel in pool storage is brought to cutting operation, which is conducted in vertical mode in a high hot cell enclosure. The bundles of fuel rods separated from the extension structural tube are loaded into a 3.6 m long basket which can accommodate 102 rods for subsequent storage back in the storage pool. Metallic structures arising from the operation are packed in the hot cell for subsequent disposal. After 5 years of storage in the pool, the baskets are taken out of the pool to the dry storage area for interim storage in the CONSTOR concrete and CASTOR metal casks which are licensed from GNS/GNB. Upon loading, the internal lid and cask cover are welded to leak-tightness. The dry storage facility was commissioned in 1999 and 20 CASTOR and 34 CONSTOR casks have been put into storage since that time [18].

At the Chernobyl site, a complex of facilities for Spent Fuel Packaging Facility (SFPF) is being built at the site to make them appropriate packages to be stored in NUHOMS system for a period extending to a hundred years. The process of preparing the storage package is similar to that of conditioning spent LWR fuel into a disposal package by rod consolidation. The incoming spent fuel assemblies and absorbers in cask are sorted for appropriate treatments in a tall hot cell where the long spent fuel assembly is removed of extension shafts and upper and lower bundles of fuel rods separated for consolidation into a stainless steel cartridges to be seal-welded and inerted before being put into a canister which is also seal-welded and inerted. This packaging process provides a double containment to the spent fuel rods. The absorber rods are subject to similar treatment, i.e. the extension shaft is sectioned from absorber part, which is put into a cartridge to be seal-welded, and inerted for separate storage. The shaft sections are separated from the spent fuel assemblies and absorber rods and are cut into pieces for treatment as metallic waste. Each canister, which is compatible with typical Nuhoms storage system, holds 196 cartridges equivalent to a total of 98 spent RBMK fuel assemblies. The interim storage facility at Chernobyl site is designed to accommodate 25,000 spent RBMK fuel assemblies and 3,000 absorber rods [19].

In Russia, a new facility for preparing RBMK-1000 spent fuel for dry storage has been developed as an addition to the AFR storage at the Leningrad NPP. The 10–m long fuel assemblies are cut from the upper end-fitting (which is decontaminated and then melted for disposal) and then separated into the two fuel bearing sections in a hot cell. The fuel sections are packed in ampoule (canister) and then placed in a metal-concrete cask capable of holding 114 sealed cans (see Annex IV).

(3) Provisions for future of AFR storage

Nuclear fuel designs have been changing over time in an attempt to improve their characteristics. Utilities have been increasing their use of higher burnup fuels, a trend that is likely to increase and envelope different types of fuel such as MOX fuel. In the case of MOX fuel or fuels containing reprocessed uranium, remote handling would have to be considered even for fresh fuel, depending on the cases, due to the radiation emitted from those fuels. Based on the characteristics of the spent fuel existing at the time of the selection of the AFR storage facility, some allowance may have to be made to make room for the future development of the fuel used in the reactors. The modular approach for AFR storage will allow the required flexibility to take into consideration any unforeseen changes that could take place in the future, including changes to fuel characteristics, containers, regulatory requirements, and the knowledge base of storage systems. A modular approach will also allow future improvements in storage systems themselves to be accommodated based on lessons learned in the initial stages and from feedback from storage operations.

Since the AFR storage is not the final stage in the disposition of spent fuel, retrieval requirements are important at any time during the storage period and in particular at the end of the lifetime of the storage facility. To this effect, fuel handling and loading systems and equipment would have to be an integral part of the storage system. Need for spent fuel handling during long term storage may arise from transfer to another storage system for various reasons. The DTS type of facility mentioned previously would be required for storage-only AFR facilities. The lifetime of the AFR storage facility should be determined based on the necessary interim storage period prior to any future disposition, be it reprocessing or direct disposal. In cases where such a period is indefinite or very long, one may be constrained by the achievable design life of the facility, in which case the spent fuel may have to be transferred from one facility to another during the storage period. Transferring of stored spent fuel from one facility to another may take several years, even decades, depending on the amount of fuel and loading and handling constraints at the facility. Such limitations would have to be given consideration in developing AFR storage, particularly in terms of facility durability, licensing conditions with regard to facility design life, and any licensing agreements with respect to extended use of the storage facility beyond the licensed period.

2.1.3. Cask operations in spent fuel management

Spent fuel transportation has long been established as an important part of the industrial activities in nuclear fuel cycle backend, especially for reprocessing industry. Several companies have been developed for the transportation service, operating a number of spent fuel transportation casks that have been licensed in compliance with national and international regulations. The bulk amount of spent fuel transportation in the past has been to bring spent fuel in storage in AR pools to AFR pool at reprocessing plants. However, the role of casks has significantly expanded recently with the increasing demand for additional spent fuel storage in AFR facilities since the eighties, as the transportation cask has begun to find its way into dry storage service in a dual purpose mode, together with concrete type casks which have been newly developed mainly for storage only.

A crane specially manufactured for heavy cask handling is shown in Fig. 7.

During the past several decades of development, the cask industry has matured providing products and services with reliable safety and competitive supply that it as now become a matter of selecting a system offered in the market for spent fuel storage requirements. The general requirements of transportation and storage should be identified at the beginning of the facility selection process including the accessibility for rail/road/water between the fuel cycle components. If there is any preference related to the fuel handling and preparation before storing the fuel in the AFR facility (such as spent fuel drying, inert gas filling and sealing of containers before placing in dry storage), it should be defined. Such preferences may also relate to the location where such activities are carried out, i.e. NPP sites versus AFR storage at a centralized facility site.

FIG. 7. Special crane for cask handling.

(1) AR operations

An important functional operation performed at reactor water pool storage facilities is loading of spent fuel into transportation casks (or unloading of spent fuel in some special cases) for shipping elsewhere. The packages used for transport of spent fuel are heavy, shielded casks which may or may not be filled with water. Spent fuel is loaded into the cask in the pool and the lid is placed before the loaded cask is to be taken out of the pool and follow a sequence of operations (such as draining and drying, sealing of the lid and bolting the cover, decontamination, etc as required). Careful preparation of the shipping cask for transportation has become an important issue, especially since the recent finding of cask surface contamination in Europe. As more spent fuels are stored for long term at dry storage facilities, the sealing of the lid on top of the canister (or basket) which is usually done by remote welding and /or cover with a metal gasket tightened by bolts, has also become a critical issue.

To address the technical issues in spent fuel loading under water at AR pool, some reactor designs (the 1 300 MWe and 1 400 MWe series PWR in France and in Belgium) have incorporated a technique of spent fuel loading under the pit of AR pool. The empty cask which is brought to the spent fuel bay is positioned on a transfer lorry, instead of being plunged into the pool, and the cask lorry is tracked to the funnel station under the spent fuel pool pit. After removing the cover, the cask is accosted under the opening of the pit bottom to assist the removal of the pit plug by a kind of shutter mechanism for spent fuel loading from above. The loaded cask is brought by lorry back to the funnel station where preparatory steps for shipping are taken. A large part of the operation are amenable to remote automation thus reducing operator exposure and possibly costs in a similar comparison with the dry unloading at T0 facility at La Hague" [20].

Licensed transportation containers are usually readily available from a variety of suppliers or can be readily developed to meet specific requirements if necessary. However, one must pay attention to docking arrangements and systems for handling of fuel from transportation containers. Depending on the type of fuel involved, containers may have to be customized in some cases. Leasing of these containers and subcontracting of transportation services are also available options for consideration

(2) Canister operation and maintenance

The increasing use of casks for dual purposes on one hand and ramifications of diverse storage casks with canisters on the other have also raised an issue of longer term consideration for the optimisation of the overall operation by use of a uniform container design which would be compatible with diverse package designs. The USDOE came up with the Multi-Purpose Canister (MPC) concept which is supposed to provide a standardization as required for compatibility of interface between different stages of the spent fuel management [20]. The implementation of this proposal came to an impasse, however, due to the absence of definition of disposal containers which is the terminal step of the MPC. Several vendors have nevertheless developed MPCs and applied licensing for possible use in the future.

One of the key requirements for the spent fuel management facilities is the strict containment of radioactivity that can be released in fission gases from spent fuel rods. Canisters are the most common method used as barriers for such containment, as it is widely used for management of defect fuel of AR storage. Depending on the requirement, the closure of a canister or cask can be effectuated by such mechanical method as clamping with packing, but welding is the most popular method used ubiquitously for canister, while the clamping/bolting method is used for cask closure for the inner lid. As a measure to enhance safety, the sealed canister is filled with inert gas most often with helium gas. All these operations involved in the closure of canister have to be performed remotely to minimize dose to workers.

As the welding of the canister opening with the cover, together with subsequent operations, is the crucial operation for interim as well as long term AFR storage, active developments have been pursued in the related industry. Highly automated welding systems for spent fuel canister welding are available in the market. Some technical problems associated with welding of canister closure in storage casks were reported in the US by USNRC inspection and appropriate corrective measures were taken [21].

(3) Remote technology applications in cask/canister operation and maintenance

Due to the heavy weight and large size of spent fuel casks, heavy duty handling facilities capable of accommodating at least a truck access are required at the reactor sites, interim storage facilities, reprocessing or disposal facilities. Although the cask surface is supposed to be within acceptable dose limits to the workers, there are on-going endeavors toward remote automation to minimize human access and work on the cask surface. Major equipment for remote automation of cask operation will include bolt/stud tensioners, robotic manipulators, alignment devices, etc. An illustrative example is the automated system for unbolting the outer lid of transportation casks received at the Sellafield reprocessing plant in UK. The routine work for cask decontamination and maintenance in spent fuel management facilities are additional areas that may be desirable to be remotely automated.

Some R&D efforts have been reported from USA (SNL) and ROK (KAERI) for automation of spent fuel cask handling with a view to enhance performance of cask operation and to minimize dose to operators (see 4.3.1)

2.2. REPROCESSING AND RECYCLE

Reprocessing of spent fuel by means of the conventional PUREX technology was the classical option of choice for almost all the Member States until mid-seventies having pursued recycle of plutonium in the form of MOX to be used in FBR. However, an increasing number of countries have shifted spent fuel management policy since the eighties from reprocessing to direct disposal for one reason or another. Countries belong neither to reprocessing nor to direct disposal have delayed policy decision with a ‘wait and see’ position.

While reprocessing has been commercialized in some countries where roughly one-third of the world inventory of spent fuel has been reprocessed, the general failure in commercialization of FBR had driven shift of MOX fuel use from FBRs to LWRs. Commercial use of MOX fuel in LWRs began in the eighties, with several plants for MOX fuel fabrication having been developed and built in Europe. The remote systems design for these commercial facilities have been based on contact maintenance concepts derived in several countries in Europe (France and UK).

Aside from the existing reprocessing and MOX fuel fabrication plants which have adopted contact maintenance approach, there have been several remote maintenance concepts developed for reprocessing facility. The full remote maintenance may find its way to application in the future, although there has been no commercial plant application of remote operation and maintenance.

2.2.1. Remote systems technology for commercial reprocessing

Reprocessing has conventionally been a major area of remote systems technology applications, due to the heavy requirement for operational and maintenance work to be performed for a large-scale radioactive plant. This means the maintenance concept in the design of the reprocessing plant is crucial to the successful performance of the plant with an important implication in the economics of the plant in operation.

Whereas there had been significant efforts in early period of nuclear energy development to develop remote technology for application to reprocessing (and MOX fuel fabrication) plants, the actual implementations at industrial scale had mostly been driven by cost-benefit considerations. Subsequently, most of the current reprocessing plants have adopted contact maintenance concept which has evolved with decades of industrial experiences. With the contact maintenance approach, the processes are installed in a number of separated hot cells so that each cell can be accessed for hands-on maintenance by workers after evacuating radioactive inventory. However, the actual applications of maintenance concept in reprocessing facilities are made selectively depending on a number of factors such as level of radioactivity.

A summary of major technical aspects associated with remote technology for commercial plants are as follows.

(1) Spent fuel receiving and buffer storage

A sequence of operation in reversed order of operation for the shipping cask at AR storage facilities (and similar to an interim storage facility like CLAB) is usually performed for the reception of transportation casks at reprocessing plants. Arrival of spent fuel shipped in transportation cask from AR or AFR storage facilities is subject to a set of checks required for the receiving. Cask surface is surveyed for detection of any possible contamination that has to be removed by decontamination. Casks are temporarily stored on site before unloading.

Traditionally, the largest scale AFR facilities for spent fuel storage have been built at the reprocessing plants as a buffer for reprocessing operation. This tradition is still valid until now, with the largest two facilities for spent fuel storage being at the two commercial reprocessing facilities, one at La Hague (14 000 tHM) and the other at Sellafield (6 500 tHM). These storage facilities are storing not only respective national deliveries, but also spent fuel imported from foreign countries for commercial reprocessing.

At these storage facilities handling large amounts of spent fuel, the automatic mode has replaced some of the manual mode of spent fuel operation obviously at extra investment but with good justifications. The La Hague plant has a big complex of spent fuel storage pools in which spent fuel operations such as spent fuel unloading, storage, transfer, measurement, are performed by remote automation including the maintenance work from the control station. An impressive example of total automation is, among others, the To facility, which was built for dry unloading of spent fuel assemblies received in a transportation cask. According to COGEMA (Compagnie Generale des Matieres Nucleaires), the gain in dose reduction achieved by this automation is six-fold, from 1.8 mSv/a down to 0.3 mSv/a with respect to the equivalent function of wet unloading in the manual mode at NPH facility [22]. Another example of remote automation at La Hague is the T1 and R1 facilities where spent fuel assemblies are retrieved from baskets by means of a tilt bridge for subsequent measurement of burn up. Comparable experiences at the Sellafield facilities, which have been in operation with many decades of experiences, were reported by BNFL (British Nuclear Fuel Ltd).

There are several other buffer storage facilities associated with reprocessing operation in the Russian Federation, Japan and China with varying degrees of automation and remote systems integration.

- The Japanese reprocessing facility at Rokkasho-Mura with 800 tHM/y capacity is now nearing completion expected in several years, and its storage pool with a capacity of 3 000 tHM has begun to receive and store spent fuel.
- The Chinese reprocessing facility in construction in Lanzhou has its storage pool built with a capacity of 540 tHM and received the trial lots of spent fuel transported in 2003 from Daya Bay NPP.
- The large storage pool facility of RT-2 plant at Zheleznogorsk (formerly Krasnoyarsk-26) in the Russian Federation there is an exceptional case in that it was built as a preliminary part of a large reprocessing plant for spent fuel from WWER-1000 model NPPs, which cannot be reprocessed at the RT-1 plant at Chelyabinsk (Mayak) plant because of some technical limitations. While the 6,000 tHM capacity of spent fuel storage pool at RT-2 is already half full, it has never been entailed by subsequent construction of the head- and tail-end parts of the plant due mainly to financing problem. On the other hand, a plan to build a large dry storage facility of vault type, with a capacity of 10,000 tHM and eventually expandable to 40,000 tHM, has been in preparation by Minatom for construction with a view to long-term storage of spent RBMK fuel. The new facility will be located in the granitoid massif in Kansk some 30 Km south of the existing facility.

In the USA, the Midwest Reprocessing Plant in Illinois was built in the seventies as a civil reprocessing plant, like the West Valley reprocessing plant which operated, but never commissioned due to technical problems. It has a buffer storage pool which has been in use for commercial storage of spent fuel now with an inventory of 750 tHM.

(2) Head-end operation

The head-end process is a preparatory part of reprocessing plants in order to make the spent fuel feedstock amenable to further separation processes using solvent extraction (PUREX technology) called tail-end treatment. It comprises such preparatory steps as removal of structural end-pieces, dissolution of pellet materials, and removal of cladding hulls, etc. As the spent fuel characteristics can be very different from fuel type to another depending on the reactor design and operation, technical feasibility of mechanical treatment of spent fuel is an important criterion for head-end processing at a reprocessing plant. Some fuel types could not be processed because of the physical constraints of some earlier reprocessing plants (the case of RT-1 at Chelyabinsk) or could be processed only after suitable refurbishments at the relevant head-end facility (HAO of UP2 at La Hague).

As the head-end operation is performed before any chemical separation of radioactive fission products, it is highly radioactive and thus requires extensive applications of remote technology, both for the process operation and maintenance. In the hostile radiation field, in-cell equipment systems are prone to failure because of the high duty required for the mechanical processes and associated control systems.

Remote operation for spent AGR fuel disassembly and pin consolidation for example has been reported to be large-scale applications for decades of remote technology as a preparatory step for head-end treatment for reprocessing at Sellafield. Separation of spent fuel rods to facilitate subsequent head-end operations was also considered for advanced reprocessing technology, in particular for FBR fuel reprocessing.

- Spent fuel introduction to head-end cells

After the storage, spent fuel transfer to head end process cells can be done by a variety of techniques depending on the design of the plant.

A conventional method has been to use a basket loaded with spent fuel assemblies to be slid up from the storage in pool to the dry cell by means of a ramp rail tugged with belt mechanism. For example, at the Russian RT-1 plant, remote-controlled vehicles on rails have been used to remove limited number of capsules, moving them to the next process. Automated cranes supervised from the control room move baskets of capsules to their next destination. Automated conveyor belts move capsules up from the pools for the next process at another facility. Remote operated buggies move designated number of capsules to the drying room at another facility.

More recent developments include dry unloading through a transportation opening in the plughole of the hot cell floor of the head-end hot cell, a method used at To facility of La Hague reprocessing plant. Spent fuel assemblies are lifted up by a telescopic mast crane into the hot cell from the cask mated up to the floor of hot cell from which a shielding plug is to be removed. Such unloading method is fully remotized operation requiring standardization of the cask design and has many automated features in the remote operational procedure which can reduce dose rate to the operators.

- Shearing

Spent fuel assemblies are usually not suitable for direct treatment in terms of size, weight, and form for the dissolution of uranium pellets by acid leaching. The long LWR fuel assembly needs to be cut to size in order to get the pellet inside the cladding exposed to boiling acid for leaching in the subsequent dissolution process. Among the various technologies developed for the cutting operation, shearing is the most widely used in the commercial plants today. The shearing rig is a rugged design and construction to minimize mechanical problems such as wearing or breaking of blades, etc. To facilitate the remote maintenance for the shearing system, the design of machines for the shearing system uses parts easily replaceable by means of the remote maintenance system.

- Dissolution

After mechanical preparation of the spent fuel, the spent fuel feedstock is usually sent to the dissolver where strong acid is used as the dissolvent. In large reprocessing plants, the spent fuel rod segments from shearing falls into a basket, with perforated wall, to be submerged into dissolver vessel. Once the dissolution is complete, the dissolution basket with cladding hulls left over from the dissolution is taken out of the dissolver vessel to be sent to rinsing process. Due to the highly hostile conditions including the need for handling pieces of spent fuel rods cut to sizes by a mechanical process, the heating process involved, and strong acid boiling in the highly radioactive solution, the dissolution is one of the most failure-prone processes in the reprocessing plants. The dissolver basket is prone to corrosion or erosion and needs replacements [23]. The dissolver vessel needs repair for any defect that may develop through continued operation. Careful engineering is required for both operation and maintenance provisions of the dissolution and associated processes.

A technical innovation to enhance the speed of dissolution process is the rotary-type equipment developed and used at La Hague plant. Spent fuel rod pieces are poured semi-continuously into a chain of buckets rotating around a shaft assembly in the dissolver vessel. The cladding hulls left over in the buckets after dissolution are poured out of the dissolver vessel in tune with the rotating of the assembly. In case of maintenance, the bucket assembly can be taken out of the dissolver vessel by removal of the vessel lid.

A well-known example of remote technique applications in the head-end part of reprocessing plants is the remote inspection and maintenance operation to repair the dissolver at Tokai-mura reprocessing plant. A radioactive leakage occurred in one of two dissolvers of Tokai Reprocessing Plant at JNC Tokai-works, Japan in April 1982 and the similar leakage occurred in another one in February 1983. JNC examined the leaked dissolver and planned to make repair using a remote weld device. After examining the weld repair condition, the design of devices, manufacturing and a mock-up test, the repair work of the dissolvers started in September 1983 and was completed during period of two and a half months [24]. Another example is the more recent repair work performed at the La Hague plant, making use of a specially designed and built remote controlled system. In this context, it was a similar work previously conducted at Tokai Reprocessing Plant in Japan in the eighties. The repair work included request for authorization from safety authority, fabrication of remote intervention system, examination of defective spot, and welding of the problem spot. The task was successfully accomplished with 18 months of work involving various specialists from concerned bodies like CEA, COGEMA (now AREVA), and machine companies [25].

- Handling of solid wastes

The wastes arising from head end processes are mainly of the solid type (with the exception of off-gases arising from dissolution of spent fuel pellets by nitric acid) that has to be disposed of after appropriate treatment. These wastes include the structural materials of spent fuel assemblies, cladding materials (hulls), debris or fines from shearing, residues from filtering or rinsing of solid wastes. These solids are containerized with or without preparatory treatment like super compaction, depending on the processes, before being mixed with cement in a standard size drum for disposal.

As these solid wastes are moderately radioactive classified as medium level waste (MLW), the treatment and handling operations are performed in shielded hot-cells equipped with remote systems similar to high level waste.

(3) Tail-end operation

Once the spent fuel feedstock is transformed into solution by dissolution, the subsequent fluidic processes, collectively called tail end in the PUREX reprocessing, will be performed by unit operations with such equipment as contactors, tanks, and pipelines, etc. The tail-end processes includes as a major function the chemical separation of fission products to be removed as radioactive wastes, from the fissile material (plutonium and uranium) to be recycled for reuse.

As the tail-end processes involve little mechanical operations, the equipment is not as prone to mechanical failure and the extensive provisions for remote maintenance required for the head-end part are not considered in the industrial reprocessing. Instead, technical problems resulting from chemical exposure do happen for which contact maintenance is usually adopted for industrial reprocessing plants, especially for those processes with lower radioactivity content at the later steps of the tail-end processes. In the case of contact maintenance, workers get into the hot cells for necessary repair work on the process equipment after evacuating the radioactivity holdup in the process equipment and decontamination of radioactivity on the surfaces of the equipment and the hot cell. For some equipment that requires extensive repair work, the whole unit is replaced with a new one depending on the efficiency of the work. In order to facilitate such removal/replacement work, remote connector technology had been used at several plants, for which the process equipment is modularized for easy mating with the process line in the hot cells.

(4) Vitrification of HLW solution

The bulk of radioactivity separated from reprocessing plants is the highly radioactive solution arising from the first extraction cycle of PUREX process. The high radioactivity solution is stored in buffer tanks provided with cooling system. Because of the liability of leakage from the storage tanks, the liquid waste has to be solidified for disposal after an interim storage. Among the methods developed for the solidification of HLW solution, the most widely used process technology for industrial reprocessing plants is vitrification. Although there are some differences in the process for vitrification being used depending on the reprocessing plants, the technological requirements for remote systems application to the vitrification and associated systems is essentially the same. Main processes involved in the vitrification plants are:

- Feeding of HLW solution
- Glass melting
- Off-gas treatment
- Vitrified canister handling

The representative development in vitrification technology making use of continuous process was achieved by the Atelier de Vitrification à Marcoule (AVM) plant which was commissioned in 1978 in service to UP1 reprocessing plant at Marcoule in France. The AVM used calcination process for feed treatment in preparation for glass melting in induction furnace from which vitrified waste are poured into standard HLW canister. The technology was later used for larger reprocessing plants like UP2/UP3 plants at La Hague [26] and Thorp plant at Sellafield [27]. Extensive effort was exercised for the development of remote systems engineering of the AVM in which all the in-cell process equipment were able to be operated and maintained remotely, without any human intervention in the hot cell enclosure.

Another case of developmental programme for remote maintenance of HLW vitrification plant was implemented in Japan. JNC has adopted a full remote maintenance concept for the Tokai Vitrification Facility and Recycle Equipment Test Facility in Tokai Reprocessing Plant. This remote maintenance concept includes a Two-arm Bilateral Servo Manipulator system, in-cell crane and rack system in a large cell. On the other hand, Advanced Robot Research Association has carried out the Advanced Robotics Technology project from 1983 until 1990 for further basic technical development. In this project, total concept for robot and control system was investigated and some demonstration systems were manufactured based on this concept. As the result, many robotics technologies were developed and basic technologies for future development of remote technology were established (see Annex II).

A prototypical development for vitrifcation of HLW was conducted in the eighties at the Eurochemic pilot reprocessing facility located at Mol in Belgium by contractual support by DWK with a view to application to the Wackersdorf reprocessing plant of which construction in West Germany was in preparation [28]. After a couple of years' tests for the vitrification using PAMELA process at Mol and large scale mock-up test at Fernhantierte Modultechnik (FEMO) facility in Lahde/Hannover in Germany for benchmarking of remote maintenability, the programme had come to a halt due to the canceling of the Wackersdorf reprocessing plant. An annex facility for vitrification of high level waste at Lanzhou pilot reprocessing plant in China is reported to have applied the PAMELA process [29].

A special case of HLW vitrification for civil reprocessing of spent fuel is the West Valley Demonstration Project (WVDP) in the USA. The WVDP is a demonstration project for decommissioning of the reprocessing plant of Nuclear Fuel Services which was shut down in the seventies after having reprocessed 194 MT of spent fuel from various NPPs in the US, including vitrification of high level waste solution left over from the reprocessing operation. The vitrification technology used at WVDP, called Slurry-Fed Ceramic Melter (SFCM), was based on the process developed at Pacific Northwest Laboratory (PNL). The WVDP started in early eighties for construction of vitrification facility which started operation in 1988 and has recently completed the required mission of vitrifying 600,000 gallons of HLW into 275 canisters [30].

2.2.2. MOX fuel fabrication

Compared to fresh fuel, fissile materials recovered from reprocessing (by PUREX process) retain some radioactivity, which requires protective measures against radiation and remote manipulation techniques for fabrication into a new fuel to be recycled to reactors in the form of mixed oxide (MOX) fuel. Depending on the radiation protection requirements, appropriate remote systems technology is selectively used in the design and operation of such facilities.

The radiation level of fissile materials to be recycled usually in the form of MOX is such a weak level that glove box type of shielding (and containment) is adequate for fuel fabrication facilities. As worker's manual access to the process line is possible with the gloves at the MOX fuel fabrication facility, rather than using manipulators, semi-remote mode of work are widely adopted for operation and maintenance of the MOX facilities, especially for the processes involved in the bulk material handling for pellet production. Once the pellets are sealed inside a fuel rod and the outside surface of cladding tube decontaminated of traces of plutonium, the MOX fuel rods can be handled outside of an enclosure. But the handling of the MOX fuel rods or assembly may still require restricted contact work due to the possible radiation from actinides.

Although there have been a host of small laboratory or pilot scale MOX fuel fabrication facilities, only a few commercial plants have been built to date, i.e. MELOX in Cadarache (France) and SMP in Sellafield (UK). Most of the others which were developmental ones for MOX fuel for FBRs, have been shutdown or decommissioned, a representative example having been the prototype process line in the FMEF in Hanford which integrated a lot of advanced remote technology and automation features for fuel fabrication. It was shutdown in the eighties with the USDOE decision to discontinue with the FFTF program [31].

A MOX fuel fabrication built at Hanau in Germany by Siemens/KWU is known to have incorporated the most recent technical features of remote technology and automation.

However, the plant has never been operated due to the political decision taken in Germany and disposition of the plant has been sought. It was reported in the media that there is an on-going deal to sell the equipment to be salvaged from this plant to CNNC in China [32].

2.3. SPENT FUEL CONDITIONING AND PACKAGING

Spent fuel needs appropriate conditioning and packaging for safe storage or disposal. Extensive research and development efforts have been extended over a couple of decades in several Member States to implement a spent fuel disposal policy. Some other countries are conducting R&D on spent fuel conditioning and packaging for long term storage in mind. The method of conditioning and packaging is not only a function of the design concept for the repository or storage facility, but also a variety of other factors such as regulatory, economics, public acceptance, etc.

From the standpoint of spent fuel integrity, there are three kind of conditioning and packaging methods considered; intact fuel assembly, rod consolidation, destructive compaction. The scope of the last option, destructive compaction, may be extended in a sense to the partitioning and transmutation, which has been attracting interest (see 4.2.3).

2.3.1 Intact fuel

The simplest among the methods for conditioning and packaging spent fuel is to keep the spent fuel assembly intact, as adopted by the majority of disposal programmes such as in the USA, Sweden, Finland, etc. One or multiple number of spent fuel assemblies is placed in the canister which is usually considered as a further barrier, in terms of radioactivity release, in case of leakage through spent fuel cladding.

The conditioning and packaging operation for spent fuel, as a preparatory step for permanent disposal or long term storage, will also require substantial application of remote technology. The representative case for intact fuel conditioning and packaging is the Swedish programme for spent fuel disposal. The concept developed by Swedish Nuclear Fuel and Waste Management Co. (SKB) plans to use a copper canister packaging to provide corrosion resistance to underground humidity for hundreds of years. The cylinder type package accommodates 12 spent fuel assemblies from BWR and 6 from PWR within its graphite iron basket fitting in the copper canister, totaling 25 to 30 tonnes with a dimension of 1 m diameter and 5 m length.

A critical process of the encapsulation is the welding of the copper canister followed by non-destructive tests for quality examination. The most promising technology for welding the copper canister was found to be electron- beam welding at reduced atmospheric pressure. The fabrication of copper canisters of the size required by the SKB is by no means a trivial technology, although full-scale canisters have been manufactured and tested. A recent research conducted in France on encapsulation of intact spent fuel from PWR for very long term storage (over a century to several centuries) proposed an additional layer of barrier which is I effect a basket sealed with a set of 7 canisters each encapsulating a PWR assembly [33].

All these processes involved in the conditioning and packaging have to be carried out remotely in a hot cell enclosure.

2.3.2 Rod consolidation

During the latter half of the eighties, there had been some interest prompted by the technical possibility of spent fuel rod consolidation as a method to compacting the spaces between fuel rods by removing structural materials of the assembly. First construed for AR storage capacity expansion, the techniques used in the fuel inspection, repair, and reconstitution had also been applied to demonstration programmes of spent fuel rod consolidation conducted in storage pools in the USA during the late eighties. Some experimental and demonstration programmes were initiated later in the U.S. and in several other countries for some other applications, for instance, for compact conditioning of spent fuel in preparation for disposal [34].

The technical features of rod consolidation is similar in some respect to the head-end processes of reprocessing spent fuel from AGR type reactors at Sellafield reprocessing plant in UK where the cover sheath structure of spent AGR fuel is removed to facilitate the subsequent process of dissolution (see 2.3.1). The technical concept for reprocessing of FBR spent fuel also involves some process for mechanical removal of structural materials from the fuel assemblies.

(1) Removal of structural materials

In order to get rods released from the spent fuel assembly, the structural materials (skeleton, end-fittings, etc.) — which are collectively called Non-Fuel Bearing Components (NFBC) in the USA — have to be removed by some suitable method.

As a first step, the end-fittings have to be removed from the spent fuel assembly to get the tip of individual fuel rods exposed for extraction work. The actual removal can be accomplished by either cutting the control rod shafts accessible through the gap between fuel rod tips and the end fitting on either side of the assembly, or mechanical unfastening of one or both sides' end-fittings of the assembly.

(2) Rod extraction

After removal of end-fitting(s), pulling out the fuel rods, one by one, or a multiple of them in a bundle, can be accomplished with a suitable gripper device (called collet) that engages to the tip of fuel rod(s) to pull it, and therewith can extract by pulling the fuel rods out of the grid structure assembly.

(3) Reconfiguration of fuel rod array

The separated fuel rods can be reconfigured into a compact triangular pitch array, from the square pitch of the fuel assembly. The reconfiguration can be done by means of a suitable device, which can be a funnel, trough (orientation by vibration) or a series of spacer grids with changing hole pitch.

(4) Encapsulation of rods

The consolidated rod packaging step involves the equipment necessary to insert the individual fuel rods into the storage/disposal canister. This can be accomplished by continuous handling mechanisms that feed the fuel rods through the transition funnel or trough device directly into the canister. It can also be accomplished in a stepwise manner by inserting the fuel rods into the canister individually or in a bundle.

(5) Handling of structural materials

The structural materials (NFBC) arising from rod consolidation can be processed by appropriate treatment methods including volume reduction, placement into a container, and moving to storage for further treatment. This additional burden to treatment and disposal of NFBC to be entailed by choosing option of rod consolidation was one of the disincentives to implement rod consolidation despite the 2:1 compaction ratio achievable for further compact storage of spent fuel.

(6) Off-normal rod handling

The off-normal rod-handling step consists of retrieval, transfer, and preparation for storage of stray rods or portions of broken rods that are encountered during the rod consolidation process.

2.3.3 R&D status of conditioning and packaging

(1) Germany

Those countries pursuing direct disposal of spent fuel have been developing technologies required for design, construction, and operation of spent fuel conditioning and packaging facilities along with the spent fuel repository. A prominent example of technical development for spent fuel conditioning and packaging has been reported by Germany with its pilot conditioning facility called Pilotkonditionungsanlage (PKA), which was built, at the Gorleben site to demonstrate industrial feasibility of the German concept for disposal of spent fuel packaged in the POLLUX cask. This pilot plant integrated state-of-the-art remote technology features both for the spent fuel processes and maintenance systems [35]. The construction of the PKA facility was completed in 1998, but since then has been put in stand-status by the policy decision taken by the new German Government.

(2) Sweden

Sweden has a much advanced stage of implementing the programme for spent fuel disposal and the responsible body is Swedish Nuclear Waste Management Company (SKB), which has already designed an industrial level encapsulation plant to be built as an extension to the interim storage facility of wet type CLAB. A laboratory for testing the critical processes has recently been built in support of the programme. Major processes of the encapsulation include preparatory conditioning of spent fuel, loading into disposal canister, seal welding (by electron beam) and finishing of the canister. A key technology in the encapsulation process is the seal welding to be performed by electron beam welding, but an alternative technique by friction stir welding is also being developed [36]. The encapsulated package is to be thoroughly examined by radiography by linear photon accelerator, complemented by non-destructive testing of the by ultrasonic inspection with phased array matrix scanning. This sequence of processes is performed in hot cell complex, which will have to be integrated with all the necessary remote technology operation and maintenance functions.

(3) United States of America

Representative projects for development demonstration of rod consolidation technology for the purpose of conditioning spent fuel in preparation for disposal were conducted by USDOE for the Dry Rod Consolidation Program (DRCT). The DRCT was a rod consolidation test project conducted in the dry mode at the Test Area North (TAN) facility at the Idaho National

Engineering Laboratory site where 48 PWR assemblies were consolidated into 24 canisters. The DRCT exercise was followed by Prototypical Rod Consolidation Demonstration Programme (PCDP) [37]. Even though most of these test projects were terminated in the early nineties without any further implementation on an industrial scale, they provided valuable technical experience associated with spent fuel management requiring elaborate remote technology applications.

The USDOE has been developing a technical concept for a massive process system for packaging large amounts of spent fuel as required by Federal Waste Management System for the US disposal programme. In the current design of the surface facility, the primary function of the Waste Handling Building (WHB) is to receive casks of both spent fuel and HLW and transfer them to disposal containers to be sealed by welding leading to a final disposal package for delivery to a sub-surface system. For the integration of remote technology in the WHB, extensive analysis by engineering simulation have been performed to identify the dose constraint for the workers as well as the performance of the process and maintenance systems (see annex, US Country Report).

With the recent designation of the Yucca Mountain site as a proposed repository for the disposal of commercial spent nuclear fuel work is proceeding on the design of surface facilities to receive, unload, and package the waste into waste packages for emplacement in the repository [38].

Work is also underway to develop a remote-controlled system to close spent fuel containers, called Waste Package Closure System, to be built and tested at INEEL site, in Idaho, parting this year 2004 [39].

(4) Remote technology applications in rod consolidation

The rod consolidation equipment that has been developed in the past has different levels of automation and robotics applications. Each system has distinct advantages and disadvantages depending on the facility within which the process will be performed.

As the rod consolidation involves a series of mechanical processes for dismantling of spent fuel assemblies, collection of fuel rods and encapsulation, and waste compaction and packaging, etc, to be performed in a hot-cell environment, it is an area of extensive application of remote systems technology both for the operation and maintenance of the process and associated systems. Application of those technical elements used at reactor sites has been extended to the development of some projects for spent fuel rod consolidation which have been challenging examples of remote technology application to spent fuel management with potentials to wide applications in storage and reprocessing or disposal of spent fuel in the future. For some operations like fuel inspection and reconstitution which are usually carried out in the temporary storage pools at reactor stations (see 2.1.1), many technical features relevant to remote handling systems are required in the equipment development, operation, and maintenance.

2.3.4 Destructive conditioning methods

While the previous two options (intact fuel assembly and rod consolidation) pursue maintaining the fuel cladding integrity as a containment barrier against leakage of radioactivity, it is possible to imagine some methods for conditioning the spent fuel by destructive processes with a view to make in a better package or to gain benefits in the overall optimization of fuel cycle back end.

(1) Cutting of spent fuel rods

Various cutting machines perform remote cutting of fuel rods for later processing and encapsulating. The PKA facility at Gorleben site has a provision to cut the consolidated fuel rods into half-length for packing them into the disposal cask POLLUX [40].

Examples of cutting machines are the shearing machine that used dozens of different units, the main one being the knife that cuts the fuel into small pieces of given sizes. Another cutting machine uses a high-speed steel circular saw that cuts the fuel into smaller sizes. Both of the above machines are of the automated types. Another cutting machine uses a laser to slice the fuel to precise sizes; this method uses the man-in-the-loop process.

(2) Reduction of oxide fuel into metallic package

An ultimate method of spent fuel conditioning with minimized volume (and decay heat or radioactivity, in that matter) for storage or disposal would involve pyrometallurgical type of processing of spent fuel pellets. Some R&D activities are being conducted in the USA and ROK with a view to come up with a dense package by metallization process. The conceptual study conducted in the R&D in ROK reported some quadruple or quintuple reductions in heat and radioactivity by the conditioned packages in comparison with the intact spent fuel assemblies. [41]

Extensive applications of remote technology will be required in this type of spent fuel conditioning operations, due to the bulk processing of highly radioactive materials.

2.4. MODIFICATIONS TO FACILITIES

Any of the spent fuel management facilities may undergo refurbishment during its lifetime due to modifications required to facilities. The need for modifications may arise various reasons: to enhance facility function, economics or safety, change in regulatory standards, etc. Some common modifications to improve facility function include changes to allow such functions as [42]:

- Storage of higher burnups or enrichments or of different types;
- Improvements to spent fuel or cask handling capability;
- Additions of spent fuel treatment or conditioning systems;
- Improvements of pool water treatment or cooling systems;
- Improvements in structural constructions or seismic provisions.

Whatever the motive of the modification is, the facility should maintain the applicable safety criteria required for normal operating conditions, anticipated operational occurrences and design basis accident conditions for the lifetime of the facility. The implementation of modification may involve the following steps:

2.4.1. Feasibility assessment

Before starting a modification, a feasibility assessment is to be made to see the cost/benefit justification and an initial safety evaluation. For the safety assessment, a systematic analytical approach (failure mode and effect analysis) would be necessary to determine whether the modification would bring any safety impact and to check it is compliant with the regulatory conditions as approved for the facility design and operation. If appropriate, it should be reviewed by an independent safety expert. This assessment should consider the modification implementation phase as well as facility operation after its installation.

Depending on the initial safety assessment, a more detailed and comprehensive safety assessment may be needed. The extent and complexity of the additional assessment required will depend on the nature and extent of the safety impact of the modification which would fall on one of the following categories:

- Little or no safety impact within the defined safe operating limits and conditions for the facility. For this category, the licensee will generally make the decision based on the initial safety assessment.
- Significant safety impact, but not sufficient enough to require a change in the licensing basis for the facility. For this category, the licensee should prepare a detailed safety assessment and not proceed with the work until the results of a detailed assessment have been accepted by the regulatory authority.
- Serious safety impact that require a change in the license or a new licence for the facility. For this category, the detailed safety assessment will usually be subject to a formal licensing procedure by the regulatory body before acceptance and implementation.

2.4.2. Implementation of work

Having applied the necessary controls to categorization and authorization, the implementation of work needs to be subject to rigorous control. The structured consideration of the following factors is a key element in ensuring that adequate thought, assessment and control of the work are achieved:

- Exposure to radiation;
- Radioactive waste management, including transport, decontamination, and dismantling as applicable;
- Provisions required to minimize the spread of contamination;
- Safe operation of the facility during the modification period;
- Industrial hazards such as high voltage, fire, use of chemicals/explosives.

Consideration should be given to the need for special temporary emergency procedures in cases where potentially hazardous situations have been identified in connection with the facility conditions during the installation.

The safety of an implemented work should be verified through a testing programme which involves checks, measurements and evaluations prior to, during implementation, and at the completion of the modification. The completion of the project must include a check that all temporary connections, procedures, arrangements, etc. that were necessary for implementation have been removed or cancelled and the facility has been returned to full operational status. Confirmation of all aspects of completion of the implementation is important: i.e. drawings have been updated, procedures and instructions amended and any necessary training delivered. The commissioning report should cover all of these aspects.

2.4.3. Remote technology for facility modification work

The applications of remote technology in facility modifications are akin to dismantling of a part of existing facilities to replace with a new functional equivalent or additional function(s) to be built as required for the modification. In this regards, much of the work involved in the facility modification would share the implementation procedures associated with decommissioning on the one hand, and construction of additional facilities on the other. However, the interface between the two disparate types of work is a very important factor, which is applicable to neither the former nor to the latter.

The actual work to be performed by means of remote technology would of course be very much dependent on the type and design of the facility where the modification work is required. In the case of the common facility like spent fuel inspection and repair system, which might be required as an add-on function, design modification would have to give due consideration to:

- Radiological safety of the additional system to the operator;
- Potential for malfunction or mishandling of the equipment or subsequent rupture of the fuel under work and appropriate measures to recover or mitigate the consequences (e.g. underwater gas collection and local water purification systems, appropriate sealable tubes for failed fuel, etc.);
- Potential for damaging the inspection equipment due to routine operation of the storage facility (i.e. collision of fuel handling machine with the additional inspection machine installed);
- Potential for dropping of both fuel and equipment during remote handling.

Much of the work for facility modifications have common features with decontamination and decommissioning. Aspects of which have amply been covered in the relevant literature.

2.4.4. Dismantling of facilities

An area of remote technology application, which has been gaining importance in recent years, is the decommissioning of obsolete nuclear facilities of which requirement is continuing to grow with the aging facilities are due to retirements. In terms of workload, nuclear power plants represent by far the largest decommissioning challenge by the number and complexities of work. The first step for decommissioning of a nuclear power station is to remove spent fuel which represent the majority of the radioactivity inventory in the station in order to facilitate subsequent activities. The removal of spent fuel from the nuclear power stations would involve those remote technologies used for most of the spent fuel assemblies and cask operations discussed above (see 2.1.3).

Decommissioning of nuclear facilities other than reactors (mainly fuel cycle facilities) bears some distinctive technical features as well as many similarities with respect to those pertaining to reactors. The global status of decommissioning fuel cycle facilities, including spent fuel management facilities, are reported in the recent IAEA publication on decommissioning of nuclear facilities other than reactors [43].

Among the spent fuel management facilities, spent fuel reprocessing facility requires the most extensive involvement of remote technology for decontamination and dismantling work to be performed in radioactive environment. France reported the decommissioning of some old facilities including the UP1 reprocessing plant, which was closed in 1998. The French estimation of remote technology usage in the dismantling of the Marcoule plant is around 20 % of the total workload, but it might reach up to 50 % in some special cases. UK reported a similar experience from the decommissioning work of B204 plant at Sellafield, which was mothballed in 1973. There are a host of laboratory or pilot scale reprocessing facilities being decommissioned or to be decommissioned in the future [44].

In the actual harsh environment of dismantling, advanced type machines will have reliability problems and selection of appropriate technology would be critical for the successful performance of required work. Special attention is needed to take care of possible consequences from equipment failure during active work and recovery methods with economic and dose justifications

3. METHODOLOGY FOR APPLICATIONS

The special features associated with the remote systems technology for handling radioactive materials used to be dealt as 'special techniques' of nuclear engineering discipline. The methodology for applications of remote technology to spent fuel management includes a variety of technical requirements and criteria which are by and large common to other radioactive materials. Due to the variety of technical applications, the approach is very often specific to each task and it is in general hard to derive general methodology.

Compared to the large number of papers reporting on specific applications of remote technology to remote handling of radioactive materials, mostly on facility or equipment development, there is little publication which provides integral guidance on the remote technology applications addressing spent fuel (or radioactive waste) management. A unique exception in this regard is the design guides published by the Remote Systems Technology Division (RSTD) of the American Nuclear Society (ANS). The Design Guides of the ANS covers the following technical topics [45]:

Guide No.1 General Criteria

Guide No. 2 Shielding Wall Service Penetrations

Guide No. 3 Direct Viewing Windows

Guide No. 4 Access Doors and Transfer Devices for Personnel and Equipment

Guide No. 5 Illumination

Guide No. 6 Manipulators, Auxiliary Tools, and Remote Handling Devices

Guide No. 7 Atmosphere Control and Heat Removal Systems

Guide No. 8 In-Cell Utility Requirements

Guide No. 9 Fire Prevention, Detection

Guide No. 10 Wall Finishes, Protective Coatings, and Liners

Guide No. 11 Operations & Maintenance

Guide No. 12 Decontamination and Decommissioning

The publication of the ANS has been the major source of technical information through the series of proceedings of Topical Meetings on the subject. There are several other publications from other international and national organizations such as European Nuclear Society (ENS), British Nuclear Engineers Society (BNES), etc.

Another notable reference in the literature which provides a comprehensive overview of remote technology and robotics covering various areas of applications, including not only nuclear but also a variety of other areas, is the book by Vertut et al [46].

3.1. BASIC REQUIREMENTS FOR REMOTE SYSTEMS DESIGN

The application of remote technology in radioactive environment is closely related with relevant safety implications subject to national / international regulatory requirements for radiation protection from the radioactive sources. The IAEA Basic Safety Standard provides design requirements for radioactive facilities [47]:

- based on sound scientific and professional principles and criteria;
- based on the results of an optimization analysis, where appropriate, wherever required and to the extent possible, using defence-in-depth procedures;
- to comply with codes and standards;
- to be constructed and tested to quality standards commensurate with their protection and safety objectives;
- to minimize, wherever applicable, the production and accumulation of waste materials;
- to ensure that exposures when the generators and equipment are not in use are minimized;
- to ensure that leakage of any radioactive substance under normal operating and adverse conditions is prevented from any sealed source of radiation or any article containing or embodying radioactive substances;
- to appropriate engineering, performance and quality specifications, in order to ensure that the sources and equipment in their intended situations of use provide protection and safety that is consistent with the principles of the system of protection and safety of these Standards, including, in particular, design and construction to any defined protection and safety or reliability targets;
- to operate under the environmental conditions that would be expected to exist when they are required to function;
- based on sound ergonomic principles so as to facilitate operator use or of equipment, to reduce the possibility of operator error leading to accidents and unnecessary exposure, and to reduce the possibility of an operator misinterpreting indications of abnormal conditions;
- to ensure that inspection and testing appropriate to the preservation of the protection and safety aspects can be carried out without undue exposure of workers, and that remedial measures can be readily implemented in the event of an accident;
- incorporating means for detecting errors in operating procedures that might contribute to accidents and for correcting or complementing for them.

The IAEA standard also gives a guideline on safety features by redundancy and diversity on radioactive facility design, consistence with the defence-in-depth concept in order to prevent events that might cause potential exposure and mitigate the consequences if such events occur. Where redundancy is necessary, the redundant safety featured, being independent each other such that failure of one does not result in failure of the other.

There are several publications also from OECD/NEA on the safety of nuclear fuel cycle facilities. [48]

3.2. APPROPRIATE APPLICATIONS OF REMOTE TECHNOLOGY

Remote technology as applied to spent fuel management can be distinguished in two distinctive features: one pertaining to process operation and the other pertaining to the 'intervention' type of operations for maintenance of operation in normal or off-normal conditions. The former is in general more amenable to automation while the latter are apt to tele-manipulation type of work as has most often been implemented with the man-in-the-loop concept and used in most of the hot-cell facilities. For highly structured processes requiring many repetitive motions, hard automation of simple and robust designs with fewer degrees of freedom is preferred to more sophisticate ones with higher degrees of freedom, which are usually more prone to failure.

The issue of major concerns for remote technology applications is the contingency measures for intervention in case of system failures, not only of the process systems but also the maintenance systems themselves inside radioactive enclosures where human intervention is difficult or impossible. For such preventive measures, tele-operations and tele-robotics would best replace human intervention for the maintenance and repair work to be done in the hostile environment. In the current state of affairs, however, actual uses of advanced robotics has been very limited so far, due to such problems as reliability, lack of experience, etc.

In the preceding discussions it becomes clear that every application of remote technology in spent fuel management is unique and in most cases it is not possible to describe an entire solution. However, there are elements from existing solutions that might be used to compose new applications which must be tailored with regard to the special conditions. Every application of remote technology is unique and in most cases it is not possible to copy an entire solution. However, there are elements from existing solutions that might be used to compose new applications which must be tailored with regard to the special conditions.

3.2.1. Types of remote control systems

Hot cells for the nuclear energy development have been one of the primary applications areas for teleoperation systems, because of the hazardous radioactive environment involved. A classical example of tele-manipulator as was publicized in the press during the peak era of nuclear technology development can be glimpsed by the cover page picture of the German magazine Der Spiegel [49].

FIG. 8. Photograph of tele-manipulator on the cover page of Der Spiegel.

Apart from the teleoperators, a number of other tools and devices have been applied to nuclear facilities and with the development of industrial robotics the non-nuclear applications have been merged with teleoperation technology of nuclear origin.

Hot cells for the nuclear energy development have been one of the primary applications areas for teleoperation systems, because of the hazardous radioactive environment involved. Apart from the teleoperators, a number of other tools and devices have been applied to nuclear facilities and with the development of industrial robotics the non-nuclear applications have been merged with teleoperation technology of nuclear origin.

- Hard automation includes all automatic machinery that is built for specific purpose. Optimized for a specific task prior to installation, hard automation usually performs its task reliably. Such machines are not programmable and can only be reconfigured by physical re-arrangement and manual settings. Examples discussed include automatic fuel handling and loading machines in the Russian Federation and the USA, and cutting and grinding machines in India.
- Telemanipulators are mechanical or electromechanical machines (e.g. master-slave manipulators) directly controlled by human operators to perform a task at a distance. A telemanipulator is often composed of a master arm and located in the operator side and the other side of the manipulator ('slave' arm) located in the working enclosure, from where information (visual, sound, force, etc.) is fed back to the human operator who controls the master arm linked to the slave manipulator. At hot-cell facilities, a pair of master manipulator arms are usually installed to match with human arms (both right and left) of the workers.
- Telemanipulators are generally more complex and expensive than manual tooling, require periodic maintenance, and are potentially less reliable than manual tools. However, over 50 years of continuous use and improvement has proven telemanipulators generally reliable. A large number of telemanipulators are in use at a variety of nuclear facilities around the world.
- A telerobotic system is capable of performing either a bi-lateral mode (between the master side and slave side, like the telemanipulator) or in a unilateral mode from the master side to the slave side (like the electro-mechanical or 'power' manipulator). In the latter case, the end-effector trajectory and force/impedance of slave arm are determined by computer command rather than master arm inputs. The advantage of this unilateral mode is to perform repetitive tasks by automated program thus to avoid the operator intervention in the loop.
- Robotic machinery has been used primarily in production modes and structured environments, usually for material movement between processes. Examples presented include fuel production and dismantlement in India and the USA, and automated inspections and fuel reconstitution in Germany. Robotic machinery has also been installed at reprocessing facilities in France and the UK.

Force reflection refers to the capability of reflecting the external force experienced by the slave side to the master side and is typically described as bilateral control. Applications of force reflection systems are often hindered by radiation effects on electronics or control medium like hydraulics which suffer sometimes with seal degradation. More recently, advances in equipment and control capabilities have enabled design of flexible robotic systems for unstructured environments and off-normal event recovery. Specifically, the convergence upon telerobotics has put the human into the robotic control loop. Telerobotics refers to computer-assisted manual operations, or conversely, manually-assisted computer operations. This combination allows a human operator to concentrate on the task without concern for the operating details, resulting in potentially faster and safer execution of operations in difficult environments.

Robotic systems can be significantly more complex than telemanipulators, raising reliability issues and questions of radiation tolerance. In the past, robotic systems were primarily programmed by laborious teach-and-repeat methods, operating thereafter in autonomous mode. This has not been conducive to application beyond the production facility. Further, capital expense of robotic systems can be significantly higher than manual and teleoperated tools. However, operational experience in France and systems analysis of future US facilities have shown that robotic systems can have substantially lower operating costs than manual operation or telemanipulation, while increasing speed and safety. This operational cost reduction can offset capital costs, in some cases quickly.

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3.2.2. Remote maintenance in hot cell complex

Hot cell complex handling high radioactivity in contaminated environment is usually provided with adequate equipment systems for in-cell operation and maintenance (such as overhead crane, manipulators, CCTV, etc.). For the maintenance of the remote equipment, some service areas are usually reserved for the required work, including a crane maintenance cubicle at the upper side of the hot cell, a maintenance room for decontamination and repair of manipulators and other remote control equipment, waste collection and evacuation area, etc. (Fig. 9).

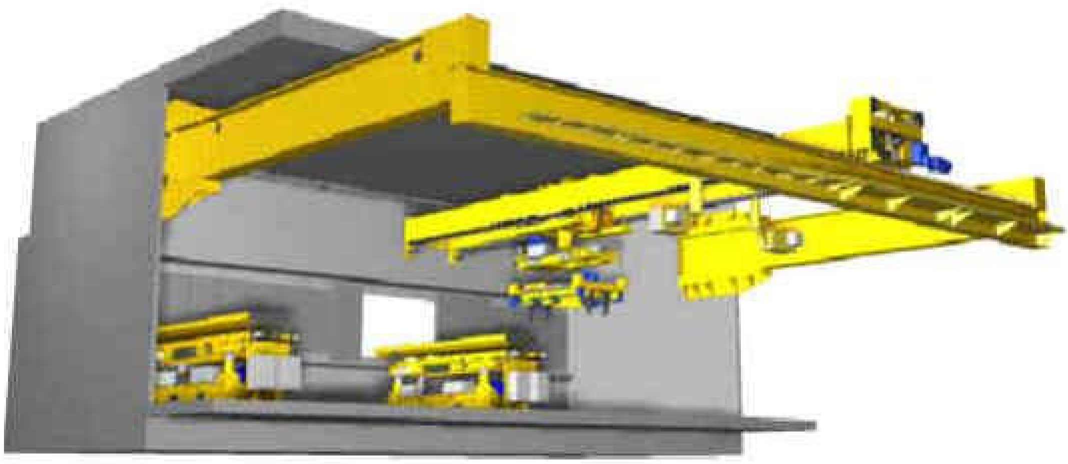

FIG. 9. Remote maintenance cubicle.

The configuration of the hot cell construction is optimized to facilitate the movement of materials as required for the maintenance work. A piece of equipment widely used in Europe is a movable container (called MERC in France) which is developed from a fuel handling machine used for gas cooled reactor operation. It is a shielded carrier for transfer of part or equipment into or out of hot cell enclosures for replacement work. The opening of the shielded container is rigged with a remotely controlled plug which can be opened to mate the cavity with hot cell plug through which the introduction or removal can be performed [50].

3.2.3. Development of advanced remote technologies

(1) Fully remote maintenance systems

Due to the heavy involvement of remote technology applications in spent fuel management and especially in reprocessing, a concept for facility maintenance with fully remotized system was developed in the past US program for FBR fuel reprocessing. Each unit of the process equipment is designed in a module to fit in the structured position array on the hot cell floor and vertical position provided with connectors and penetrations on the walls in the hot cell.

In comparison with the conventional hot cell complex which used to be highly compartmentalized in a number of functional cells, the fully remotized hot cell concept is usually an open hall enclosure equipped with all necessary remote monitoring and control systems for the operation and maintenance. A strip of middle zone of the hot cell is reserved for movement of a service system which can be a carrier of mast rigged with remote maintenance manipulators and camera. Or the floor track can be used for equipment transfer carrier, while the manipulator system can be a suspended type from overhead bridge rail. In the case of failure in any of the process equipment modules, the problem unit is replaced by means of the remote systems provision.

The remote maintenance concept was applied to the design of the Wackesdorfer Reprocessing Plant of which construction was cancelled in the eighties (see 2.2.1) It was reported that mockup tests were performed at the FEMO facility to check up the workability of the process equipment and associated remote maintenance concept for the designed plant.

For some other countries committed to close the back-end of the fuel cycle, especially with fast reactor systems, there are continuing efforts for development and application of remote technology required for such a strategy [51]. In Japan, for example, a technical concept of full remote operation and maintenance using advanced robotics for fast reactor fuel recycle is being developed and tested at the Tokai Vitrification Facility and Recycle Equipment Test Facility at JNC (Fig. 10).

(2) Auxiliary remote equipment

Although not specifically discussed in the meetings, the use of certain remote equipment capabilities are worth mentioning since they do enhance the efficiency of the remote operations. One capability that can be especially useful is a rotating hook on the overhead system. This is particularly useful in the correct positioning of objects and eliminates the need for passive features on the components to perform the rotational operations.

Another feature that can be very useful is the installation of ‘swing-free’ controls on the overhead system to eliminate the pendulum effect. Control systems have been designed and are adaptable for installation on existing cranes at a very reasonable cost to provide this capability.

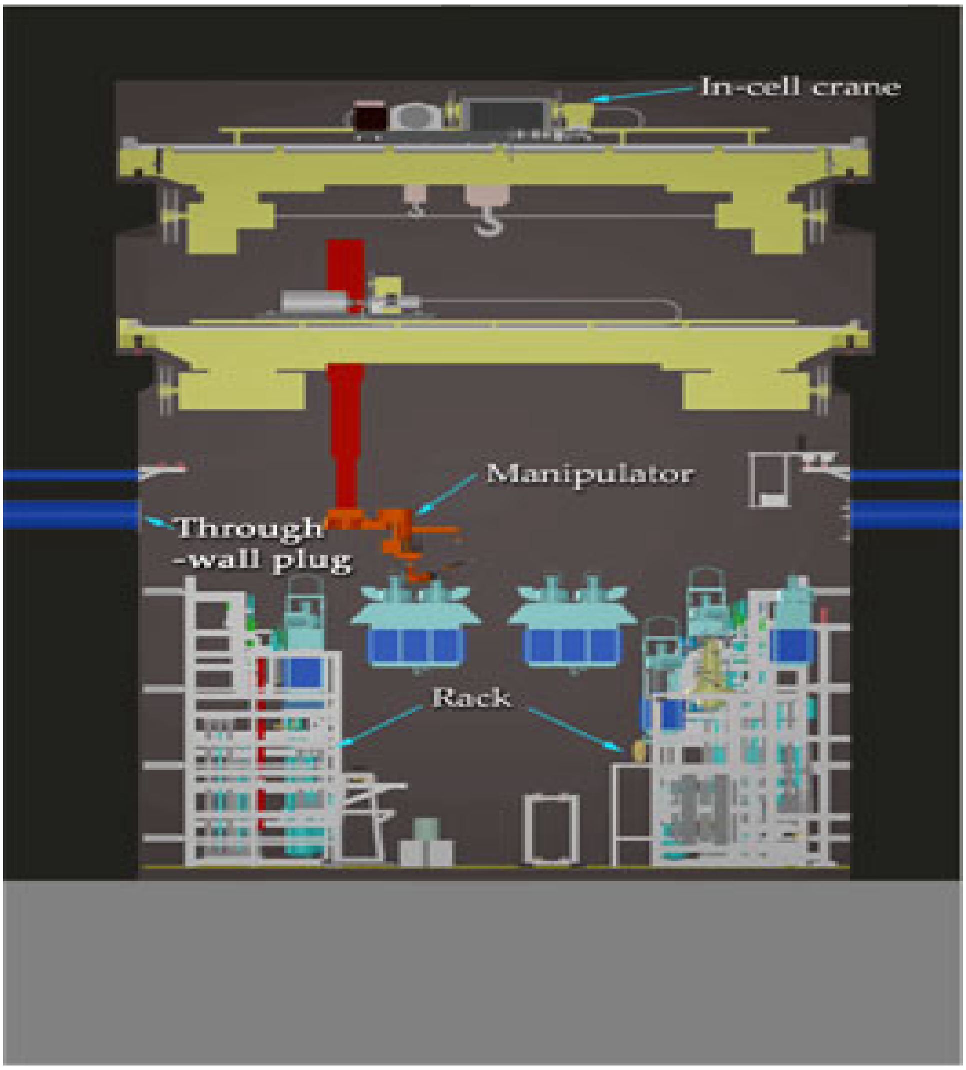

FIG. 10. Fully remote maintenable hot cell concept.

(3) Human-machine interface

The design of the human-machine interface (i.e. control panel) for remote operations can have a significant effect on the efficiency of the remote operations, particularly for telerobotic applications in which a human operator is involved and performs many of the operations. There is a tendency, when designing the layout of the panel, to include more information than the operator needs. The items most important to the operator are good views of the work space on TV monitors, an audio system which allows the operator to hear the results of his work (particularly if a tool or a component is dropped), and, if deemed necessary, a collision avoidance system. It has also been found that a two-operator team is more efficient than a single operator. The second operator can monitor the tasks being performed by the primary operator, provide advice or warnings, and operate other equipment (overhead cranes, lighting, etc.) to allow the primary operator to concentrate on his main tasks with the manipulators. The two-operator team also allows the operators to trade positions in the event of fatigue or to take advantage of particular operator skills.

In the controls for the servo-manipulators, certain features have proven to be useful while others are not worth the cost (Fig. 11). For example, operators are able to perform tasks more precisely with high definition television while stereoscopic television is not useful and is tiring for the operators. Also colour television is not particularly useful since most of the components being worked on by the manipulators are shades of gray particularly after being in a high radiation field for periods of time. Another servo-manipulator capability that has been highly touted is adjustable force reflection for the manipulator arms. In numerous tests conducted in the US, operators prefer not to have any force reflection. For delicate tasks, which, in any case, should be minimized for remote operations, the operators would rather depend on their views of the work area than the force reflection feature.

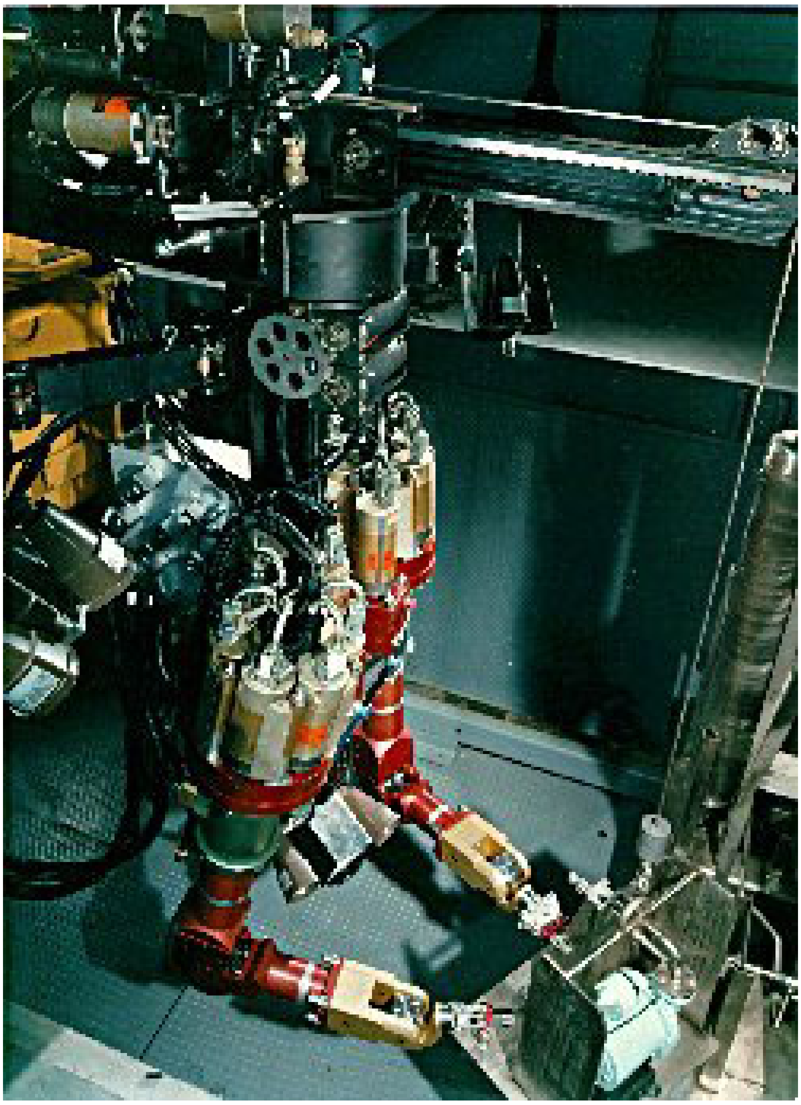

FIG. 11. Dual arm serve manipulator.

3.3. SELECTION CRITERIA FOR TECHNICAL OPTIONS

Selection of appropriate technologies for nuclear fuel handling is a function of economics, physical constraints, process volume, flexibility needed, maintenance, system reliability and consequences of failure. A summary of the criteria and their categories is given in Table III.

Remote hand tools have been used more readily in unique, relatively low volume or one-time operations. They are relatively inexpensive and rapidly fabricated, require little maintenance, and are generally highly specialized. Such tools are generally reliable and as effective as the skills of the operator within the constraints of a given environment. Examples of remote manual tooling development and applications in the USA and Iraq were presented.

Remote hand tools are less desirable where a high radiation dose potential exists; necessary human presence requires extra shielding and/or extra-long handles, making manual manipulation more difficult. Because of specialization, a large number of hand tools may be required to complete a sequence of operations. For these reasons, remote hand tools are used less frequently in production facilities, where economies of scale permit cost effective means of speeding operations and reducing radiation exposure. Telemanipulators have been used worldwide in production modes, fuel movement and other handling activities in production, reprocessing and reactor facilities, inspections and destructive evaluation of spent fuel.

Table III Criteria for selection of technical options

CATEGORIES	CRITERIA
(1) Functional requirements	• Capacity /throughput
	• Location of system application
	• Technical alternatives
(2) Selection factors	• Performance
	• Cost of implementation
	• Lead-time / Lifetime
	• Reliability / Availability / Maintainability (RAM)
	• Simplicity / Flexibility
(3) Others	• Experience
	• Licensing
	• Safety
	• Safeguard ability

(1) Remote versus hands-on operation
In nuclear technology the radioactivity, of the items handled usually determines whether remote technology needs to be employed. In accordance with the ALARA principle, remote technology is encouraged in order to reduce the collective radiation doses to the operating staff. There may be factors such as low radiation level, low frequency, or ready access (by the operator), which can make hands-on operation the preferred option.

There are many factors that determine whether a manual or automated process is the optimum solution. Manual operations are less desirable where high throughput and/or high radiation protection are required. Automation provides enhanced productivity and can realize higher quality standards if required, but require more complex machinery. Flexible automation can rapidly respond to low volume, high radiation protection requirements. The higher capital investment must be justified e.g. by less dose exposure and/or by higher process efficiency.

(2) Location of process
Where processes must be designed into existing facilities, many constraints are placed on the design. Such constraints include available space, process interfaces, limitations on changing the existing process and operating philosophy. If a new facility is being designed, it is

important to minimize the volume of such a facility in order to minimize costs and environmental impact. It is important, however, to also consider flexibility for future uses and to provide adequate space for maintenance.

(3) Throughput and capacity
Two of the most influential factors in process selection are throughput and capacity. These govern the size and overall cost of the solution. High throughput requirements can justify higher investment. A process designed for higher throughput generally requires logistically optimized solutions with high reliability and provision of buffer stores.

(4) Quality
The quality to be achieved in the process is fundamental. High quality is often achieved through a high degree of automation. Another aspect is the way in which the desired quality is to be achieved. The traditional technique of final testing requires a different approach than more modern techniques such as statistical process control.

(5) Lifetime
The lifetime of the process equipment to be considered is of major influence to the design. Process equipment for long-term use must fulfill different design criteria than those for short-term use since design lifetime often dictates materials of construction, safety margins and choice of components. The present experience is that facilities often operate longer than the original design lifetime.

(6) Lead time
Whatever the lead-time is, the process equipment must fulfill all necessary design and safety criteria. However, if the available time to prepare the process equipment is very short, less optimized solutions might have to be adopted. If the lead-time allows for more detailed design, better-optimized equipment with better technical performance and economy can be provided.

(7) Licensing and safety
Licensing requirements are one of the major influencing design parameters. The safety requirements differ from country to country, thus sometimes preventing direct transfer of equipment or processes already in operation in another country. However, a positive licensing statement in one country may be used to support licensing elsewhere.

(8) Experience
Experience is a very valuable factor when designing a remote technology process. It is usually gained through the process of designing, building and operating facilities. Designs guides published by the IAEA, ANS, BNES, etc. are also useful references. Although new technology may seem beneficial, proven technology is sometimes chosen to provide a higher degree of confidence. A regulator who may wish to see a working example of the process involved can influence choice of solutions.

(9) Flexibility
When designing a process it is important to build in flexibility for current and anticipated future needs. The degree of flexibility depends entirely upon the application and in certain cases for very specific tasks; however, it may not be necessary to take flexibility into account.

(10) Maintainability
Each process must be designed with specific consideration of maintainability. Even processes, which are essentially maintenance free, should have provision made for possible failure. If such provisions are made then the impact of failures on operational cost and plant outage are reduced. A wide variety of remote technologies are available for specific maintenance operations.

(11) Simplicity
Simplicity of a process is often an advantage since it usually results in fewer failures of the process, lower capital cost and easier maintenance. This is a particularly important factor of consideration for contamination environments where human intervention for repair work is costly or robotic intervention is failure prone.

Another benefit of simplicity consideration is that parts are readily available off the shelf which makes replacement work faster and cheaper than the case of special fabrication of the parts.

(12) Costs
The price of procurement is of course a primary consideration for selection of a remote system, in compromise with other associated criteria. Because of the production costs, standard products off-the-shelf from the market are usually much cheaper than producing in-house and therefore, this aspect of economics is a useful criterion in the selection.

Lifetime costs (including consideration of decommissioning and waste processing) should be the basis of cost comparisons rather than initial capital outlay alone. A preferred solution may not always be possible to realize due to financial constraints on the project.

(13) Safeguards
It is of great advantage to incorporate safeguard requirements at an early stage of design since this can avoid costly rework that can happen after completion of facility design, or even worse after construction, should any requirement associated with safeguards is found not implemented or not in compliance.

4. TECHNICAL HORIZONS

Even though the earlier momentum for the development and applications of remote systems technology in nuclear sector has become sluggish due to the shrinking market in recent years, the growing interest in the development of innovative nuclear technologies, as observed in the recent international initiatives (i.e. INPRO, GEN IV, MICANET), in the context of sustainable development, may lead to a development of nuclear systems that requires for extensive applications of remote systems technology in the longer term future [52].

In view of the fact that remote technology bears significant implications in terms of radiation safety and operational performance which are closely related with economics of the nuclear systems to be developed, the applications of remote technology call for optimal integration of remote technology development in the innovative systems to be developed. This has a direct implication in other issues such as economics, safety, and non-proliferation aspects. In preparation of the future requirements for remote technology, the state of the art remote systems technology currently being applied in spent fuel management need to be evolved for transition to comply with the future requirements of innovative nuclear fuel cycles. Such transition will need enhancement in terms of various criteria including higher performance at lower costs.

Some major trends and perspectives on remote technology in spent fuel management may be summarized as following:

4.1. TREND TO HIGHER BURNUP AND ADVANCED FUEL

There is a continuing trend to higher burnup and MOX fuel use in the nuclear power generation industry with relevant implications which should be addressed in the fuel cycle backend.

4.1.1. High burnup fuel

The continuous enhancement in performance of nuclear power plants in the past decades is due by large part to the successful increase in the nuclear fuel burnup mainly driven by economic incentive. At more and more plants around the world, the burnup level has reached almost to double compared to the initial times of operation. And the general burnup trend is heading up to still higher level, even though there should be a plateau level in confrontation with regulatory constraints [53].

The trend toward higher burnup results in hotter and more radioactive fuel discharged as spent fuel, which will bring relevant impacts in the downstream management of spent fuel. For some AFR storage facilities, for example, several cask designs have already had to be modified in order to accommodate higher burnup fuel than licensed specifications. The trend to high burnup will certainly need to be reflected in the design of relevant steps in spent fuel management, giving rise to higher requirements in remote technology applications.

4.1.2. MOX fuel utilization

MOX fuel has begun to be used in LWR reactors in Europe and there is an on-going plan to consume plutonium that is coming from weapon dismantling in the USA and in the Russian Federation in the form of MOX fuel to be burned in nuclear power rectors**.** It is not yet clear however how much MOX fuel could be used in the power reactors, in competition with UOX fuel, in view of the economic prospect of nuclear power market [54]. The large amount of plutonium available from civilian reprocessing may be disposed of by methods other than MOX fuel (such as dilute and melt), depending on the future market of nuclear economics.

As spent MOX fuel is to be managed in a similar way to the spent UOX fuel (at present, there is no plan to recycle spent MOX fuel again by reprocessing), and because of the higher heat and radiation emission from spent MOX fuel than from spent UOX fuel, the requirement for remote technology applications in spent fuel management could grow in the future, in a similar way to the trend to higher burnup fuel as mentioned above.

4.2. INNOVATIVE NUCLEAR FUEL CYCLE DEVELOPMENT

As indicated before, there have been a variety of actions taken to adjust nuclear energy sector to new realities that have been set in motion since the early nineties. One of those endeavours is to prepare for the future by development of innovative nuclear energy systems for long term sustainability of nuclear energy utilization, of which criteria could be measured in terms of such criteria as safety, economics, proliferation resistance, etc [55]. At present, there are several international initiatives that have been implemented in an effort to pave the way toward the innovation of nuclear systems with enlarged utilization scopes including such non-power applications as sea water desalination and hydrogen production.

The technical concepts envisioned in the scope of innovative systems development include some new systems like accelerator driven system (ADS) for nuclear transmutation of actinides or long-lived fission products, but the majority of them are evolutionary technology based on the technology which have already been in more or less advanced stage of research and development in the past. Particular reference has to be made in this regard to the past efforts extended to the development of fast neuron reactor and associated fuel cycle systems at national labs in the US and in the former Soviet Union where progresses had been advanced to pilot demonstration phase, but came to a halt short of industrialization due to decline of FBR programmes in most countries during the eighties and nineties.

Some new requirements emerging for innovative systems are common to many applications (such as high temperature and extended burnup operations) while some other requirements are particular to some other applications (such as fast transmutation rate). Those technical factors of the innovative nuclear systems that might bring impacts on the applications of remote systems technology in the future development of nuclear fuel cycle may be identified as following:

4.2.1. High burnup fuel cycles

Many of the reactor concepts considered to be innovative anticipate taking advantage of high burnup fuel, which can be regarded in this sense as an extension of the current high burnup trends noticeable in the commercial operation of LWRs and HWRs. This aspect implies that those issues arising from use of high burnup fuel (and in that context MOX fuel) with corresponding impacts on the downstream fuel cycle are also relevant to be considered for the innovative systems.

Some of the design features for achieving high burnup include dispersion or particle type of fuel forms as well as new cladding materials that are corrosion resistant or that have improved creep strength.

4.2.2. Plutonium burning

The past objective of FBR which was meant to breed plutonium from fertile material (U-238) has been faded out, due mainly to the cheap price of uranium and proliferation concern of separated plutonium stock. The design of the fast neutron reactor can be converted to such mode that the fertile fuel is not used so that plutonium is consumed instead.

4.2.3. Partitioning and transmutation

While most of the major programmes in FBR technology development have subsided through the past decades, the renewed interest in innovative reactor and fuel cycle systems in the context of partitioning and transmutation (P&T) might call for increased applications of the remote concepts, especially for processing and fabrication of radioactive targets for spallation.

In the long-term case of sustainable development of nuclear energy, remote technology applications would be required for fabrication of some types of fuels, which bear gamma radioactivity. That would be the case when minor actinides are included in the MOX fuel for example by adding of Np-232 which will increase the gamma source due to Pa-233 or build up Pu-238 resulting in additional neutron source by (α, n) reactions. Significant increase by a factor of 4.5 in gamma dose can result from addition of americium to the U-Pu powder. In the worst case of curium, the neutron dose from MOX fuel could increase as high as a factor of hundred that substantial shielding and subsequent remote systems would be required for the powder blending process. Another case of extensive application of remote technology would arise for refabrication of thorium fuel elements that contain Th-228, which decays through a series of daughter product emitting gammas. In a similar way, fuel using recovered uranium from reprocessing requires remote systems technology because of the associated U-232, which is a gamma emitter [56].

The technological experience of remote operation and maintenance in head-end processes for spent fuel reprocessing could become an important base for future industrial implementation of advanced fuel cycle concepts for innovative nuclear systems now in research and development as an international initiative.

4.2.4. Remote fabrication of radioactive fuels

The Republic of Korea (ROK) reported some R&D activities associated with laboratory scale test of remote fuel fabrication for direct use of spent PWR fuel in CANDU reactors (DUPIC) which has been recently conducted in hot cell facilities at Korea Atomic Energy Research Institute (KAERI). In collaborative work with Atomic Energy of Canada Ltd (AECL), the DUPIC fuel fabrication demonstrated extensive application of remote systems technology both for the sequence of fuel fabrication process operation and maintenance. Several pins of DUPIC fuel were refabricated at an AECL hot cell facility for irradiation in a test reactor. This exercise was followed by another campaign with full processes of powder-pellet route equipment in a larger hot cell facility at KAERI [57]

While this technology would be simplified in comparison with the conventional PUREX type of aqueous process, the radioactivity that is encountered throughout the processing will require fully remotized operation and maintenance of the hot cell facility. Another example of remote systems applications that has recently been development is the direct refabrication of spent fuel into a new fuel for reuse, a case in point being the DUPIC (*Direct use of spent PWR fuel in CANDU reactors*). This concept requires fully remote operation and maintenance over the entire process of radioactive fuel refabrication that must be contained in shielded hot cell facilities. Another challenge in the DUPIC concept is inspection and quality control in a remotely operated facility.

India reported another example of remote disassembly and refabrication of some radioactive fuel for fast reactor programme. Sophisticated automation and robotics systems have been developed for application to the refabrication of advanced fuel and dismantling of irradiated fuel from the fast breeder test reactor at Kalpakkam, near Madras. It is to be noted in this context that the fast reactor fuel recycle programmes in some countries have historically been home to extensive applications of remote technology.

4.3. APPLICATIONS OF ADVANCED TECHNOLOGIES

As some countries have set up plans for spent fuel disposal, packaging of spent fuel in hot cell environment will emerge as a new area of remote technology applications in the future, together with the decommissioning of old nuclear facilities, as mentioned previously.

This section reviews the trends foreseen in remote technologies for spent fuel handling, including automation, robotics, simulation, and expert systems. It also discusses issues related to quality.

While manual and tele-manipulation techniques as well as hard automation remain in widespread use, increased emphasis on flexible (robotic) automation can be found in advanced nuclear facilities. The potential increases in speed; safety and economic advantages are driving forces in such application. In France, consideration is being given to a requirement for basic robotic infrastructure in all new nuclear power plants. In the USA, the monitored retrievable storage (MRS) facility design was analyzed and lifecycle costs found to be substantially lower when most of the operations are robotically automated.

In the area of automation, future developments and improvements will benefit from the fast development of computer and instrumentation technology for sensor fusion in remote measurement and control systems. Continuing efforts have been reported at some laboratories in the world such as CEA/CEREM (France), BNFL/Risley (UK), SNL (USA), JNC (Japan) actively involved in robotics development for nuclear applications including spent fuel management.

4.3.1. Application of automation systems

The use of automation for most operations in the handling of spent fuel is widely applied throughout the nuclear industry worldwide. Facilities, relying on automated operation of systems for spent fuel handling have been used for decades with good records of reliability, thus increasing the confidence in process automation.

Further automation of those systems may be foreseen as more and more nuclear power reactors use higher burnup and MOX spent fuel, and as the regulatory limits for operator exposure become more and more stringent. A good illustration of this tendency is the automation of the unbolting of the transportation cask lid that is currently manually performed at some facilities. For example, the fuel receiving facility of the new reprocessing plant in Sellafield (THORP) is equipped with an automated system for unbolting the lid of transportation casks. Research and development for remote handling and automation for cask operation were reported by SNL and KAERI.

With the increased reliability of automated systems, additional automation in the facilities for spent fuel handling may be considered for the improvements of activities such as quality assurance (QA), i.e. establishing and maintaining QA records, and material accounting. Further applications of this technology may also be foreseen as the standardization and availability of automated systems develop.

Future developments and improvements in the automation of processes will benefit from the continuous development of computers. Eventually the work being conducted on sensors (improving sensitivity and resistance to radiation) and interfaces with programmable controllers (improving the transmission of information through the use of fiber optic) should increase the performance and the reliability of the systems.

4.3.2. Robotics

Emerging trends in facility operation include the use of flexible automation such as robotics. Flexibility, which includes multi-tasking, and effective use of available space become strong arguments for using robotic and telerobotic devices. Examples where such devices have an advantage include:

- Facilities processing large amount of spent fuel, such as reprocessing (or MOX fuel fabrication) plants;
- Facilities where several cask and canister designs must be managed, such as the Centralized Interim Storage Facility (CISF) or Federal Repository in the United States of America;
- Facilities where different designs of fuel assemblies are handled, dismantled, reconstituted or refabricated, such as the Direct Use of Spent PWR Fuel in CANDU Reactors (DUPIC) in the Republic of Korea;
- Facilities with stringent restrictions on operational volumes, such as at Bhabha Atomic Research Centre (BARC) 'in India.

However, we have to recognize factors which have been hindering the implementation of robotics in the nuclear industry. Lack of relevant nuclear application experience and exposure to the technology appears to be the primary issue. Greater acceptance will follow demonstrations of reliability and effectiveness of robotic and telerobotic systems.

4.3.3. Simulation

Visualization by graphic simulation has become a commonplace in various areas including remote technology applications, with the wide availability of high performance software tools at affordable prices. Simulation is becoming more wide spread for validation and acceptance of process and facility design.

Graphical simulation has been used to analyze costs for a central interim storage facility. Here, processes were simulated using models of actual equipment executing the required operations. This resulted in high confidence estimates of capital and operational costs, as well as throughput. A similar type of simulation is reported in the SNL contribution, where human processes can be graphically modeled and verified, followed by the tracking of radiation exposure from all included sources. This type of simulation results in a more precise tracking of exposure to all regulated points.

With better dose and cost estimates, together with the visualization capabilities, simulation is expected to enhance communications with regulatory authorities, project sponsors and the public. Further potential benefits include visual training for operators, and the ability to operate equipment directly from the simulation environment (thereby improving operational transparency).

A typical example of graphic simulation of the tele-robotic operation on cask bolts is represented in the Fig. 12.

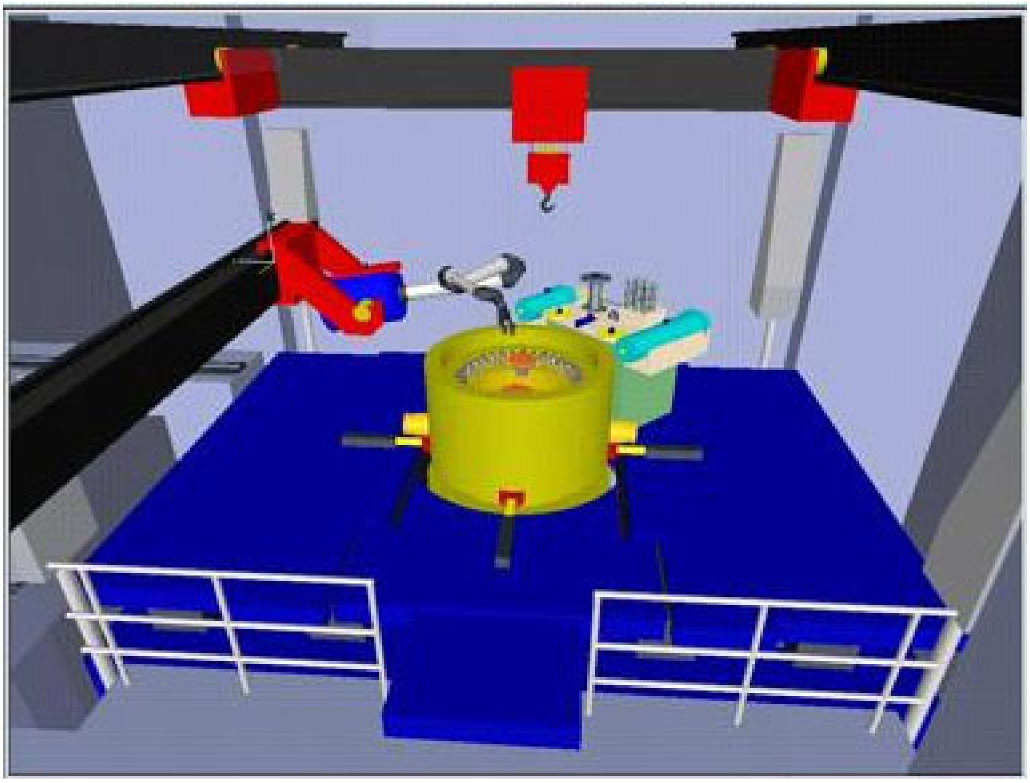

FIG. 12. Graphic simulation of telerobotic operation of cask bolts.

4.3.4. Expert systems and artificial intelligence

Expert systems have rarely been used in spent fuel handling. However, application genetic algorithm was reported to be used for analysis of optimal mixture of spent fuel of different batches to a uniform composition for DUPIC fuel fabrication in Korea [58].

Experience gained in these areas will give the confidence to apply expert systems to spent fuel management, as any other areas of technical applications.

4.3.5. Quality assurance (QA) issues

As the design and implementation of new systems and equipment continues to evolve, the role of QA remains vital. The participants of the meeting emphasized the following two aspects concerning the QA related to remote automated technology application in spent fuel management:

(1) Process qualification for computer-aided operations can provide a potential benefit for QA. In process control the reliability increases thus diminishing the requirements for end product or status inspection, especially in areas difficult to access;

(2) Computer software qualification is a new challenging area of QA. To assure acceptance of programmable systems by regulatory agencies, appropriate procedures for software development and testing must be further developed.

However, we have to recognize factors, which have been hindering the implementation of robotics in the nuclear industry. Lack of relevant nuclear application experience and exposure to the technology appears to be the primary issue. Greater acceptance will follow demonstrations of reliability and effectiveness of robotic and telerobotic systems.

5. CONCLUSIONS

In this report an overview of remote technology applications in spent fuel management identified the requirements for lifecycle management of related facilities in the short and long term perspectives, together with associated R&D status. A summary of the applications of remote technology in spent fuel handling and storage is shown in Table IV below:

Table IV Applications of remote technology in spent fuel management

	Spent Fuel Assembly	**Cask/ Canister**	**Facility**
At Reactor (AR) Spent Fuel Storage	Discharge Examination Reconstitution (Re-racking)/Storage Loading/Unloading	Shipping Transhipment Canister/Cask Welding O&M	O&M D&D
Away-from Reactor (AFR) Spent Fuel Storage	Unloading/Loading Movement Long-term Storage	Receiving Transfer Storage Opening/Closing O&M	O&M Refurbishment D&D
Reprocessing + MoX Fuel Fabrication	Head-end Operation Solid Waste Handling Assembling of Fuel	Receiving/Storage Solid Waste handling Storage/Shipping O&M	O&M Refurbishment D&D
Refabrication of Fuel or Target (Transmutation)	Head-end Operation Solid Waste Handling Assembling of Fuel	Receiving/Storage Solid Waste Handling Storage/Shipping O&M	O&M Refurbishment D&D
Direct Disposal (Surface Operation + Underground Repository)	Conditioning Assay/Monitoring	Cask Receiving Unloading Solid Waste Handling Overpack Emplacement O&M	O&M
Emerging Fuel Cycle Technologies (including P & T)	Head-end Operation Solid Waste Handling Assembling of Fuel/Target	Receiving/Storage Solid Waste Handling Storage/Shipping O&M	O&M Refurbishment D&D

The main incentives of remote technology applications includes dose reduction, performance enhancement, and possibly cost reduction for some types of operation and maintenance. The enabling conditions for remote technology applications in the spent fuel management have enhanced by the infusion of robotic technology which has been actively developed in the general industry and academia.

During the meetings the participants noted the following points:

- Automation is considered to have a very well established industry with potential for applications to remote systems design. Nevertheless, further development is expected for currently automated processes and for spent fuel handling operations not yet automated. In addition, use of robotic equipment can be identified as desirable for applications in spent fuel handling solution that is capable of providing flexibility with the possibility of high throughput. Application of telerobotic systems may provide further improvements in the future.

- As the remote technology develops in general, off-the-shelf products and systems will be adapted from other industries. In addition improvements and spin-offs from spent fuel management applications may go back to other industries and other nuclear applications, such as decontamination, decommissioning and waste management. This will promote more attractive and widespread use of automated and robotic systems.
- Design criteria of automated spent fuel handling processes should be taken into consideration during the design stage of any new fuel or fuel cycle type. This consideration is particularly relevant to the development of innovative nuclear systems as being researched in such international initiatives as Gen IV, INPRO, and MICANET etc. in preparation for long term future of sustainable development of nuclear energy.
- Should the present expectations for sustainable development of nuclear energy materialize in the future, there would be a potential for extensive applications of remote systems technology to the innovative fuel cycles.

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GLOSSARY

Ampoules	Sealed cans containing a single RBMK fuel bundle or assembly.
Automation	Automation may be defined as automatic control of a system by mechanical or electronic devices that replace human observation, effort and decision.
Burnup credit	A method of taking the burnup, original enrichment, inclusion of poisons, etc. Into account to permit greater amounts of spent fuel to be loaded together in either transport flasks or storage canisters. The aim is to make significant transport & storage cost savings.
Cart	Special equipment for transfer operation of spent fuel.
CARTOGRAM	New generation Gamma scanning device.
Cask cavity	Space within the cask for the fuel or waste load.
Eddy-current method	Encircling coils are used which are operated with high frequency current. These coils are used to detect inhomogenities within electric conductive material (e.g. cladding) or measure the oxidation on Zircaloy components.
Encapsulation	To separate fuel from its surrounding environment using capsules.
End effector	Tool at the end of a manipulator to accomplish some task.
Flexible automation	The ability to reprogram or multi-task an automated system. Robots are considered flexible because they are capable of redirection or being used for new purposes.
Fuel manipulator crane	Manipulation system to grip the fuel assembly and transport it within the nuclear power plant or reprocessing facility.
Gantry mounted robot	Robot mounted on a bridge with an overhead structure.
Grappler	A tool capable of holding another object.
Hard or fixed automation	Non-programmable, fixed tooling which is designed and dedicated for specific operations. Hard automation is cost effective for a high production rate. It is typically not easily changed to accommodate new operations.
Heavy-duty manipulator	Manipulator for heavy load or highly frequent loads.

Jib crane	Crane with a horizontal arm and rotation of the vertical axis.
Laser induced breakdown spectroscopy (LIBS)	Small amount of material is vapourized in a plasma generated by a pulse of laser light and a fraction of the resulting spectrum is analyzed to determine elemental composition.
Lifting yoke casks	A lifting beam typically used to lift & manipulate fuel or racks.
MA 23 operator	Electric servo manipulator.
Master slave manipulator	A teleoperated manipulator.
Neutron radiography	Imaging by projection of neutrons through an object to image low Z-materials.
Photogrammetry	Use of photography in surveying and mapping to ascertain measurements between objects.
Reconstitution	of spent fuel assemblies involves replacement of the defective fuel rods and sealing them in a separate canister.
Remote operation	Execution of tasks from a distance.
Robot	A reprogrammable, multi-functional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks.
Telerobot	Equipment with distinct re-programming capability. In nuclear applications robots are frequently adapted for telerobotic applications.
Scaffolding	Temporary work platform or support structure.
Sipping	Used to identify leaking fuel assemblies either in reactor or in pool (before reuse, transportation or during long term storage).
Suspension	Here used as the upper end fitting of RBMK fuel.
Telemanipulator	Manually controlled remote manipulator.
Teleoperation	The remote control of manipulators or other machinery by direct manual input. This is commonly seen in the nuclear industry as mechanical or electro-mechanical manipulators in hot cells. Teleoperated devices, not being programmable, are by definition not robots.

Telerobotic equipment	Equipment mixing computer control, programmability and manual control capabilities.
Telerobotics	The control of a manipulator by direct human input is augmented by computer control. This hybrid maintains the human decision capacity while relieving the operator of many details (such as joint positioning) and increasing sensor integration opportunities (such as obstacle avoidance).
TIG	Tungsten inert gas welding process.
Tilting fixture	A device, which moves another object through a certain angle
Trunnion, lifting trunnion	A feature on the side of a cask used for lifting or support.
Ultrasonic	High frequency sound waves used to find material inhomogenities, also used for dimensional measurements on core components and leak detection of individual fuel rods.
X ray radiography	Imaging by projection of x rays through an object reflected or absorbed by high Z-materials.

ABBREVIATIONS

AFR	Away-from-Reactor
AGR	Advanced Gas Cooled Reactors
ALARA	As low as reasonably achievable
AVM	Atelier de Vitrification a Marcoule
BWR	Boiling Water Reactor
CASTOR	Metal cask developed by GNS/GNB
CISF	Centralized Interim Storage Facility
CLAB	Central Interim Storage Facility for Spent Nuclear Fuel (Sweden)
COGEMA	Compagnie Générale des Matières Nucléaires
CONSTOR	Concrete cask developed by GNS/GNB
DTS	Dry Transfer System
DTS TSAR	Dry Transfer System Topical Safety Analysis Report
FBR	Fast Breeder Reactor
FEMO	Fernhantierte Modultechnik
FFTF	Fast Flux Test Facility (Hanford, USA)
FMEF	Fuels and Material Examination Facility (Hanford, USA)
GCR	Gas Cooled Reactors
HLW	High Level Waste
HWR	Heavy Water Reactors
ICEDEC	(Commercial name of product developed by Westinghouse Co.)
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
JNC	Japan Nuclear Cycle Development Institute
LWR	Light Water Reactors
MACSTOR	Concrete cask developed by AECL (Canada)
MELOX	MOX fuel fabrication facility at Cadarache (in France)
MOX	Mixed Oxide fuel
MPC	Multi Purpose Canister
MRS	Monitored Retrievable Storage
MVDS	Modular Vault Dry Store system
NPH	One of spent fuel storage pools at La Hague Reprocessing plant (in France)
NUHOMS	Nutech Horizontal Modular Storage System
PAMELA	Pilot test facility for vitrification of HLW solution located at Mol (Belgium)

PHWR	Pressurized Heavy Water Reactors
PUREX	Plutonium and Uranium Reduction and Extraction
PWR	Pressurized Water Reactors
RBMK	Water cooled, graphite-moderated pressurized tube reactors
SFCM	Slurry-Fed Ceramic Melter
THTR/AVR	High temperature reactor developed in Germany
WVDP	West Valley Demonstration Project
WWER	Wodo Wodyanoi Energetichecki Reactor (Russian type of PWR)

Annexes I–VI

COUNTRY REPORTS

Annex I

STATUS AND TRENDS OF REMOTE TECHNOLOGY APPLIED TO SPENT FUEL MANAGEMENT IN FRANCE

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Abstract

The French R&D on remote technology applications in spent fuel management have been led by CEA in cooperation with several industrial partners with a view to meet technical requirements over the various stages of concerned facility life cycle. The scope of R&D includes programmes to develop a variety of robotic systems, among others, incorporating innovative technologies for applications to a variety of tasks to be performed in the industrial facilities, with a view to reduce dose to operators, increase performance, enhance safety, etc. This paper gives an account of those robotic systems in research and development at CEA with a description of their functions and technical performances in remote systems applications.

1. INTRODUCTION

The nuclear industry in France, and especially the spent fuel management industry, is highly demanding of new remote equipments and technologies in order to carry out an increasing number of tasks of maintenance in active operations facilities and decommissioning in older plants which have been shut-down.

For more than 20 years, the Atomic Energy Commission (C.E.A) of France has been developing advanced technological solutions in the field of teleoperation, remote handling and robotics, in collaboration with industrial partners (COGEMA, EDF, FRAMATOME) and for its own needs. The research and development projects have been conducted along two main axes

- Development of remote technologies applied to existing facilities requirements
- Development of advanced technologies for on-going and future remote handling applications

Most of these developments reflect the current status of R&D in the domain in France.

2. DEVELOPMENT OF REMOTE TECHNOLOGIES APPLIED TO EXISTING FACILITIES

Dextrous Arm for Teleoperation (BD250)

Dextrous Arm is a general purpose manipulator developed for remote teleoperation and robotics applications in maintenance and intervention on process equipments. It is a 7 axes redundant manipulator, 25kg payload capacity, radiation tolerant (10 kGy), providing force feedback control. This prototype is being industrialized by COGEMA company.

Dual-arm Mobile Working Platform (PTM)

One of the first targeted application of Dextrous Arm is the Mobile Working Platform. This platform is a dual-arm intelligent teleoperation system specified to carry out maintenance tasks in fuel reprocessing facilities where standard wall-mounted mechanical telemanipulators cannot be used. It includes two Dextrous Arms and a radiation tolerant (10 kGy) intelligent electronics control system. This prototype is currently under development.

Articulated Carrier for Hot-Cells Inspection (PAC)

This carrier is a very challenging robotic arm developed for inspection of blind hot cells in nuclear fuel facilities. It can be installed in small engineering wall penetrations (ϕ100mm), has a total length of 6 meters and a payload capacity of 1 kg. It is equipped with on-board hardened control electronics (10 kGy). This prototype is currently under development.

Light Modular Carrier (PML)

This carrier is a modular tool designed to carry out exceptional repair tasks inside very cluttered nuclear cells. It provides self construction of a long-reach beam and includes a mobile shuttle for mounting the elements and carrying the tools along the beam. Typical tasks devoted to this carrier are: welding, cutting, control and virtually any other maintenance and repair process. This prototype has been installed and evaluated at COGEMA La Hague facility.

Teleoperation of Industrial Robots

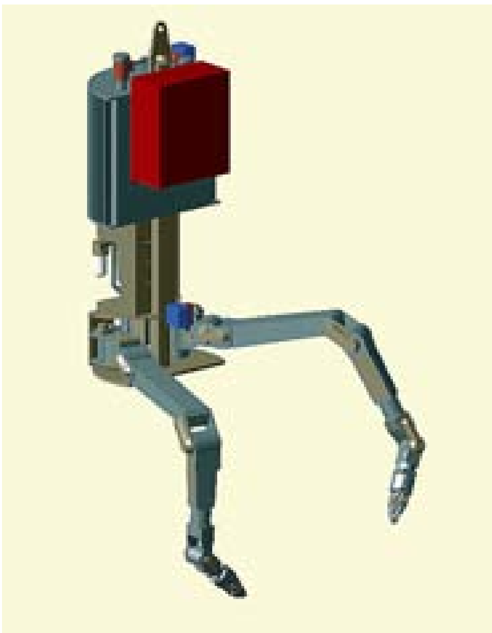
Using industrial robots is possible when the application constraints (radiation exposure, volumes, payload) are compatible. This solution provides dramatic cost reduction and higher performances when combined with a force-feedback teleoperation control system. This robot from STAÜBLI manufacturing company has been adapted to the nuclear requirements of COGEMA and is commercialized by SICN company. It has been proofed in 1998 in a real intervention carried out at COGEMA La Hague plant.

Hydraulic Robotic Telemanipulator (MAESTRO)

MAESTRO is a 6 axes manipulator combining the power of hydraulic actuators to the skill of force feedback remote control. It has a payload capacity of 80 kg and a length of 2.4 m. It is rad tolerant (10 kGy) and can be used for dismantling, off-shore and heavy tools handling operations. This arm is commercialized by CYBERNETIX company.

Hydraulic Dual-Arm Mobile Working Platform (RODDIN)

One of the first targeted application of MAESTRO is RODDIN, a dual-arm Mobile Working Platform. This platform has been specified to carry out heavy-duty decommissioning and dismantling tasks in any nuclear facilities where usual technologies and tools should not be used. It includes two MAESTRO manipulators, an embedded hydraulic power station, as well as a radiation tolerant (10 kGy) intelligent electronics control system. This prototype is currently under development.

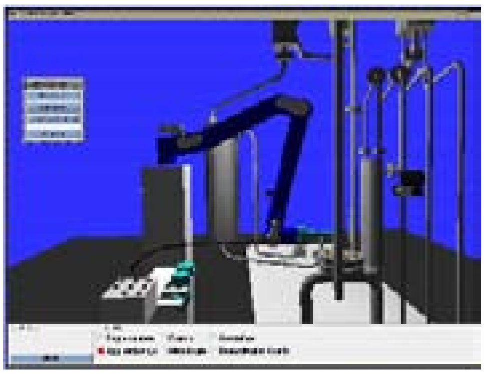


3. DEVELOPMENT OF ADVANCED TECHNOLOGIES FOR REMOTE HANDLING

Rad Hard Electronics Controllers

Rad hard electronics controller has been developed in order to control remote handling systems avoiding thick cables management and providing embedded intelligence capacity. An open and modular architecture fitting all the needs of telemanipulators has been developed and qualified up to 10 kGy of integrated dose. This development is commercialized by CYBERNETIX company.

Computer Aided Teleoperation Controller (TAO2000)



TAO2000 is a generic portable software package providing shared control optimizing human and machine performance. It allows to increase the speed and reliability of intervention tasks providing operators with teleoperation assistance functions like force feedback master/slave control, virtual mechanisms control, and other robotics functions. This software package is commercialized by CYBERNETIX company.

Interactive Environment Modeling (PYRAMIDE)

PYRAMIDE is a software package providing fast on-line modeling of remote environments by adjusting of pre-existing models or by estimating the position and orientation of the objects in the 3D space. It provides a wide range of user friendly tools for modeling in a manual or automatic way. This software package has been successfully applied for mobile robot navigation and off-shore inspection of oil rigs.

Virtual Reality for Telerobotics (MAGRITTE)

The efficiency and safety of remote interventions may be increased by using virtual reality techniques. 3D modeling based programming and operation systems, visual feedback, obstacle avoidance and operators training by means of realistic simulation are some of the benefits of this emerging technology for remote handling applications. The software package MAGRITTE is currently under development.

4. CONCLUSION AND RECOMMANDATION

The context of the nuclear industry worldwide is very favourable to the development and application of remote technologies in the next decades. The increasing pressure for reducing workers radiation dose ratings, in conjunction with the growing number of nuclear facilities to be decommissioned and dismantled should create the conditions of a significant size market for remotely teleoperated equipments.

However, a lot of remote technologies have already been developed and are now available from the industry. These technologies need to be experimented, tested and optimized in order to be well accepted by exploitation staffs. After a period a extensive test and experience analysis, new research and development projects in this field should be launched.

The analysis and comparison of real experiences and lessons learned from application of remote technologies in spent fuel management facilities should be an interesting topic to be developed.

THE STATE OF JAPANESE REMOTE TECHNOLOGY IN NUCLEAR FUEL CYCLE

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Abstract

There are many plants of nuclear fuel cycle in Japan. Fifty-one commercial nuclear reactors are operating. There are also another nuclear plants that include two uranium enrichment plants, five fuel conversion & fabrication plants, two reprocessing plants and other waste management facilities. Some plants are operated, maintained or inspected under a high-level radiation condition because spent fuel and high level radioactive waste are treated. Therefore many kinds of remote technologies have been applied to operation, maintenance and inspection of nuclear plants on the base of the Japanese robotics technologies that have been developed in many manufacturing industries like an automobile one.

This paper will report the remote technology for Japanese nuclear plants. In early days of nuclear, repair and inspection robots for nuclear power plant have been developed for reduce of operator's radiation exposure and increase of plant operation ratio. For further technical development, the project named "Advanced robotics technology" has been carried out from 1983 until 1990 by Advanced Robot Research Association. After this project, each company that was a member of the association applied these developed technologies to nuclear plant.

In Tokai reprocessing Plant, a radioactive leakage occurred in one of two dissolvers in April 1982 and the similar leakage occurred in another one in February 1983. JNC examined the leaked dissolver and planned to make repair using remote weld device. After the examinations of weld repair condition, design of devices, manufacturing and mockup test, repair work of the dissolvers started in September 1983 and completed during period of two and a half months. In another case, JNC has adopted full remote maintenance concept in a large cell to Tokai Vitrification Facility and Recycle Equipment Test Facility that will be used as a FBR fuel reprocessing test field. This remote maintenance concept consists of Two-arm Bilateral Servo Manipulator system and In-cell Crane in a large cell.

1. INTRODUCTION

In recent years robot technology is quickly spread in Japanese industry and half the number of robots in the world are operating in Japan. For example, about 800,000 industry robots are manufactured for every year in Japan and many robots are used for productive line of many manufacturing industries like an automobile one.

On the other hand, there are many plants of nuclear fuel cycle in Japan. A part of these plants are operated, maintained and inspected under high-level radiation condition because spent fuel and high level radioactive waste are treated.

Therefore many kinds of remote technologies have been developed for operation, maintenance and inspection of nuclear plant.

This paper will report the remote technology for Japanese nuclear plants.

2. STATE OF JAPANESE NUCLEAR PLANTS

In Japan there are many nuclear fuel cycle plants now that include commercial and research reactors, uranium enrichment plants, fuel fabrication plants, reprocessing plants and radioactive waste management facilities. (Refer to Fig.1).

Fifty-one commercial nuclear reactors are operating and the ratio of nuclear power to total power generation is about 37%. Two uranium enrichment plants that are JNC Prototype Plant and Rokkasho Uranium Enrichment Plant are in operation. Four fuel conversion and fabrication plants indicated to the following are in operation.

- Fabrication plant of Nuclear Fuel Industries Co.
- Fabrication plant of Japan Nuclear Fuel Co.
- Re-conversion and fabrication plant of Mitsubishi Nuclear Fuel Co.
- Plutonium fuel fabrication plant of JNC

Tokai Reprocessing Plant is in operation and about 936 HMT has been reprocessed. Rokkasho Reprocessing Plant is under construction and will start to operate in 2005. Rokkasho Vitrified Waste Storage Center and Rokkasho Low-level Radioactive Waste Disposal Facility are in operation. (Refer to Fig.2).

Especially power reactors, reprocessing plants and vitrified waste storage facility needs remote technology to treat spent fuel and high level radioactive waste.

3. DEVELOPMENT AND APPLICASION OF REMOTE TECHNOLOGY

Many kinds of remote technology have been developed from the viewpoint of reduce of operator's radiation exposure and increase of facility operation ratio in nuclear plants.

Some typical examples of development or application are described to the following.

3.1. 'Advanced robotics technology' project

This project aimed to develop robots that can carry out inspection, maintenance and rescue operation or other work in the field of nuclear power plant, undersea and disaster-preventing. This project has been carried out from 1983 until 1990 by national research institutions and Advanced Robot Research Association that were comprised of 18 companies and 2 national organizations.

In this project, total concept for robot and control system was investigated and some demonstration systems were manufactured based on this concept. Total robot system consisted of locomotion subsystem, manipulation subsystem, visual information subsystem, communication subsystem, high reliability subsystem and another subsystem. These functions of operation, locomotion and visual recognition were verified on a test field simulated a nuclear power plant. And the following elementary technologies were developed at the same time, that is, Motion stereo vision system, Optical wireless communication system, Manipulation, Ouadrupedal walking, On-wall locomotion, Radiation resistance, Fault-tolerant robot controller and Robot health care system. (Refer to Fig.3)

As the result, many robotics technologies were developed and basic technologies for future development of remote technology were established.

3.2. Repair of dissolver in Tokai Reprocessing Plant

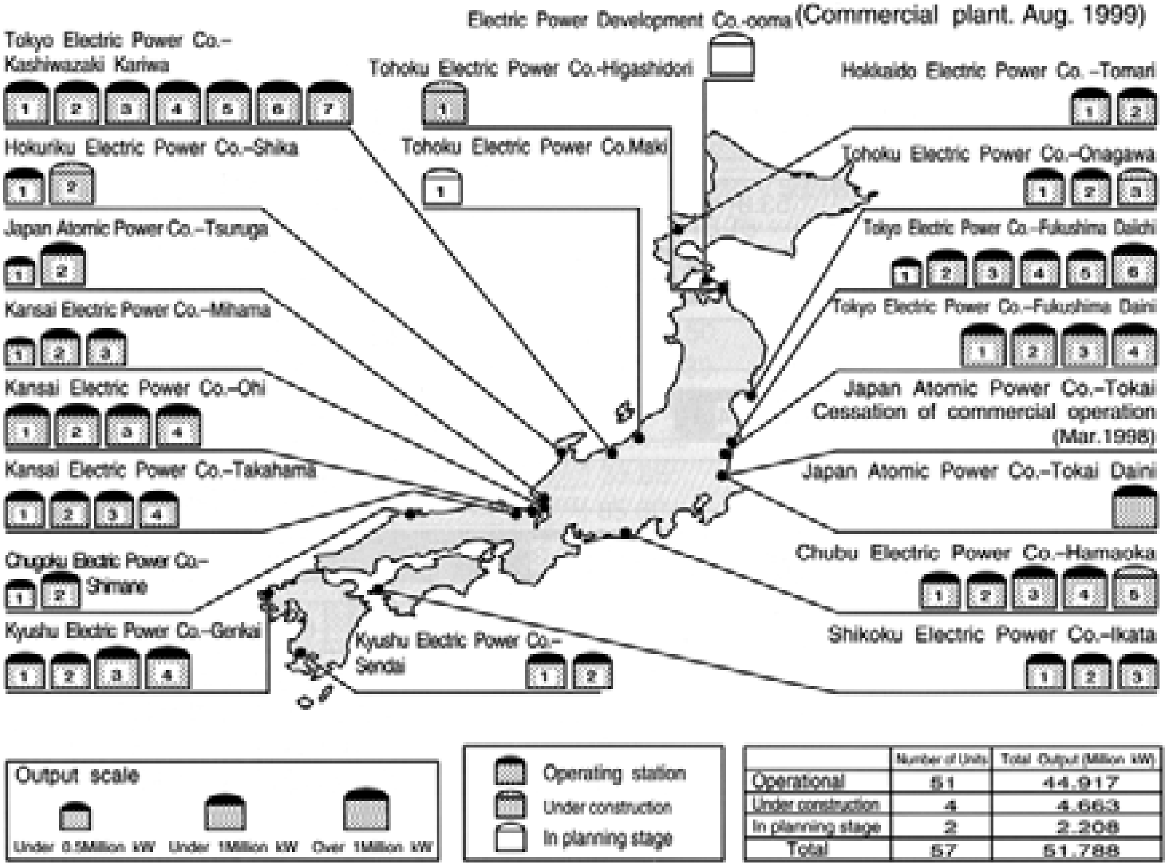
In Tokai Reprocessing Plant, a radioactive leakage occurred in one of two dissolvers in April 1982 and the similar leakage occurred in another one in February 1983. (Refer to Fig.4) The dissolver was consisted of two cylindrical barrels that were connected to a slab tank by four connecting pipes. Three leak defects were found on welding beads of these barrels by the series of inspection. After the first leakage, JNC examined the leaked dissolver and planned to make repair using remote welding device. The examination of welding repair condition, design of devices, manufacturing and mockup test etc. were completed for short term in spite of many difficulties, by August 1983. (Refer to Fig.5) Actual repair work of the dissolvers started in September 1983 and completed during period of two and a half months.

3.3. Full remote maintenance concept in a large cell

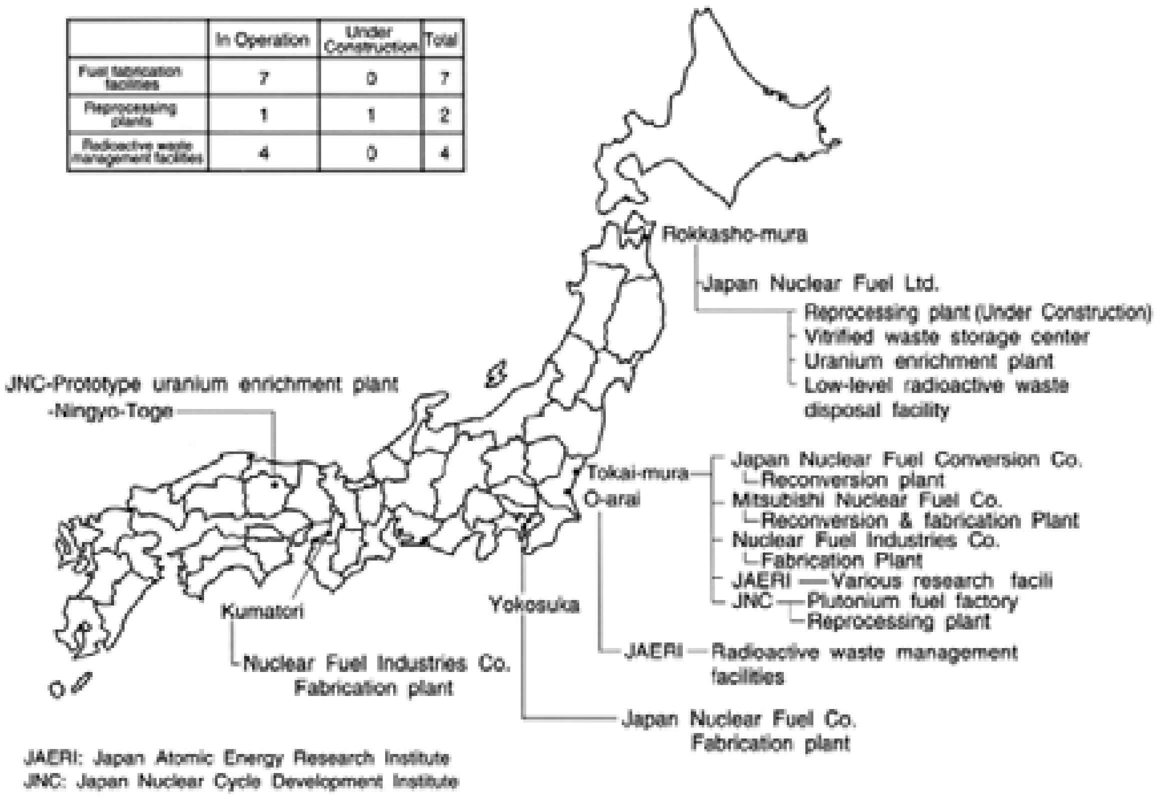
JNC decided to adopt the "Full Remote Maintenance Concept in a large cell" in order to increase the facility-operation-ratio and to decrease the operator's radiation exposure. In this concept, it is possible to repair broken equipment on its position by Two-arm Bilateral Servo Manipulator System (BSM) or to replace equipment and rack that is a module loading some equipment by BSM and In-cell crane. (Refer to Fig.6) BSM system includes two-arm Bilateral Servo Manipulator, transporter, viewing, signal and power transmission and man-machine interface subsystem. (Refer to Fig.7).

BSM has been developed since 1982 and has been applied to Tokai Vitrification Facility and Recycle Equipment Test Facility (RETF) that adopted the "Full Remote Maintenance Concept in a large cell". (Refer to Fig.8)

Nuclear Power Stations in Japan



	Number of Units	Total Output (Million kW)
Operational	51	44.917
Under construction	4	4.663
In planning stage	2	2.208
Total	57	51.788

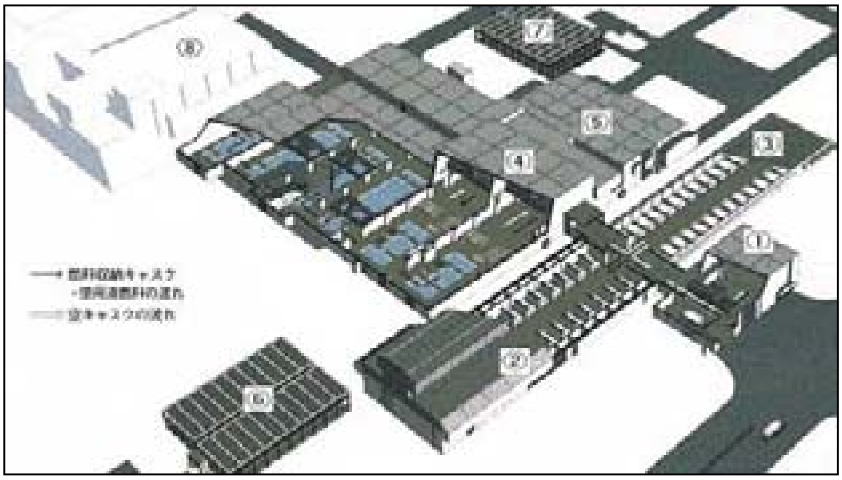


	In Operation	Under Construction	Total
Fuel fabrication facilities	7	0	7
Reprocessing plants	1	1	2
Radioactive waste management facilities	4	0	4

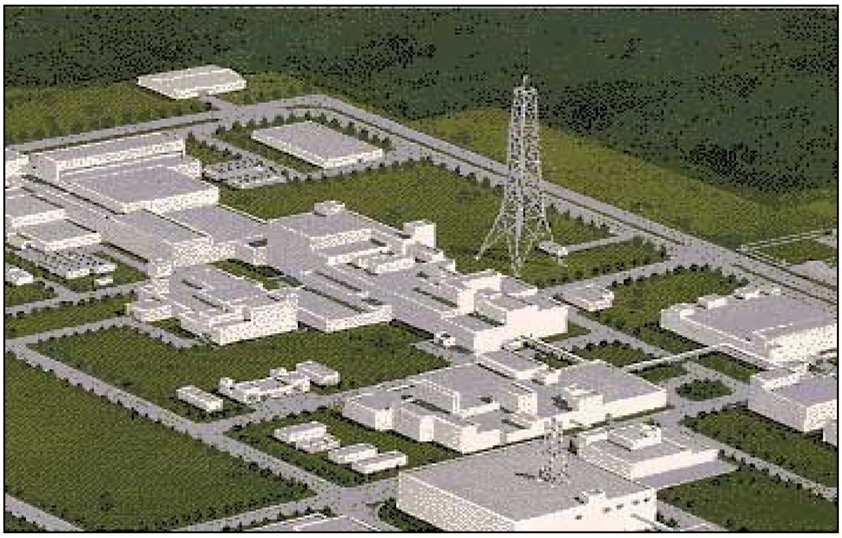
Souce: Nuclear Safety Commission: *White Paper on Nuclear Safty in Japan, 1998*

FIG. 1. Nuclear fuel cycle plants in Japan.

Spent Fuel Storage Facility (in operation)

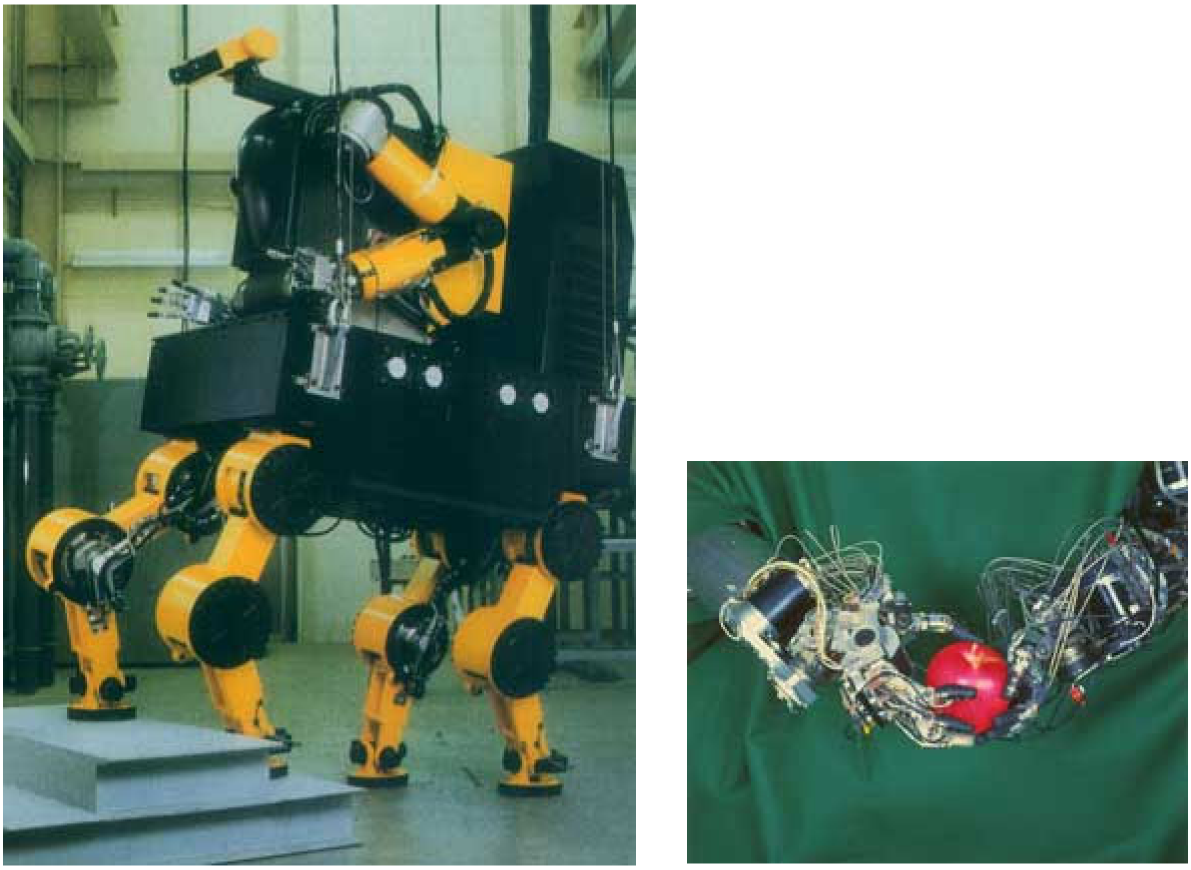


CG of Rokkasho Reprocessing Plant (under construction)

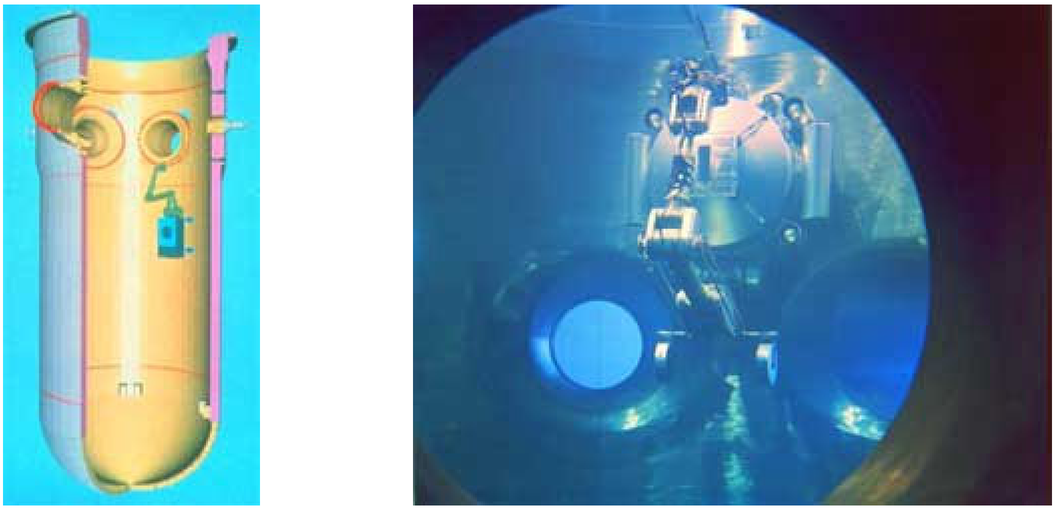


Rokkasho Vitrified Waste Storage Center (in operation)

FIG. 2. Rokkasho Site.

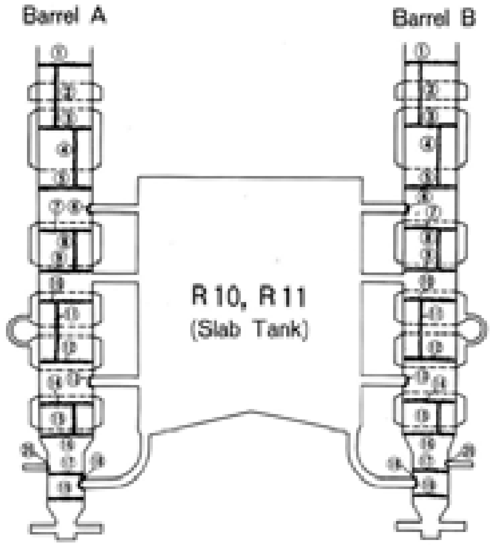


Demonstration robot



Inspection robot for pressure vessel

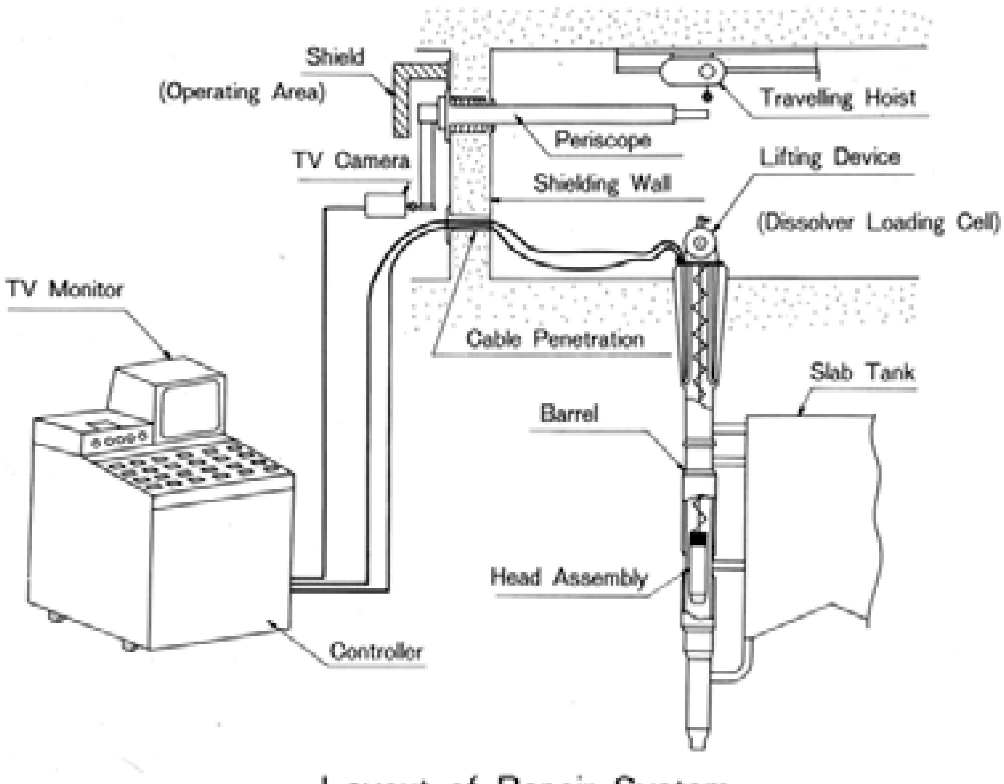
FIG. 3. Example of advanced robots.



Dissover	Barrel	Discovery of Leak	Location of Leakage
R10	B	February 1983	Circumferential Weld ⑭ Covered with the Steam Jacket
R11	A	April 1982	Circumferential Weld ⑭ Covered with the Steam Jacket
	B	July 1982	Weld ⑬ of the Third Connecting Pipe

Dissolver Barrel and Weld Bead No.

FIG. 4. Dissolver barrel and weld bead no.



Layout of Repair System

FIG. 5. Layout of repairs system.

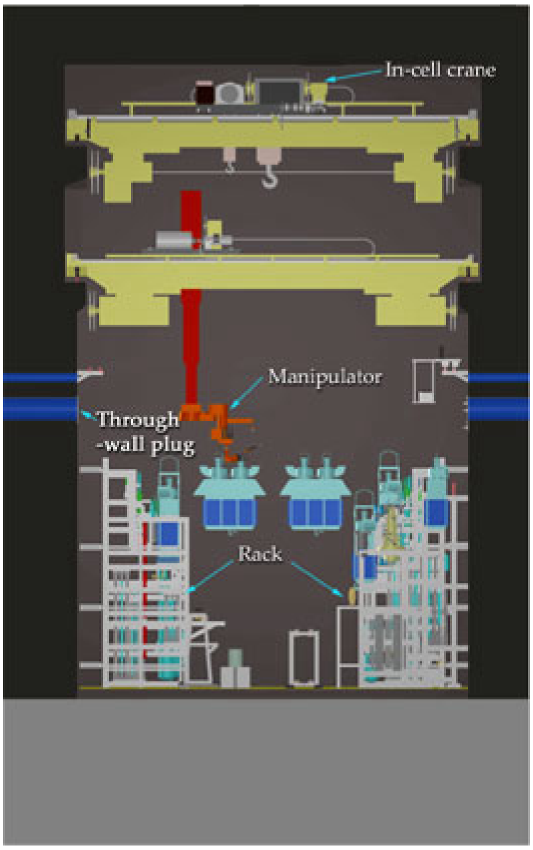


FIG. 6. Full remote maintenance concept in large cell.

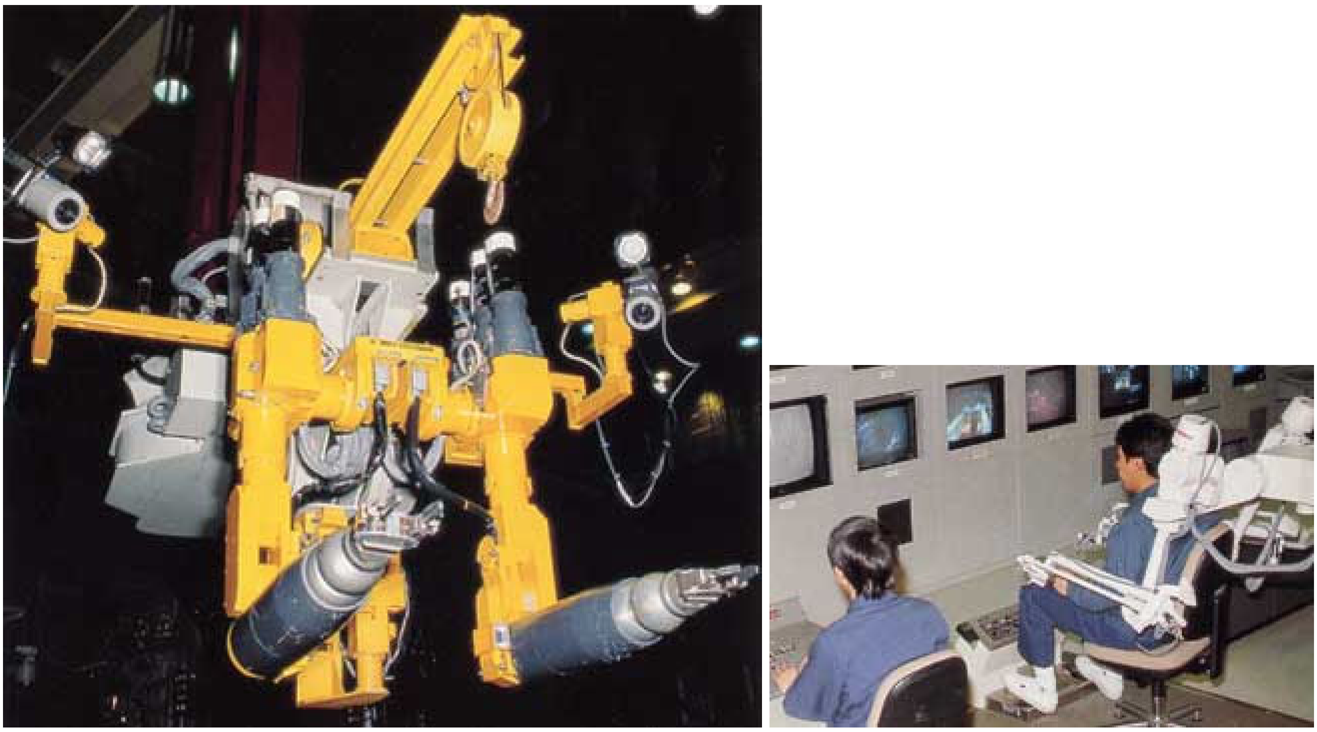


FIG. 7. Two-arm bilateral servo manipulator system.

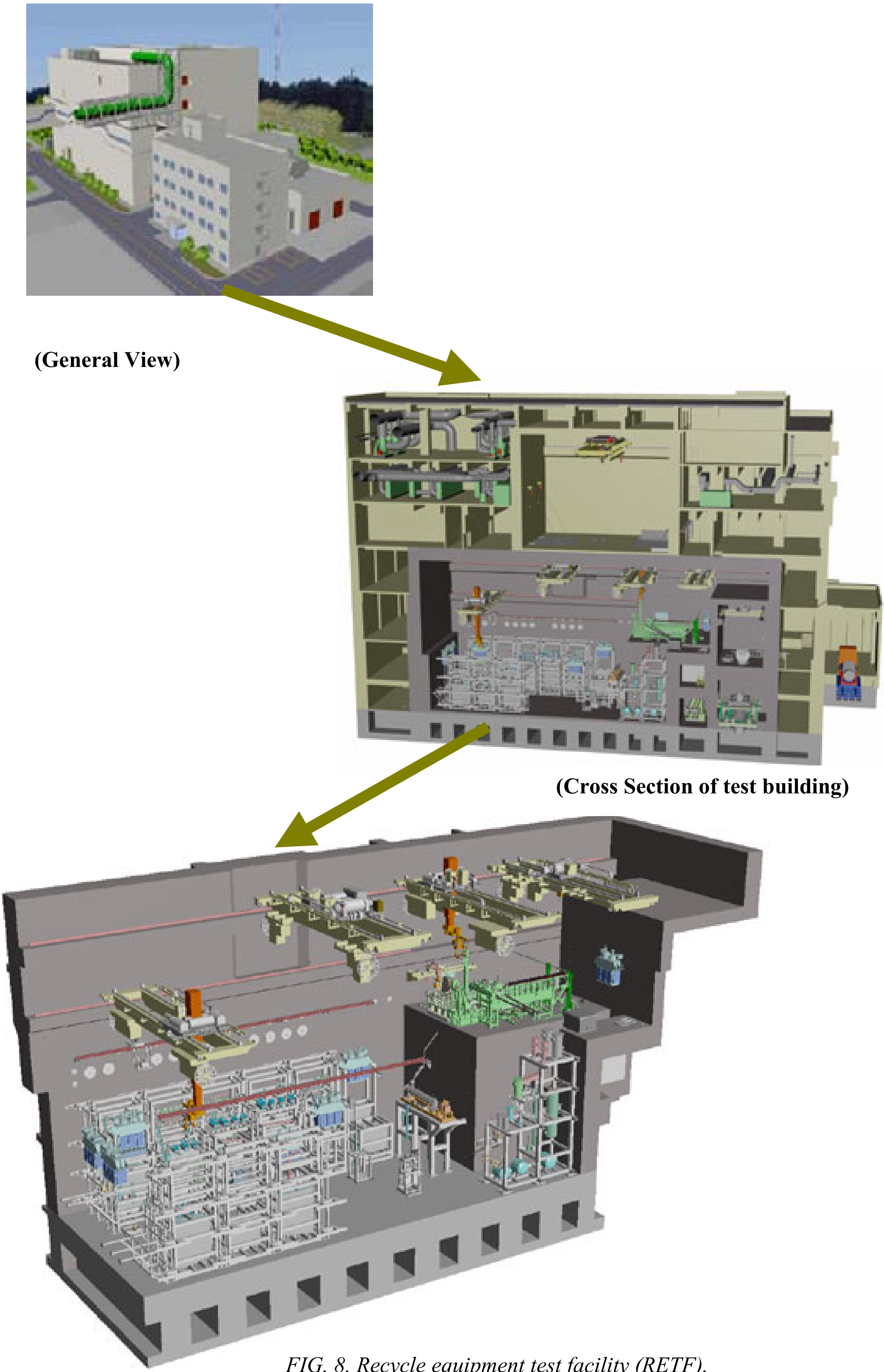


FIG. 8. Recycle equipment test facility (RETF).

Annex III

GRAPHIC SIMULATION OF REMOTE HANDLING OPERATION IN THE ADVANCED SPENT FUEL CONDITIONING PROCESS

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Abstract

Korea's primary energy consumption in 2001 was 197.8 million TOE, of which 97.4 % was imported. Nuclear energy is the only feasible alternative to meet the challenges of the energy security and the environmental protection. There are now 16 reactors in operation and 12 more reactors will be constructed by 2015. With the increase of the NPPs, the amount of the spent fuels also rapidly increased. Accordingly, the research efforts of country are directed toward developing efficient storage technology for accumulating spent fuels while providing the advanced fuel cycle concept as an alternative for spent fuel management. Some of these efforts is to develop the DUPIC fuel cycle and the Advanced Spent Fuel Conditioning Process (ACP). As well known, the concept of the DUPIC fuel cycle is to reuse spent pressurized water reactor fuel as a fuel for CANDU reactors without the reprocessing operations. The ACP is to reduce the volume of spent PWR fuels by removing volatile and high-heat load fission products and thus, by converting the spent fuel into a metallic form, which is more suitable for disposal in a repository.

In this paper, the remote handling technology developed for these processes is briefly summarized, including the fabrication process of DUPIC fuel pin, mechanical headend process of the spent PWR fuel, the 3D graphic simulator for the remote equipment design, and the telemanipultor for the maintenance of the process.

1. INTRODUCTION

Ever since the first nuclear power plant had been built in 1977, there are now 12 PWRs and 4 CANDUs in operation with a total capacity of 13.7 Gwe. Four more reactors, Younggwang #5 & 6 and Ulchin #5 & 6, are under construction as shown in Fig.1. According to the 5th national long term electricity supply plan made in 2000, the nuclear share in installed capacity will be increased to 33 % by 2015 compared to the present share of 27%. To meet the target share, 12 more units are planned to be inaugurated, including the four under construction, by the year 2015, with the potential retirement of the two oldest units (Kori #1 in 2008 and Wolsong #1 in 2013).

The cumulative amount of spent fuel from existing nuclear power plants reached 5,385 tU by the end of year 2001. With the long term nuclear power projection, it is expected that approximately 11,000 tU and 22,000 tU of spent fuels will be accumulated by the years 2010 and 2025, respectively.

To face up with the ambitious long-term nuclear power program, the reliable and effective management of spent fuel became a national mission in Korea. The Advanced Spent Fuel Conditioning Process (ACP), under development in KAERI, focuses on two ultimate targets of spent fuel disposal: the reduction of a spent fuel repository area and enhancement of the long-term safety of the repository. In support of the ACP development and the advanced fuel cycle concept, the mechanical head-end process, which is a dismantling process of the spent fuel assembly, has been developed and its cold demonstration has been performed. Also, the ACP equipment has been designed using the 3D graphic simulator. In this paper, R&D activities on the remote handling technologies of spent fuels associated with ACP are described.

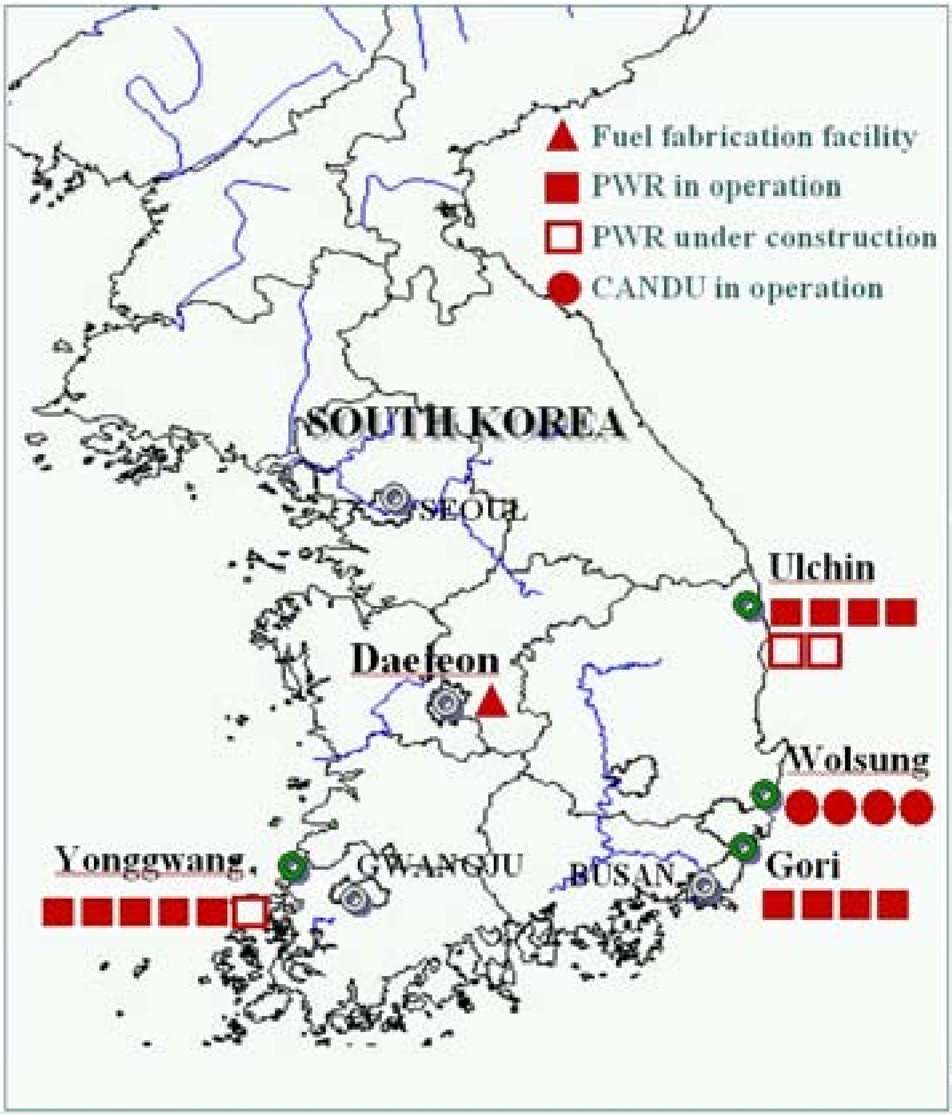


FIG. 1. Nuclear Power Plant in Korea (as of 2002).

2. SPENT FUEL DISASSEMBLING PROCESS AND REAL TIME 3D GRAPHIC SIMULATOR

2.1. Spent fuel disassembling process

KAERI has developed the mechanical head-end process in a pilot scale for storage and utilization of the spent fuel. The designed throughput is 1 assembly/week.

The process consists of an assembly downender, a rod extractor, a rod cutter, a fuel decladding device, a skeleton compactor, and the gantry-mounted telescopic manipulator as shown in Figs. 2 and 3. All the machines were designed and verified using the graphic simulator. Their performance was tested and verified by using the fuel prototype at the mockup facility.

The rod extractor consists of a clamping table, an extraction table, an extraction rotary head, a cradle, and a side transfer. The machine unfastens the securing nuts of the bottom nozzle so that the remote manipulator removes the bottom nozzle form the fuel assembly. And the machine automatically extracts one rod at a time from a 17 x 17 PWR fuel assembly mockup and transfers each rod to the adjacent rod cutter.

After removing all the fuel rods, the skeleton compactor compacts Non-Fuel Bearing Components (NFBC) of the fuel assembly for permanent disposal by implementing the method of cutting after compression.

The rod cutter cuts the fuel rods to the optimal length for pellet decladding. The machine utilizes a tube-cutting method, which shows a better cutting performance compared with existing cutting methods in terms of amount of the debris induced from cutting process and the possible risk of fire.

The decladding device mechanically extracts the fuel pellets from the cut rod by inserting a pressing pin into the clad tube and thus pushing the pellet. The device provides the most effective operation in terms of recovery rate and operational safety.

The remote manipulator suspended by a telescopic tube, which is movable into X, Y, and Z direction. The manipulator is used for handling and transporting fuel rods, bottom nozzles, and skeletons, etc. Also, it is used for the remote maintenance of the ACP equipment.

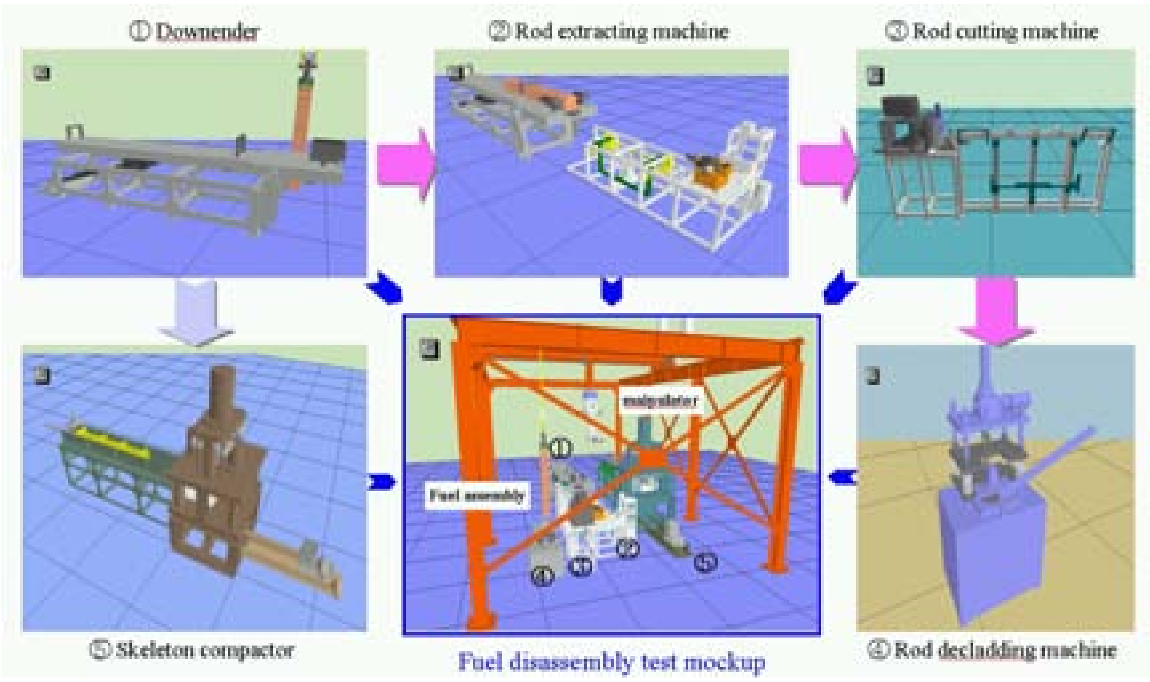
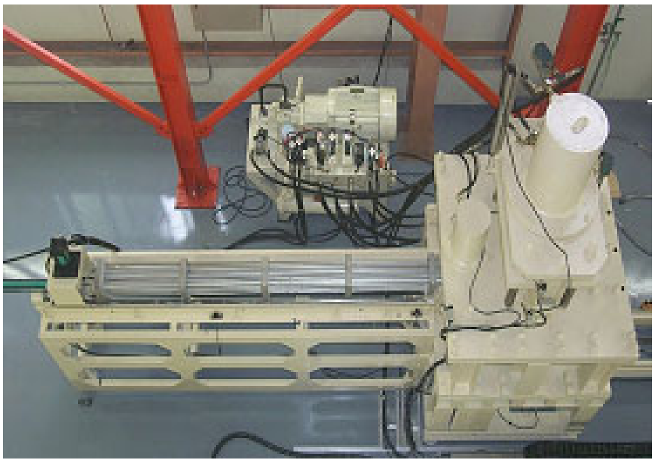


FIG. 2. Digital mockup of spent fuel disassembling process.

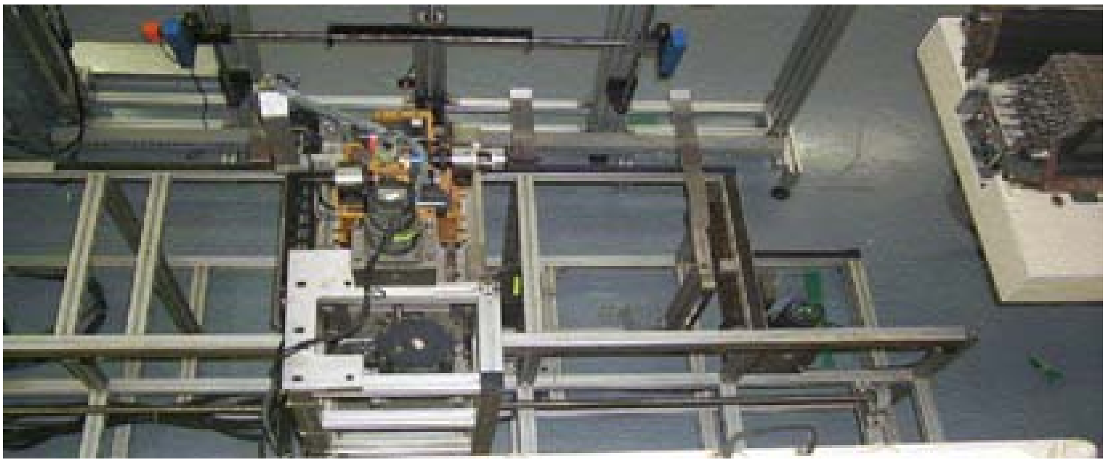
(a) Rod decladding machine

(b) Rod cutting machine



(c) Skeleton compactor

(d) Telescopic manipulator



(e) Rod extracting machine

FIG. 3. Devices of the spent nuclear fuel disassembling process.

2.2. Real time 3D graphic simulator

To monitor and supervise the headend process for reliability of operation, the real time 3D graphic simulator has been developed. As shown in Fig. 4, all the disassembling machines are installed in a spent fuel disassembling process test mockup (DPTM) facility isolated with the operators before install in a hot cell. The control PC of each machine is located in a control room. The control PCs are physically connected to the TCP/IP network and transmit the operational information to the graphic simulation server. The control PCs calculate the motion command of the machine based on these signals and forward it to the graphic simulation server through a network.

For graphic modeling and simulation of the spent fuel disassembling process, a commercial software package, Interactive Graphic Robot Instruction Program (IGRIP), supplied by Deneb Robotics Co. is used. For a realization of real-time graphic simulation, a Graphic workstation, Silicon Graphics model Onyx RE2, which has a high performance is used. For the mechanical devices, a 3D model is drawn and some kinematics property is assigned to the 3D model to build the corresponding virtual device. According to the operation information of the real device, the virtual device is operated and tested in a simulation program. After test, the virtual device is put on the same location as that of the corresponding real device. Fig. 5 shows the virtual workcell for monitoring the operation of each device in the spent fuel disassembling facility.

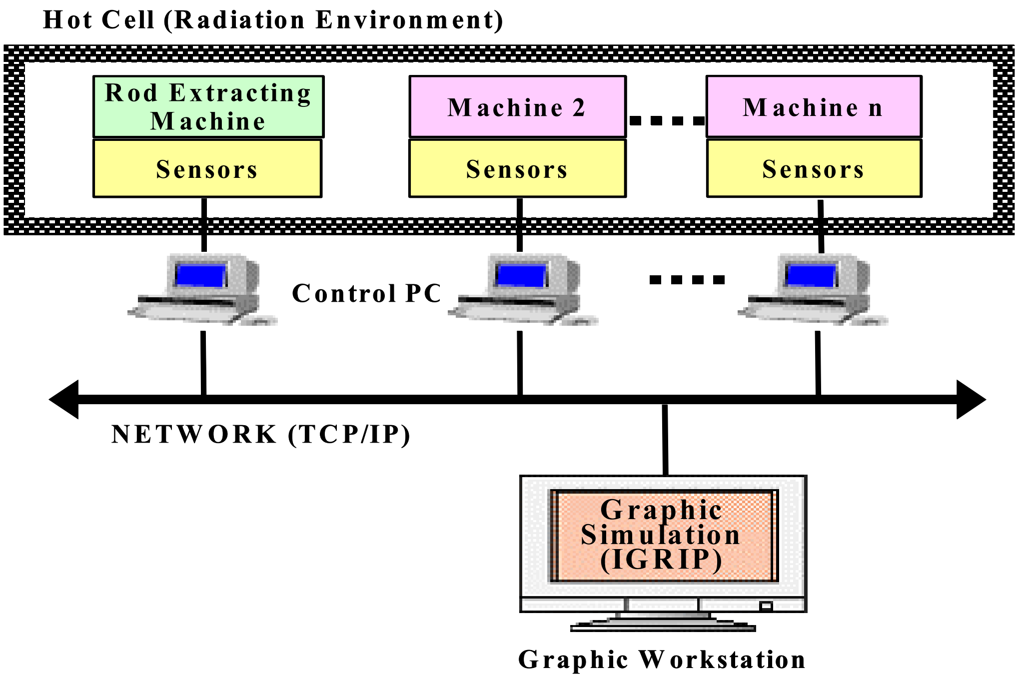
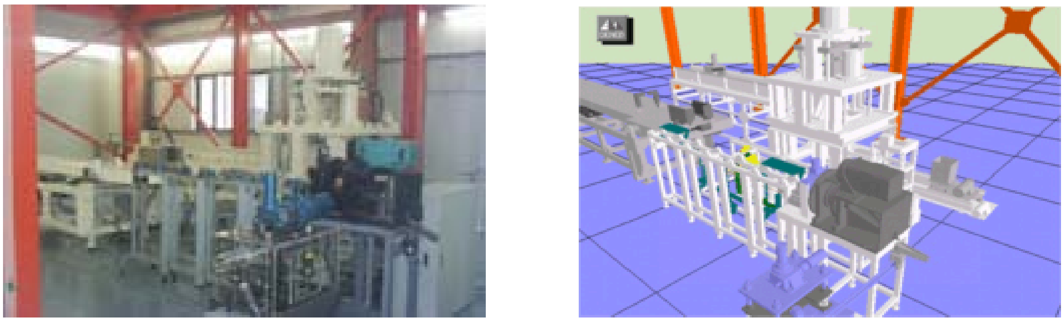


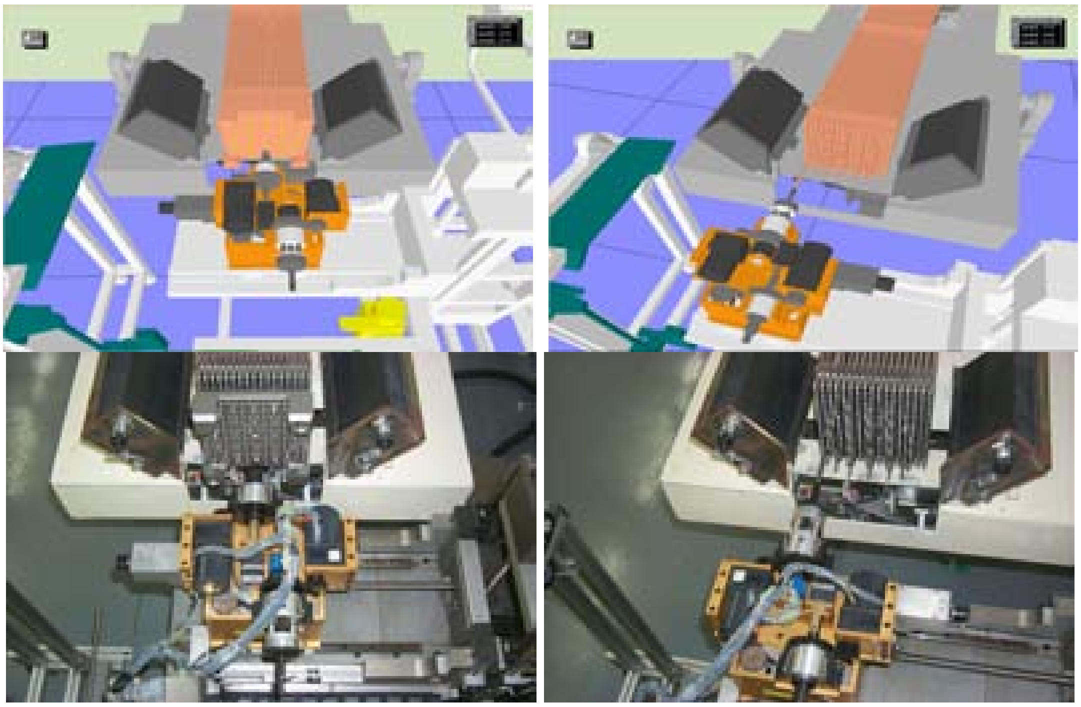
FIG. 4. Work environment for a mechanical disassembling process.



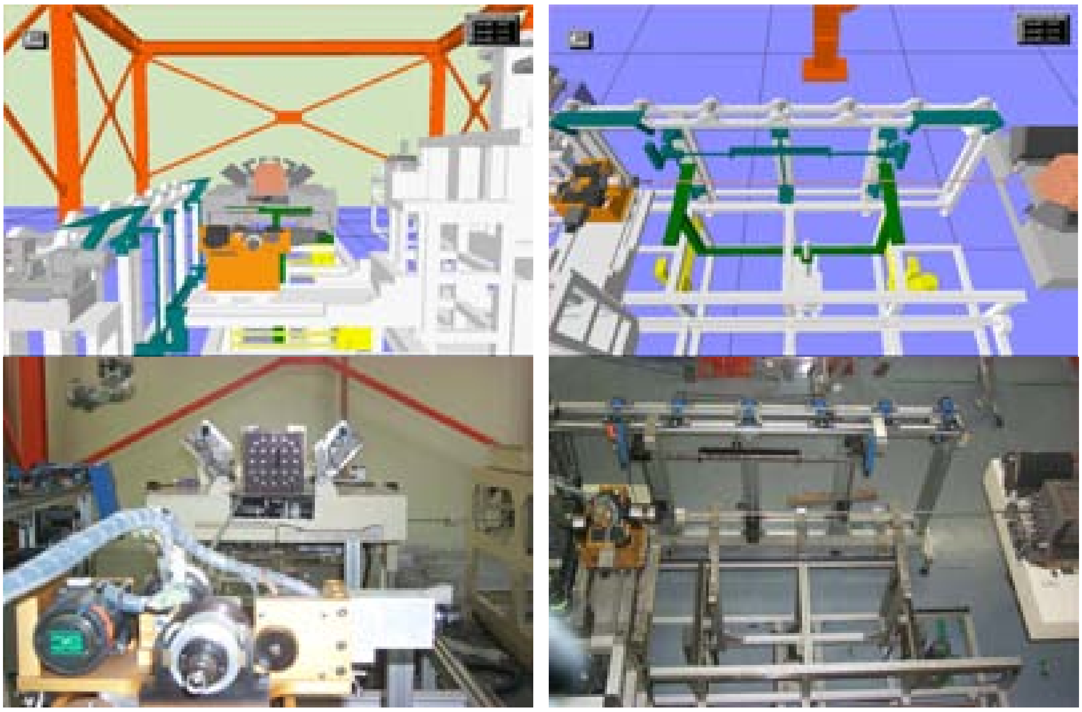
(a) Real Workcell **(b) Virtual Workcell**

FIG. 5. Workcell of the spent fuel disassembling facility.

The performance of the developed simulator should provide reliability and satisfy the real-time specification. To achieve this purpose, we tested a virtual simulator constructed for monitoring one real device prior to building the overall workcell. By connecting the control PC of the real machine to the 3D graphic simulation server through a TCP/IP network, real-time graphic simulation was successfully demonstrated. As shown in Fig. 6, the optimal views of the detailed operation are served to the operators so that the operators can easily monitor the operational status of the actual machine. For better synchronization of each operation between virtual and real devices, we adjusted the simulation speed by setting the GSL simulation variable, based on the pre-measured actual speed of device, because the simulation performance and the software real-time features are dependent on the performance of the graphic workstation. The simulation results show that the motion of the graphic simulation was synchronized well with that of the actual machine according to the operational data.



(a) Loosen nuts **(b) Extract rods**



(c) Cradle up **(d) Release rod**

Fig. 6. Real time simulation of operation of rod extractor.

3. GRAPHIC SIMULATION OF REMOTE HANDLING OPERATION IN ADVANCED CONDITIONING PROCESS

The advanced conditioning process (ACP) of the spent fuels is being developed in a laboratory scale. As shown in Fig. 7, the spent fuel is treated in a molten salt (LiCl) bath to remove volatile and high-heat load fission products and thus, to convert the spent fuel into a metallic form, which is more suitable for disposal in a repository. This process will be implemented in the IMEF hot cell at KAERI.

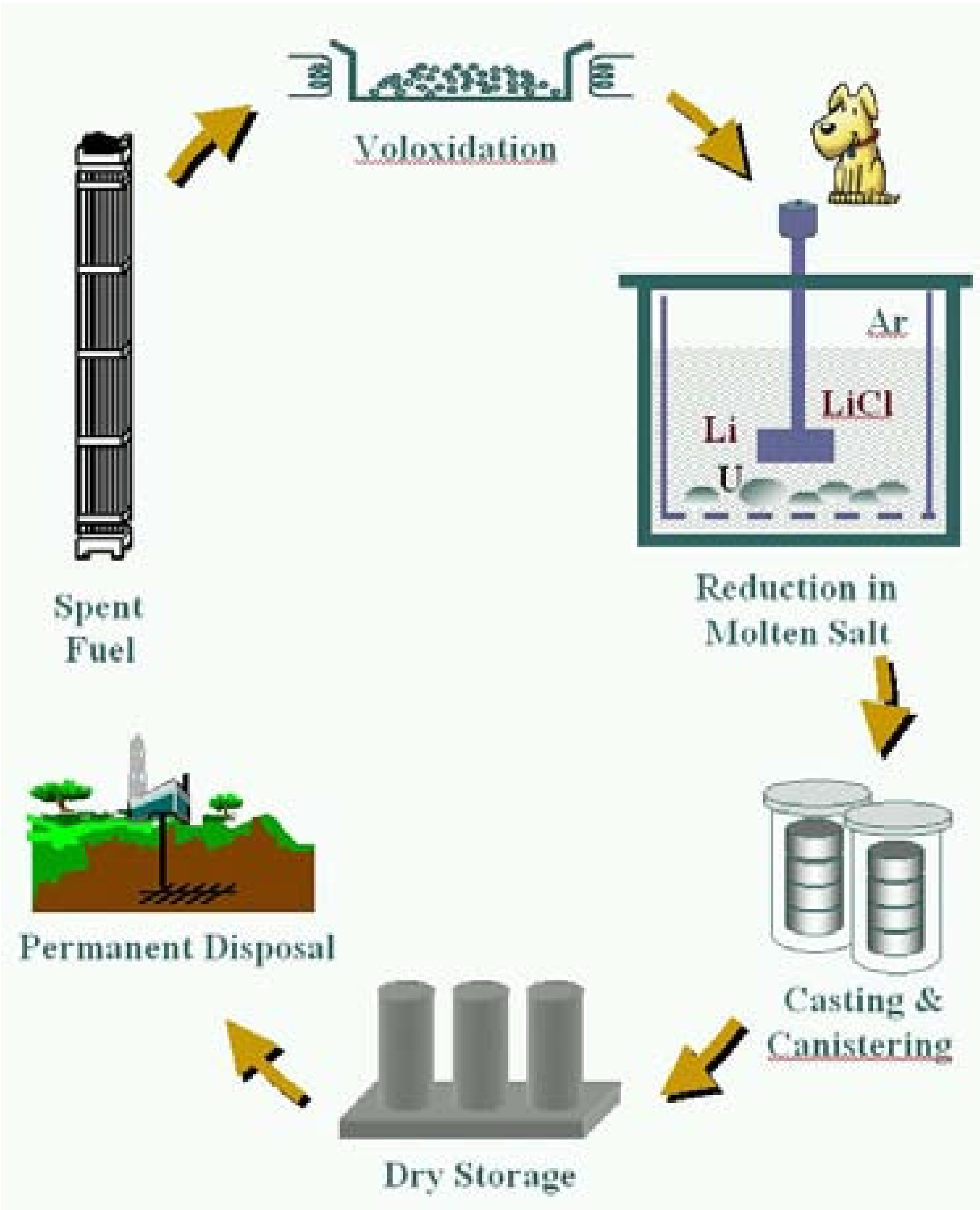


FIG. 7. Concept of AC.

The process consists of several unit processes such as decladding, voloxidation, reduction and smelting process. Fig. 8 shows some of these devices. In the process, high radioactive material including the spent fuel is to be handled in a hot cell. Thus, the process equipment should be optimally placed within the workspace of the wall-mounted slave manipulator for the maintenance operation. Also, the slave manipulator with the end effectors should be properly positioned and oriented for the dedicated maintenance operation. Hence, the workspace and the motion of the slave manipulator, as well as, the remote operational task should be analyzed before installing the manipulators and the hot cell equipment.

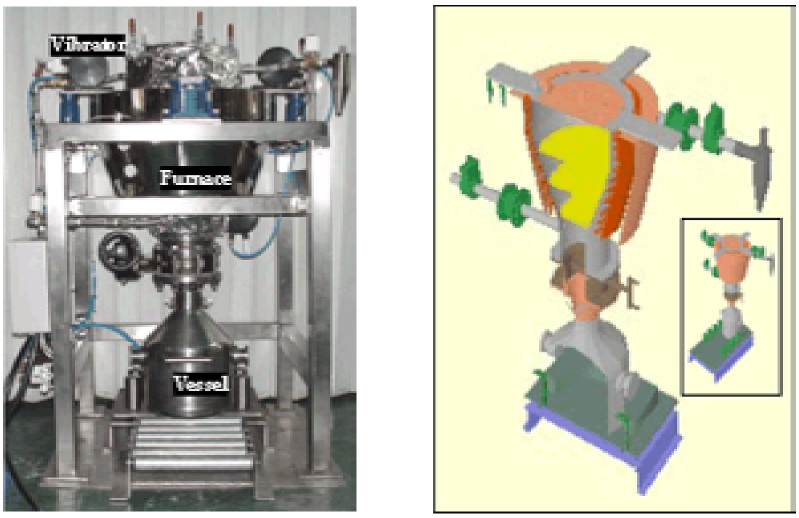
For this purpose, the 3D graphic simulator, which simulates the remote operation of the advanced conditioning process (ACP), is developed. For the graphic simulation, all the process equipment of ACP and Maintenance/Handling Device are modularized in consideration of the radiation exposure, the thermal resistance, and the corrosion resitance of the material. The various modules are drawn in 3D CAD models and are assembled into the devices using IGRIP.

3.1. Graphic model of the process equipment and handling devices

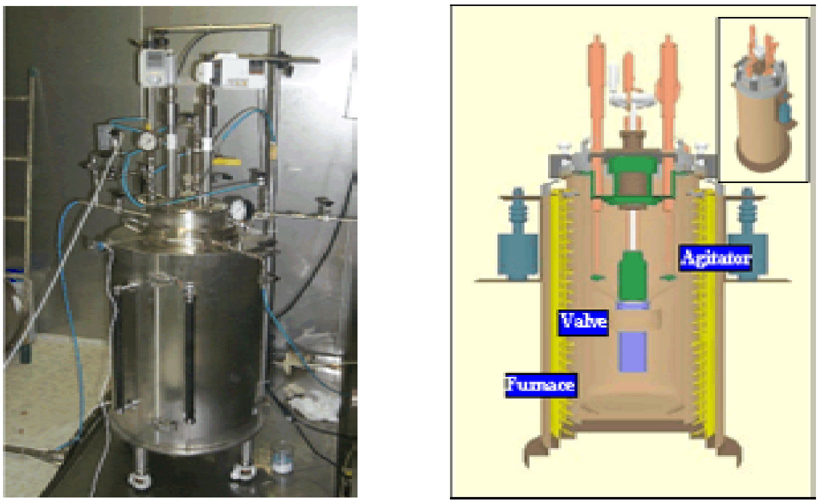
Process equipment

The voloxidizer transforms the UO_2 pellet into the U_3O_8 powder, by heating and supplying air into reactor. This equipment consists of furnace, vibrator and air cylinder for moving up and down the vessel.

The reduction reactor extracts the U metal from U_3O_8 powder. This equipment consists of a furnace that heats and dissolves the lithium, an agitator that mixes lithium and powder of U_3O_8, and the valve that exhausts a uranium and lithium solution.



(a) Voloxidizer



(b) Reduction reactor

FIG. 8. Process equipment.

Master-slave manipulator

The master-slave manipulator (MSM) is widely used as a remote handling device in the hot cell. Fig.9 shows the working range of the master-slave manipulator. For the graphic simulation, the MSM is drawn in 3D CAD model using IGRIP as shown in the figure. The size and shape of the models for all drawings coincide with the actual ones of the MSM. The standard coordinates are given to the devices, which are the graphic models of the moving parts of the MSM. Each device is assigned with various mobile attributes such as relative position, kinematics constraints, and a range of mobility.

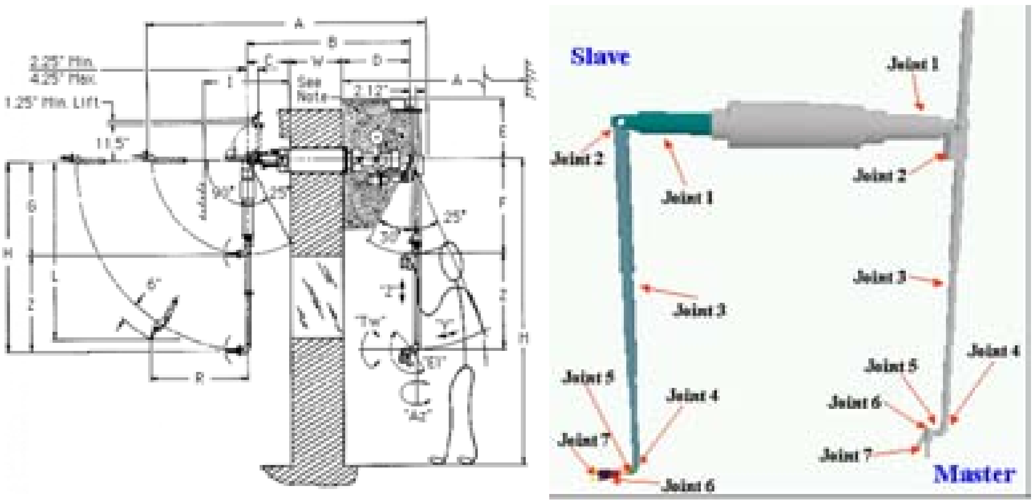


FIG. 9. Master-slave manipulator.

Device for transporting the nuclear material

Typical devices used for transportation of the U_3O_8 powder in a hot cell include a crane, a grapple and a vessel. The vessel contains U_3O_8 powder, and has a shutter. The grapple is suspended by the crane, which transports the vessel onto the reduction reactor. To feed the U_3O_8 powder into the reduction reactor, the vessel should be rotated along the axis of furnace by 180 degree. By turning the handle on the grapple, the vessel can be rotated and this is accomplished by using the MSM. After rotating the vessel, the shutter of the vessel is opened, and the powder is fed into the reduction reactor. Fig. 10 shows the 3D graphic model of the crane, the grapple and the vessel.

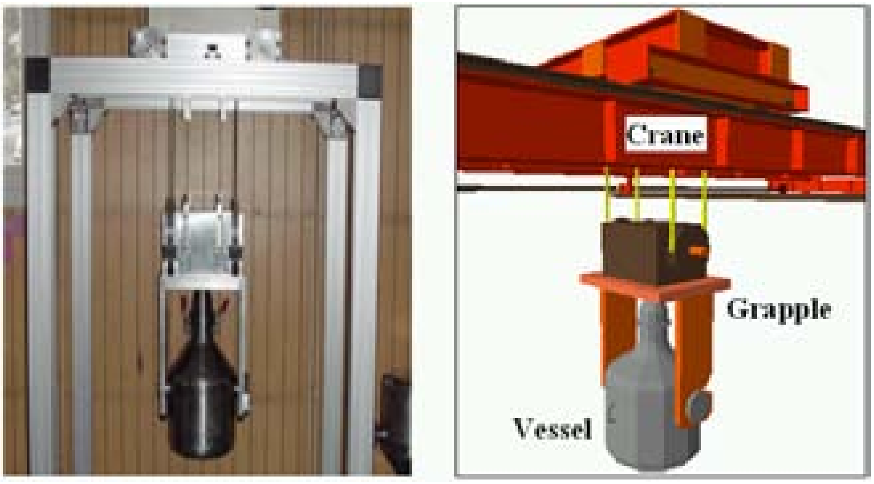


FIG. 10. 3D graphic model of grapple, vessel and crane.

3.2. Hot cell layout for ACP

The process flow of the ACP is shown in Fig. 11. The hot cell is divided into two areas, air cell and inert cell. The processes for decladding and voloxidation are carried out in the air cell and the processes for reduction and smelting of U-metal are conducted in the inert cell.

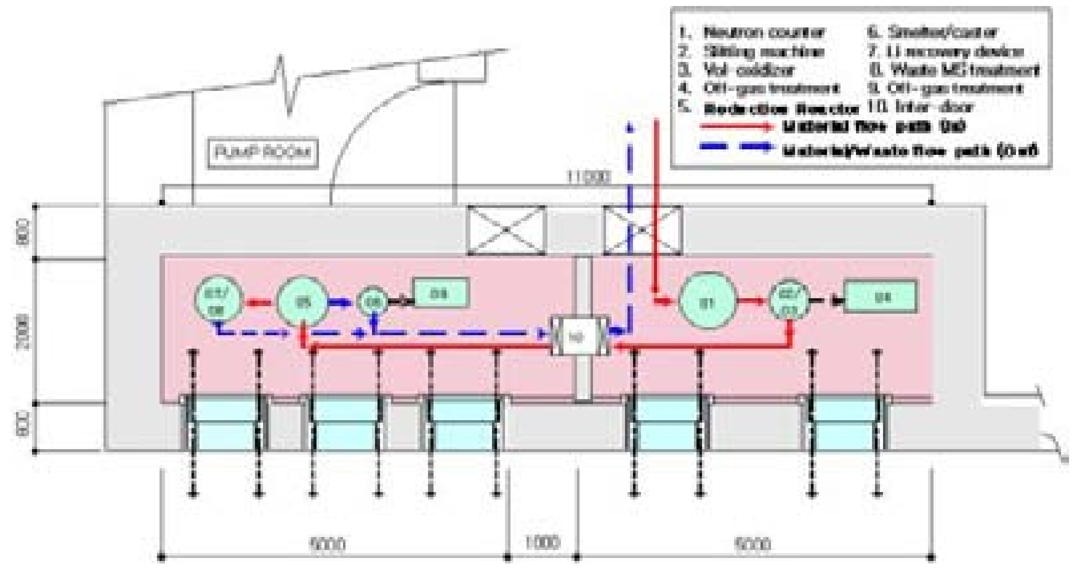
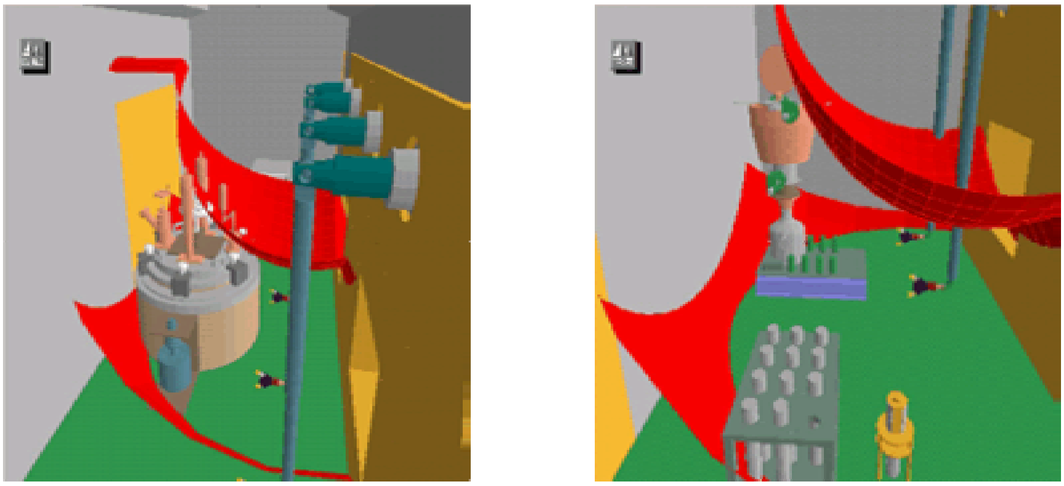
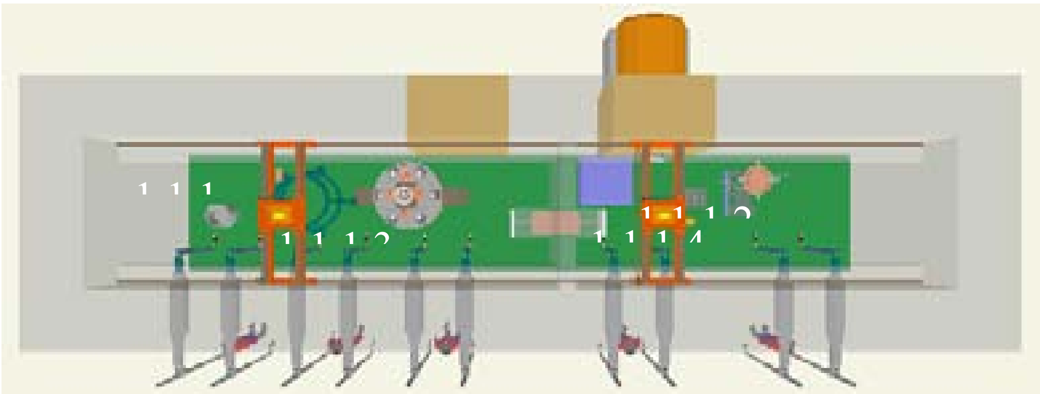


FIG. 11. Process flow of ACP.

For the hot cell arrangement of the process equipment, the work space of the remote handling and maintenance system is analyzed. Fig. 12 shows the work space of the master-slave manipulator and the virtual workcell of ACP based on the process flow. In the work-cell, the master-slave manipulator is mounted on the hot cell wall and several equipments such as crane, voloxidizer, reduction reactor, smelting furnace, non-destructive assay (NDA) system, etc. are arranged in the hot cell.



(a) Work space of M/S manipulator



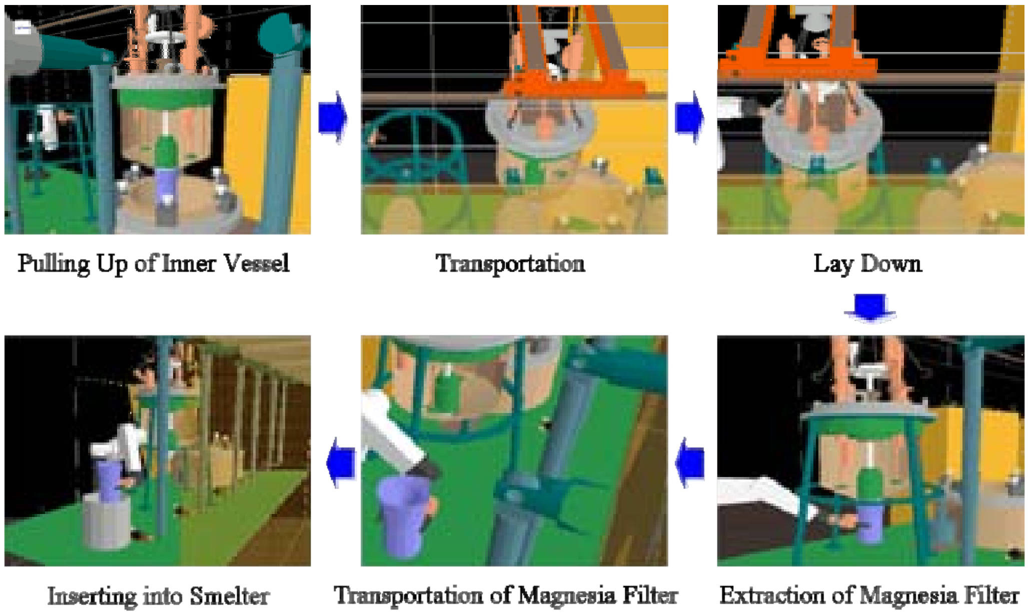
(b) Hot cell layout (Digital mock-up)

FIG. 12. Work space of M/S manipulator and hot cell layout.

3.3. Graphic simulation of remote handling for the nuclear material in hot cell

Several types of nuclear material are handled in the ACP process such as rod cuts, spent fuel pellet, spent fuel powder, U-metal, U-metal ingot. To establish the safe operation procedure and utilize the hot cell space effectively, the analysis of nuclear material handling and transport system is required. To do this, the digital mock-up (Fig. 12-b) of the real environment is implemented and the scenario of the handling process is established for the graphic simulation. The scenario and the simulation of U metal handling process is shown in Fig. 13.

(a) Scenario of the U metal process



(b) Graphic simulation of the U metal process

FIG. 13. Scenario and graphic simulation of U metal handling process.

CONCLUDING REMARKS

The Advanced Spent Fuel Conditioning Process (ACP) is under development in KAERI to achieve two ultimate targets of spent fuel disposal: the reduction of a spent fuel repository area and enhancement of the long-term safety of the repository. In support of the ACP development and the advanced fuel cycle concept, the mechanical head-end process has been developed and its cold demonstration has been performed so far. Also the 3D graphic simulator, which simulates the remote operation of the ACP and the headend process, is developed to verify the equipment design as well as to analyze the remote operation task before installing the equipment in a hot cell. The developed simulator for the headend process has a function of remote monitoring the actual devices connected through the Internet in real-time.

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Annex IV

REMOTE TECHNOLOGIES IN SPENT FUEL MANAGEMENT IN THE RUSSIAN FEDERATION

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ABSTRACT

This paper provides a summary of remote technology development and applications in spent fuel management in the Russian Federation.

1. INTRODUCTION

Nuclear power in Russia is based on reactors of 4 types: RBMK-1000, WWER-440, WWER-1000 and BN-600. Table I presents the main characteristics of spent fuel from Russian power reactors. The annual spent fuel arisings amount to about 800 tU. By now ~10000 tU have been put in storage facilities. The spent fuel from WWER-440 and BN-600 reactors are being reprocessed at the RT-1 plant of the 400 t/a capacity at the site of the Combine “PO MAYAK”. The WWER-1000 spent fuel is shipped after 3-year cooling at AR-pools to the regional storage facility located at the site of the Mining and Chemical Combine near Krasnoyarsk. The facility functions as an accumulator up to 2015 when the reprocessing plant RT-2 is put to operation.

Table I. Characteristics of spent fuel from major types of Russian power reactors

Characteristic	**Reactor**			
	WWER-440	**WWER-1000**	**RBMK-1000**	**BN-600**
1. Capacity, MW (thermal)	1375	3000	3200	1470
2. Initial, tU	42	66	180	7,5
3. Average burnup, MWd/kg	36,0	44,0	24,0	60
4. Annual discharge, tU/yr	12,5	21,0	50	6,2
5. Number of fuel assemblies (FA) in core	349	151	1610	370
6. Uranium quantity in a FA, kg	120	437	114,7	20,3
7. Length of FA, mm	3217	4570	10030	3500
8. Outer diam. of fuel rod (FR), mm	9,1	9,1	13,6	6,9
9. FR cladding thickness, mm	0,65	0,67	0,90	0,4
10. Activity after 3-year cooling, MCi/tU	0,65	0,78	0,5	3,06
10. Energy release after 3-year cooling, kW/tU	3,0	3,6	2,5	7,0

RBMK spent fuel is not shipped from the NPP site. The fuel is cooled at AR-pools during 1,5 years and then is transferred by an on-site TK-8 container from the power unit to an AFR storage facility of the 2000 tU storage capacity located at the NPP site. By now the cumulative amount of about 7520 tU (about 65500 FAs) has been stored at the sites of NPPs with RBMK reactors. The capacities of the operating storage facilities will be exhausted within 6-9 years considering storage capacity increase by a factor of 1.6 – 2. Besides, in some pools the spent fuel has been stored for already 25 years, which, period closely approximates that admissible for the wet storage mode (about 30 year). In this connection the change-over to the dry storage stands among the most vital problems of RBMK spent fuel management, especially as the world experience in dry storage points to the long-term retention of fuel cladding integrity under dry storage conditions.

The RBMK fuel assembly is distinguished by its length (10 017 mm). Therefore, the demand arose for designing a special cell for RBMK assembly separation in the process of fuel preparation for long-term dry storage.

This report deals with remote technologies of spent fuel management both currently available (for ex. at the RT-1 plant of the "PO MAYAK") and still under development (for ex. the compartment of preparing RBMK-1000 spent fuel for long-term dry storage at the Leningrad NPP)

2. SPENT FUEL MANAGEMENT AT RT-1 PLANT

2.1. SF Reception and Storage

The sequence of the main transport-technological operations on cask unloading is shown in Fig. 1.

The railway car arrives to the transport corridor of the unloading area. The doors on the car roof are opened, the TK-6 transportation cask is depressurized (through special ventilation system), cask lid unbolted and lid bolts are removed.

Further unloading operations are remotely controlled from the control board with the cask staying in the railway car. The observation of the unloading process is performed with TV cameras. A 15 t crane removes the cask lid, draws the filled baskets from the cask and puts them on an elevator of 15 t capacity which transfers the baskets to a storage facility. Here a 15 t crane removes the basket from the elevator and places it to the storage position.

Baskets with spent fuel are stored in water pools which have the total capacity of 560 tU. Then the fuel is remotely transferred from the interim storage facility to the preparation cell for cutting.

2.2. Spent fuel preparation, cutting, and dissolution.

In the preparation cell the end fittings of fuel assemblies (heads and end pieces) not containing fuel are cut off using a special mechanism. The cut off parts are loaded into transport tanks and dispatched by a special vehicle on a linear asynchronous engine along the protected platform for long - term storage.

The prepared fuel assembly comes to the shearing machine where it is flattened and cut into pieces.The shearing machine is unique and has more than a dozen of different units and components, the main one being the knife unit (see Fig. 2). The main operation is performed within the belly of the knife unit, that is, where nuclear fuel is opened and the structural materials of fuel assemblies are cut into small pieces of the given sizes. The Russian machines use unique knife units with 2 straight cutting edges. The service life of the knives is 230 thousand cuts. It is provided by multiple components the knife unit consists of and the use of a special shearing diagram. Since the shearing produces 1 – 2 % of pieces with larger sizes than it is specified, the pieces falling down the slide are received by an inertial sieve of preset mesh sizes. The pieces remained on the sieve are placed by a manipulator into the knife unit for repeated cutting.

The pieces of fuel rods passed through the sieve and are poured into a batch-operated dissolve where SF is dissolved. All operations with fuel assemblies and end pieces are carried out remotely using different type of manipulators.Pieces of claddings and other construction components are washed and after control dissolution are withdrawn from the dissolver and using a pulse pneumotransport are transferred through a pipeline to the storage bays for long-term storage where for fire safety reasons they are stored in a mixture with alumina.

2.3. Solvent Extraction Process

The SF solution is transferred for clarification and extractive purification from fission products. Uranium and plutonium purification from fission products and their separation are done in the 1st extraction cycle. Further purification is carried out in the separate uranium and plutonium streams.

The total purification factors from fission products are: 1×10^7 for uranium and 1×10^8 for plutonium. The exposure dose rate from the end product is 1.7×10^{-3} mcR/s kg for uranium, that for plutonium is 0.1 mcR/s kg. The end products from WWER-440 SF reprocessing are:

- melt of hexahydrate of uranil nitrate enriched to 2.0 - 2.4 % in 235 U (due to mixing of highly enriched uranium received in reprocessing SF from transport and BN reactors). The melt goes to an enterprise of the branch and is used for fabrication of RBMK reactor fuel;
- plutonium dioxide coming for interim storage into a special store. In future the end product of the plutonium line will be mixed uranium - plutonium fuel (MOX) fuel for fast reactors.

At the RT plant 100 % remote control and monitoring of the process is used. The operations requiring scrupulous attention to their sequence and duration (valves, drives, etc.) have programmable control.

The plant uses a three-zone layout of rooms with independent ventilation of each zone. The air from each vault goes through a tubular corridor towards the filter plant (a two-step air purification) and then is vented to the atmosphere through a tall stack (H = 150 m).

All types of contaminants in air exhausts are specified but in practice the air activity releases at RT plant are as follows:

α – release: 0.7 of the prescribed limit;
β – release: 0.2 of the prescribed limit;
iodine – 0.07 of the prescribed limit.

The first zone accommodates the equipment with radioactive materials behind the biological shielding, the second zone — the equipment for repair works, the third zone — the operator's and control rooms.

In the rooms of the zones pressure drop of 5 – 10 m w.g. is maintained, so that at opening the access ports and doors between the zones or at loosing the zone tightness the airflow is directed from the cleaner to more dirty rooms. This provides continuous control by means of not less than three barriers against radionuclide release into the environment.

The equipment of short service life has redundancy. Failed pumps, control and measuring instruments, valves, etc. are remotely changed using special mechanisms without stopping the process.

3. COMPARTMENT FOR PREPARING RBMK SPENT FUEL FOR DRY STORAGE

The current approach to the management of RBMK SF at the sites of the NPPs considers change over to the dry storage mode after long-term (10 years) storage in water pools. The construction of a regional facility for receiving fuel from all NPPs with RBMK–1000 reactors has been postponed for financial and other reasons. Therefore dry storage facilities will be located at the NPP sites for another 10 to 30 years. The on-site cask storage facility is also considered as an alternative for speedy solution of the SF management problem at the NPP sites. The cask storage provides storage safety most efficiently and satisfies all the requirements of the current Rules on nuclear fuel management. A metal-concrete cask for SF storage and transport, which is now under development will serve this purpose. If necessary the fuel can be transported to the regional storage facility at minimum costs.

3.1. Technology of preparing RBMK spent fuel dry storage.

The RBMK-1000 FAs are distinguished for their size (10017 mm) (Fig. 3). Before loading into the Metal Concrete Cask (MCC) the assembly must be separated into 2 fuel rod bundles and the suspension. The bundles are placed in casks for storage while the suspensions go for decontamination and remelting as radwastes. From safety considerations each fuel bundle should be enclosed into an ampoule made of corrosion-resistant steel. The ampoule serves as an additional protective barrier against fuel damage in the case of fuel drop during the cask loading with fuel. Moreover, the ampoule is expected to provide safe unloading of fuel from the cask after 50 year storage. All fuel cutting and loading operations will be carried out in a hot cell and remotely controlled.

According to the project being designed such cells will adjoin the AFR (RS) facility at the plant site. The technology of FA separation in the cells will be as follows (Fig. 4 and 5):

- Cans with fuel are transferred from the storage pools to a special overloading pool and placed on a transfer cart by using standard storage facility equipment. The cart has the load capacity of 2 FAs, which corresponds to the cell capacity per working shift.
- The cart transfers the loaded cans via a transport canyon to the cell. Here a cantilever crane places the FAs into a drying stand.
- After drying each FA is placed in the ampoule by the crane, the lower fuel bundle is cut off by a milling cutter, the upper bundle is transferred to the second ampoule. Here the suspension is cut off and removed for utilization. The ampoules are covered with lids. This technology has a minimum of hoisting and transfer operations and provides the maximum efficiency of the hot cell.

- The ampoules with fuel are placed into a transfer canister (item by item), which is loaded through a sluice into a cask.
- The cell's design involves the use of unified equipment applicable with any type of casks now in use for transportation and storage of the RBMK-1000 fuel.
- Upon loading the cask with fuel and setting the protective lid the cask is inspected for leakage. The moisture content in the gas medium is measured and the cask cavity dried with hot air, its outer surface decontaminated, if required.

The designed capacity of the cell equipment is 3600 FAs/yr. With such capacity a period of 9–10 years is required to prepare for dry storage all the fuel now stored in the wet AFR of the Leningradskaya NPP, thus providing the conditions for normal plant operation during the whole service life.

3.2. Main safety principles and criteria.

The safety provisions in the SF cutting and loading compartment are directed to the maximum personnel protection against radiation from SF and to the decrease as low as possible of the activity releases to special ventilation and canalization.

The detail design of the compartment should satisfy the safety requirements. In other words the total spent ionizing radiation impact from spent fuel, its fragments and aerosol contaminant upon the staff under normal operation or emergency conditions shouldn't cause the growth of radiation doses above the limits specified by the Radiation Safety Standards-96 for a number of irradiated persons from the facility staff.

The design bases on the following technical and organizing principles:

- multi-barrier protection of nuclear fuel;
- use of reliable and proved engineering and technical systems;
- guaranteed quality of constructions and equipment;
- diagnostics of equipment and systems of control and protection;
- highly qualified personnel;
- adherence to standards, rules and other normative and technical documentation.

In addition the design observes the following special safety principles:

- use of design decisions with minimum risk for protection barriers integrity;
- increase of sealing systems reliability.

Under normal as well as emergency conditions the operation safety is provided by the following constructional and organizational measures:

- Optimized volumes of protective compartments with minimum contaminated volumes and surface areas;
- Using two technological flows for SF separation, redundant system components and mechanisms, also doubling electromechanical drives with hand-operated systems;
- Cutting off the service areas of cantilever cranes in both technological flows, activation of the emergency cantilever crane by the drives of the 2-nd cantilever crane in one of the SF separation flows;

- Facing the inner surfaces of the protective compartments with polished stain steel sheets for more efficient decontamination and prevention of aerosol activity release into the ‘clean’ zone;
- Use of hermetic openings in protective walls for drives, pipelines, cables, lids, doors and windows, use of water pool gate of the AFR facility;
- Remote control of equipment in protective compartments;
- Visual and TV-control of the separation cell operation;
- Constant radiation, temperature and pressure monitoring in enclosed rooms;
- Use of proven technical decisions on the base of wide design experience and currently operating analogs;
- Use of special grips and devices which prevent applying unacceptable loads to FAs or fuel rod bundles thus precluding their damage, deformation or drop.
- Strength characteristics of the construction should provide the efficiency of safety-related systems and components under loads arising during transport and separation operations;
- The construction of drives should provide reliable fixation of FA or its components in a given and latched position upon loss of power in the electromotors of the drives;
- The circuit design and construction of control and measuring equipment applied in drives operation control should provide alternate checking of each drive ;
- Provisions should be made for possible maintenance and repair works on the equipment of the hot cells. Both remote and manual operations are considered;
- The construction of the cask and loading pit seal preclude the failure of the hot cell seal;
- The construction of rigging devices should provide safe movement and reliable fixation of loads in a given position (measure 13 and 17) also preclude accidental, damage of safety-relevant components and systems in transport, storage and rigging operation;
- Fulfillment of requirement of the quality assurance program at all steps of cell development and construction.

In conclusion, the develop technology meet the requirement of the National Standards and to provide for environmental and personnel safety in compliance with the ALARA principles.

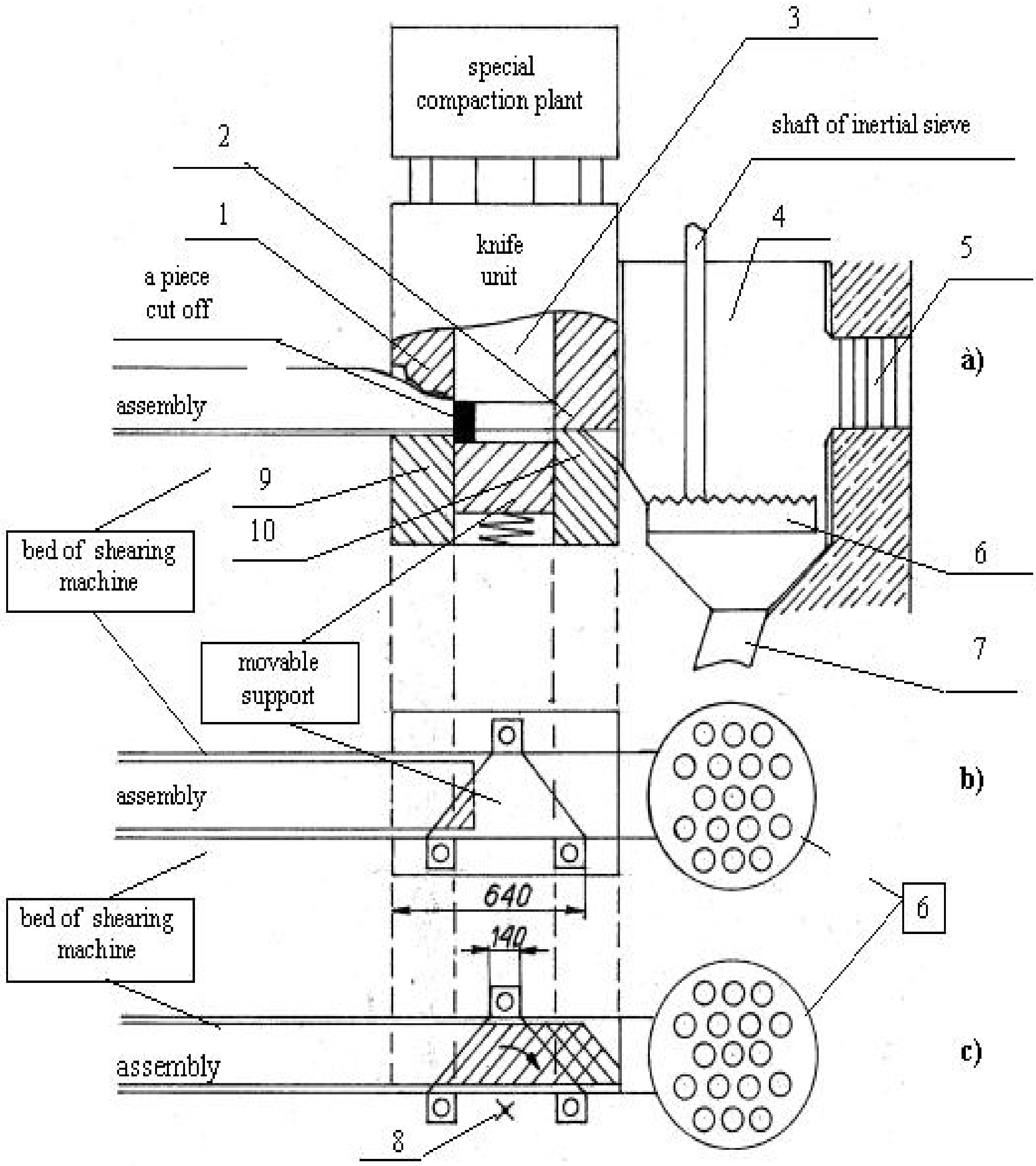

FIG. 1. Scheme of the shearing machine

a) Scheme of the knife unit
b) Section of flattened assembly clamped between upper knife and movable support
c) Next section of cut off piece of a flattened assembly according to scheme (b)

1. First clamp along movement of the feed;
2. Second clamp along the movement of feed;
3. Upper knife;
4. Piece sorting chamber;
5. Cavitation nozzle window;
6. Inertial sieve;
7. Chute;
8. Possible axis of piece rotation;
9. Bottom knife (the first along movement of feed);
10. Bottom knife, next one along the movement of feed.

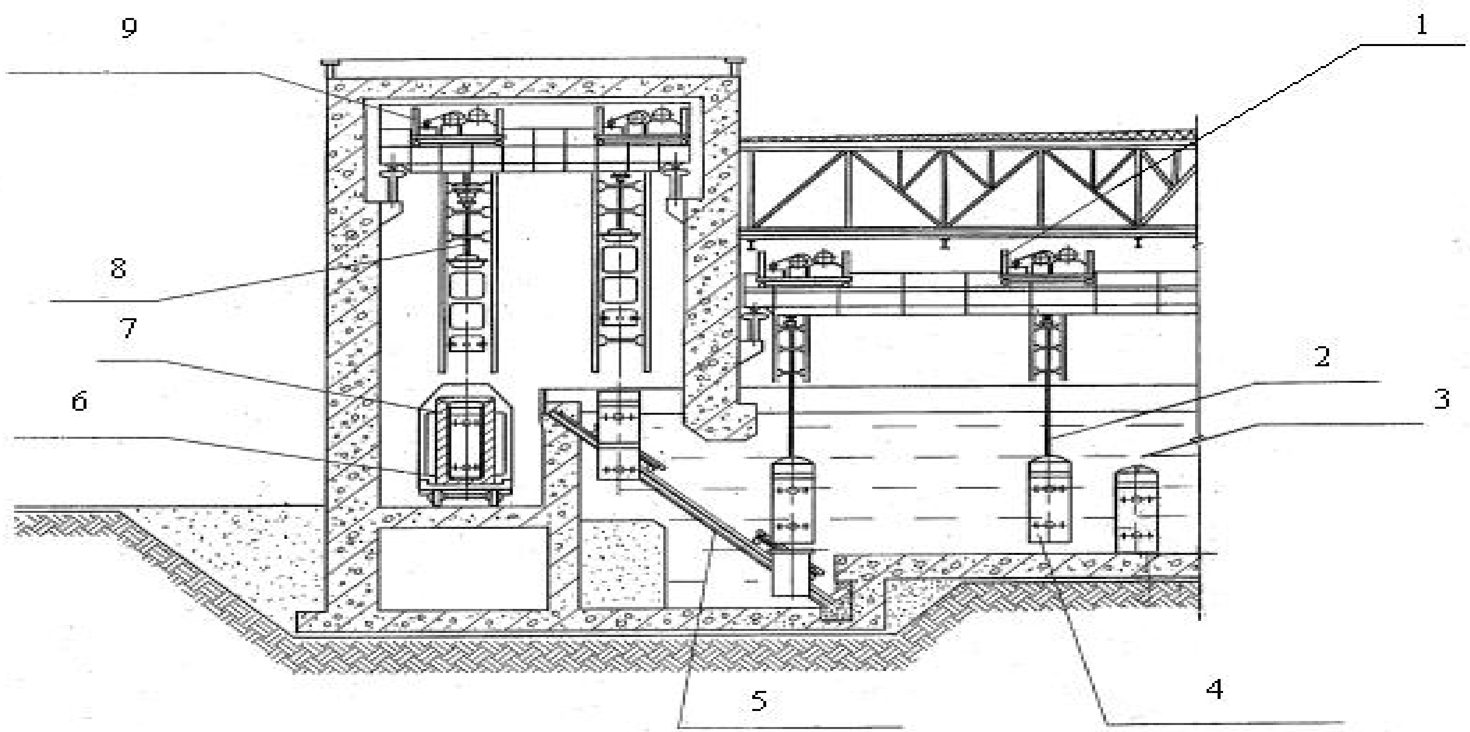

FIG. 3 SF reception and storage.

1. Crane; 2. Adapter; 3. Storage water pool; 4. Canister basket; 5. Elevator; 6.Railway car; 7. Cask; 8. Adapter; 9. Crane

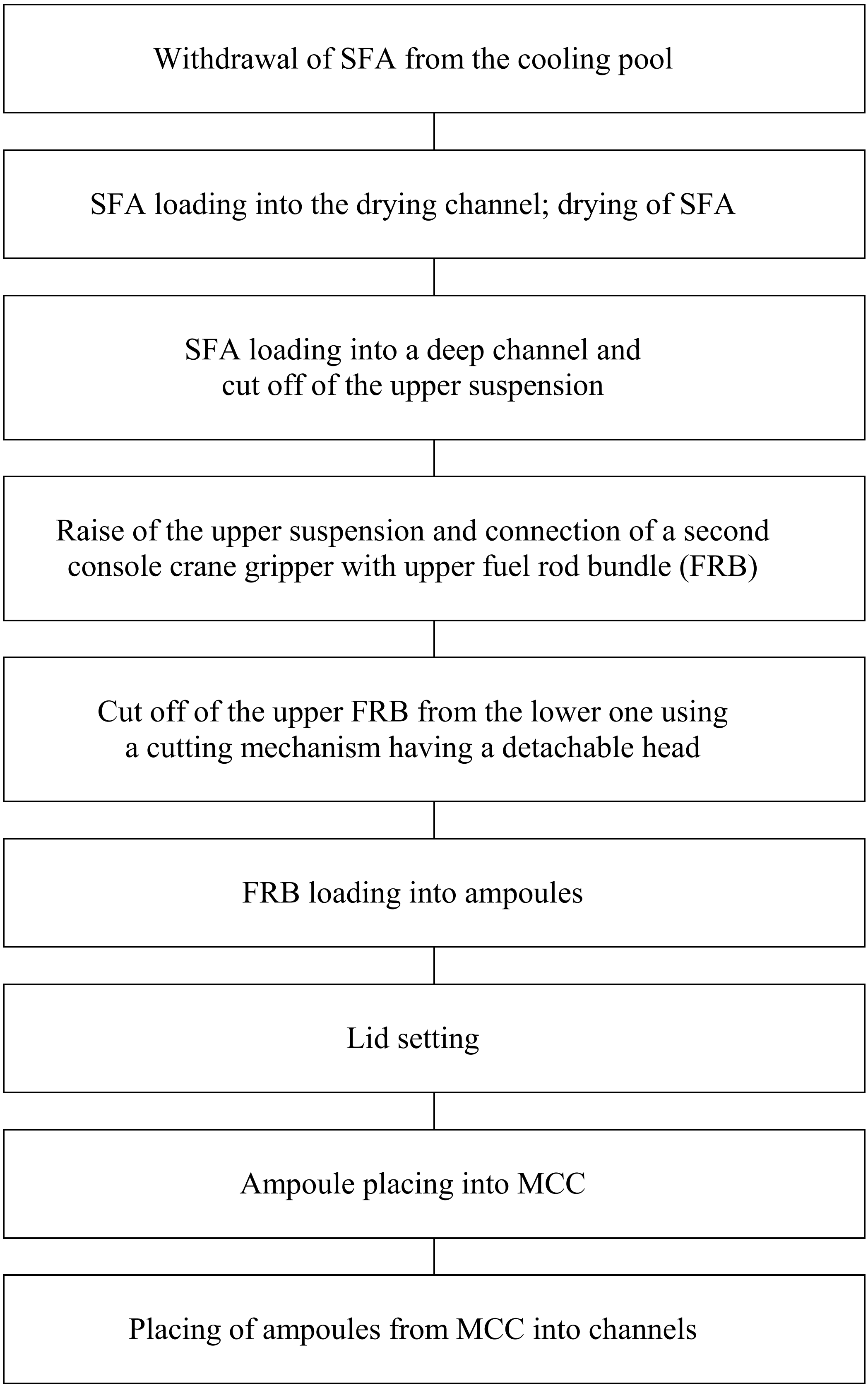

FIG. 4. Sequence of operations in SFA dismantling and loading into cask (MCC).

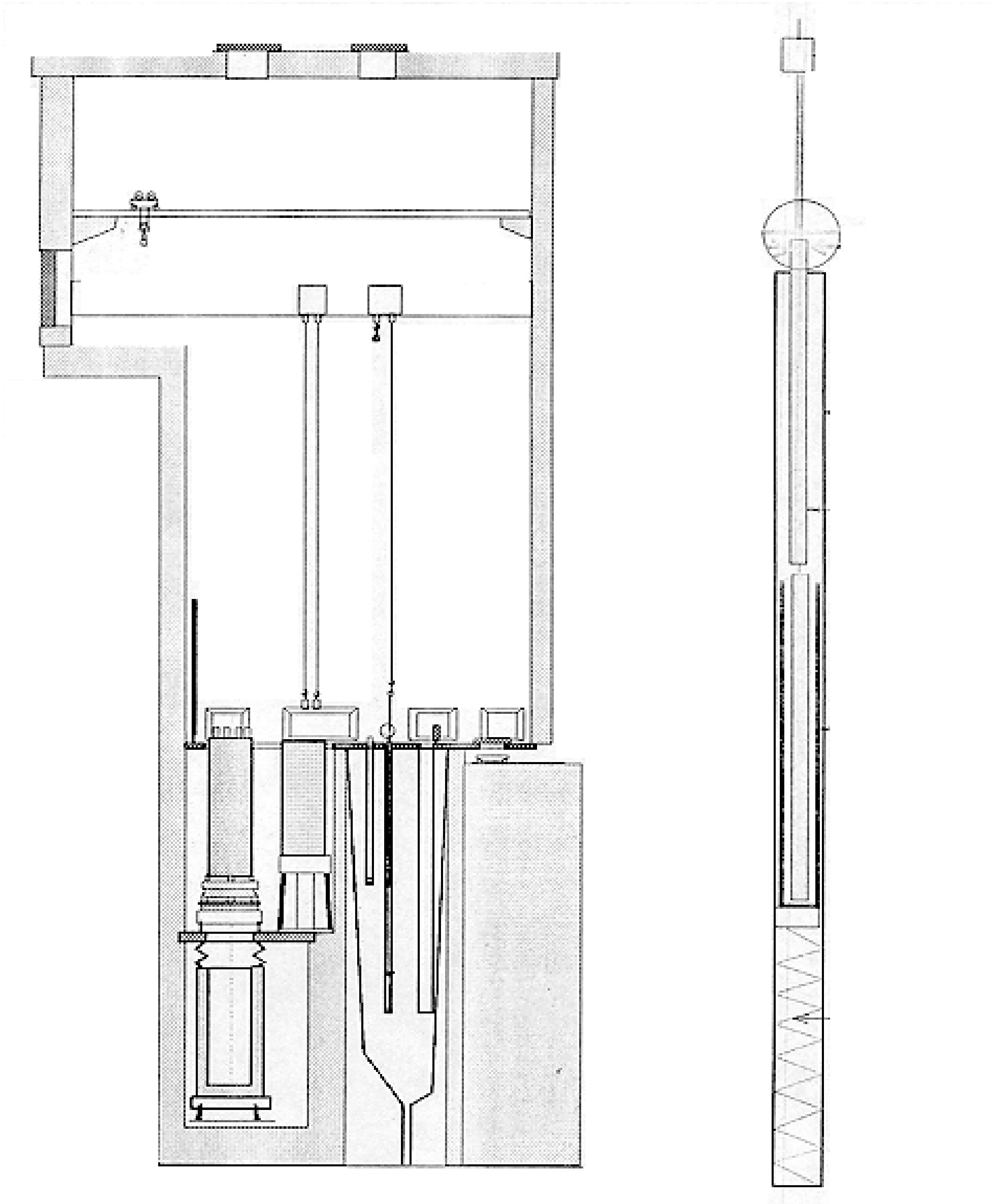

FIG. 5. Compartment for SFA dismantling and loading into MCC cask.

1. Cooling pool;
2. SFA drying channel;
3. Deep channel;
4. Shallow channel;
5. Cutting tools;
6. Tight hot cell;
7. Cable trolley;
8. Console cranes;
9. Backet for suspensions;
10. Backet for fuel rod bundle;
11. MCC cask.

Annex V

REMOTE TECHNOLOGY IN SPENT FUEL MANAGEMENT – UK PERSPECTIVE

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ABSTRACT

In recent years, as the cost pressure on electricity generation prices have increased, the majority of the installed remote equipment is kept in an operational state in the most cost effective manner. There have been no new spent fuel facilities brought into operation in the UK in the last 3 years. Most new facilities or major projects have been either to retrieve and process wastes into a stable form, to remove radioactive contaminants from effluent streams or to decommission redundant facilities. Responding to the current business climate the two major UK nuclear companies, British Energy and BNFL, have embarked upon exciting strategies to carry their businesses forward into the 21st century. For British Energy this has involved diversification and major generating acquisitions (both nuclear and non-nuclear). For BNFL it has meant the acquisition of Westinghouse (who have developed the AP600 reactor system), the commercial nuclear power businesses of ABB and a stake in the new Pebble Bed Modular Reactor. Within the BNFL group, Westinghouse and Magnox Business Generation Group (MGBG) have formed a technical support partnership aimed at servicing the UK nuclear generating stations.

An update on some peripheral technologies which were reported previously and which have gone on to find wider applications are included in this paper. The remote technologies which Westinghouse have developed and currently use in remote inspection, measuring, sampling and repair, are also briefly described in this paper. It is not known at this time what remote technologies will be employed in the two new reactor systems mentioned (AP600 and PBMR). It can be anticipated that both will employ robust and reliable systems similar to those which are in use today. Consequently it is to the areas of waste retrieval, waste treatment, decommissioning and responses to plant repairs or improvements where we need to look for stepwise advances in remote technology. Other industries such as offshore oil, is another potential source of remote technology development.

1. INTRODUCTION

In the UK the Nuclear Industry continues to change in response to commercial, public and regulatory pressures. Since the Advisory Group Meeting in 1998 the two major UK Nuclear players, British Energy and British Nuclear Fuels plc (BNFL), have both embarked upon exciting business strategies.

British Energy’s strategy includes:

- Continuous improvement in the core UK nuclear generation business, delivering planned increases in output and driving down costs ahead of reductions in electricity prices;
- Take full business advantage of the Company's generation and supply assets in the UK and North America - growing a UK energy supply business, developing flexible electricity generation to match UK customers' requirements, and developing all the nuclear generation opportunities offered by North America;
- Developing further business opportunities through partnership and investment in the UK and potentially in Europe.

British Energy have made the following acquisitions as part of this strategy:

- Formation of AmerGen in a joint venture with PECO Energy and the acquisition of a number of nuclear power stations in the US;
- SWALEC electricity and gas supply businesses;
- 2GW Eggborough coal fired power station;
- Strategic stake in the UK's No. 1 internet property search portal - HomeDirectory.com.

BNFL's strategy includes becoming a global supplier of nuclear products and services with a comprehensive backup in Research and Technology. As part of this strategy, BNFL have acquired:

- the Westinghouse global nuclear businesses (in partnership with US company Morrison Knudsen Corporation);
- the commercial nuclear power businesses of ABB (to be integrated into and operated as part of Westinghouse).

Within the BNFL group, Westinghouse and Magnox Business Generation Group (MGBG) have formed a technical support partnership with the goal to increase generation and enhance predictability at UK Magnox Stations. This joint Westinghouse/MGBG reactor services organisation will provide engineering and field services to 18 MGBG Magnox nuclear reactors in the United Kingdom. It will be responsible for the development and operation of most of the remote technology in the UK's nuclear industry apart from in the storage, reprocessing and waste treatment facilities at Sellafield.

In the 1997 UK paper to the Advisory Group a thorough review of remote technologies applied to front end reprocessing operations were described. Remote technologies in spent fuel storage options and services in the UK were also described.

In the 1998 UK paper to the Advisory Group peripheral/supporting remote technologies were described which are finding applications in the spent fuel route (and are applicable throughout reactor and reprocessing facilities).

In terms of remote technology, no significant developments have taken place in the intervening 20 month period.

The technology utilized in normal operations is mature and reliable. These facilities (including those in the fuel discharge route at the reactors) are relatively easy to maintain since the fuel cladding is generally intact and hence residual radiation hazards are low once the fuel has been discharged.

Consequently this paper focuses on the remote inspection, measuring, sampling, and repair technologies which are provided by Westinghouse. An update is also given on a number previously described technologies which have recently seen "active service".

2. COMMERCIAL ISSUES AND THEIR IMPACT ON REMOTE TECHNOLOGIES

Extreme cost pressure is being applied to all nuclear services. British Energy have recently announced a series of measures intended to produce significant cost savings to allow it to become the lowest cost generator in the UK. The package includes proposals to relocate its headquarters from Edinburgh to its existing offices at East Kilbride by the end of the year, and the closure of its six visitor centres located at its power stations around the country. A proposed pay freeze for its entire staff is being discussed with trade union officers, and is also proposing a lower-cost pension arrangements for new entrants into the company. These measures will have no impact on the continuing safe operation of British Energy's power stations.

Likewise BNFL have recently confirmed the closure dates of a number of Magnox stations as shown below:

Station	Licensed lifetime	Age at Cessation of Generation	Date of Cessation of Generation
Calder Hall	50	50	2006 - 2008
Chapelcross	50	50	2008-2010
Bradwell	40	40	2002
Hinkley Point A	40	35	2000
Dungeness A	40	40	2006
Sizewell A	40	40	2006
Oldbury*	40	45	2013
Wylfa*	33	45/50	2016/2021

NOTE: Continuing to run Oldbury and Wylfa to these dates depends upon the development and use of Magrox fuel. A decision will be taken in around 2003. Oldbury and Wylfa will also need to undergo a Periodic Safety Review in order to secure operation to these dates. Final Magnox reprocessing at Sellafield will be around 2012 and final Magnox fuel production at Springfields will be by 2010.

The decision was made to cease generation at Hinkley Point A because a business case could not justify the multi-million pound investment needed there.

In the face of such cost pressures there is little scope for remote technology developments unless major cost reductions and efficiency improvements will result.

3. REMOTE TECHNOLOGY DEVELOPMENTS UPDATES

3.1. BNFL Instruments Ltd (BIL) — RadScan™ 700

As described in the 1998 paper, BNFL Instruments' RadScan™700 has been developed to survey gamma radiation remotely in a wide variety of environments. The device is based on a CsI spectrometer located in a highly collimating tungsten shield. This spectrometer can detect gamma rays with energies between 100 keV and 10 MeV. The unit is operated from a remotesafe location using a PC-based workstation. A high definition colour video picture of the area being surveyed is displayed on which a circle, representing the field of view of the detector is overlaid. The video picture, together with associated geometrical and radiometric data is recorded by a video recorder (VCR).

FIG. 1. RadScan™700.

Since 1998 RadScan™700 has become an every day tool used to locate, assess and visualise radiation sources in many spent fuel facilities. The information generated by RadScan™700 has been invaluable in planning task and minimizing operator dose.

3.2 Remote analysis, identification of materials using laser-induced breakdown spectroscopy (LIBS)[1]

Since 1998 Applied Photonics Ltd have carried out a large number of in-situ materials analyses using the LIBS system. A special probe was engineered for the task on 528 bifurcations on AGR steam superheaters for British Energy. Although the probe was deployed manually in this case, the technique is also suitable for remote applications. In the application reported the rapid measurement cycle (<3 minutes per measurement) minimized the operator dose during the task.

The technique can be applied to HA wastes, radioactive liquids, molten glass, Pu/U materials and in-situ characterisation of fuel containing materials within decommissioning waste.

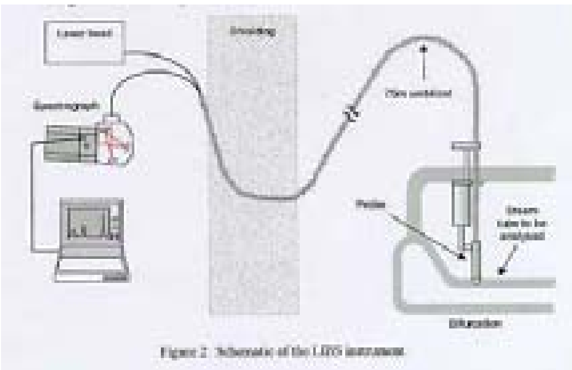

Fig. 2. Schematic of the LIBS instrument.

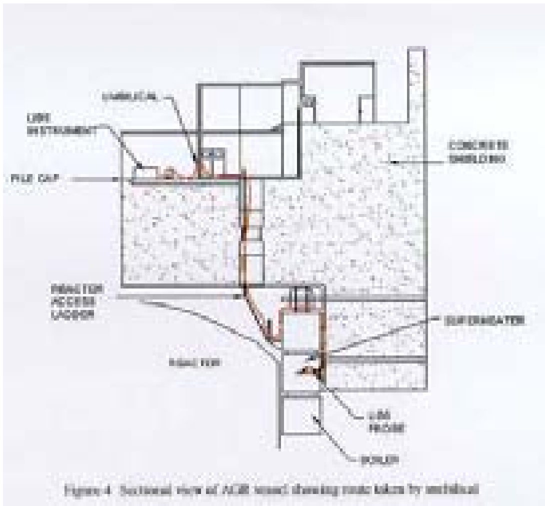

Fig. 3. Route for the umbilical in the AGR.

3.3. Light Form Modeller (3-D MODELLING)

Light Form Modeller has been developed by UK Robotics to capture data on structures, objects and environments and to convert 3-Dimensional (3-D) point data into full 3-D CAD models. These can then be seamlessly exported to a wide range of popular CAD systems.

Light Form Modeller or LFM was previously reported when it was marketed as ‘Architect’. The system has been used extensively in the non nuclear field and BNFL have utilized the technology to survey a Medium Active Cell at Sellafield. The Cell is a four storey concrete structure housing miles of process pipework and tens of vessels. Once the scanner was placed in position the operator could retreat to a shielded area. The 360 degree coverage and remote operation of the scanner minimized the number of scans required to allow the geometry of the cell to be fully modelled. Dose uptake was minimized as a result. Advantages of the system over other forms of 3-D data capture are:

- Light Form Modeller saves considerable time both in terms of data acquisition and building the appropriate 3-D CAD model.
- Remote scanning can easily be done for use in hazardous environments.

- The system can be employed where other techniques such as photogrammetry are of limited use.
- Light Form Modeller provides significant cost savings over scanning technology.
- The interface is very user-friendly.
- No targets are required.
- Scanning and model building can be done very quickly.

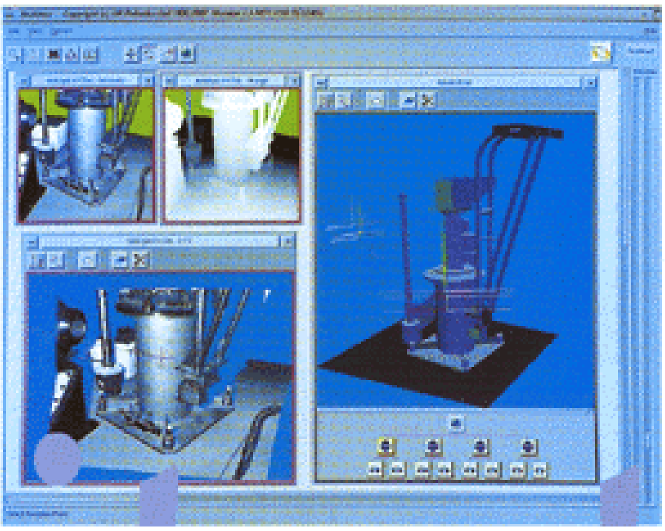

FIG. 4. Typical light form modeller screen.

3.4. Vigilant Capacitive Sensors for robotic/remote applications

The Vigilant Capacitive Sensor System from UK Robotics and sensor specialists Sensatech provides enhanced collision detection for robotic manipulators and proximity detection for other remote applications. This sensor system provides many unique features:

- High sensitivity across a wide range of materials.
- Very large operational range
- Vigilant is extremely robust.
- Vigilant is available in both standard and radiation hard versions for use in the most exacting of environments.

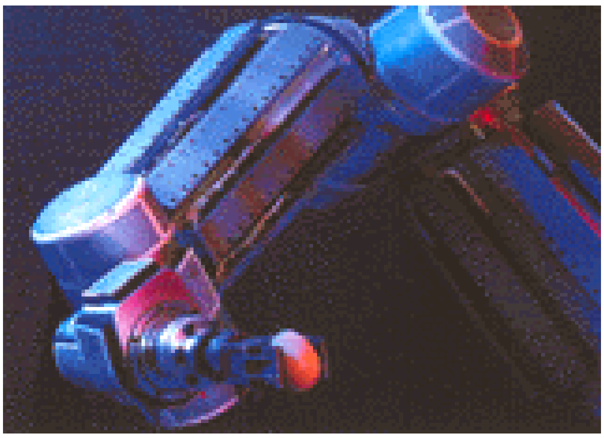

FIG. 5. Vigilant capacitive sensors mounted on robot joint covers.

The sensors have been successfully deployed in a number of highly active safety critical applications in spent fuel facilities where more conventional sensors exhibited poor life or reliability. Radiation hard versions of the sensor were utilized which have been proven to a cumulative dose of 10^8 Rads.

WESTINGHOUSE REMOTE TECHNOLOGY SERVICES

4.1. Background to Westinghouse's Nuclear Services Business Unit

Westinghouse's Nuclear Services Business Unit offers a wide range of products and services to keep nuclear power plants operating safely and competitively world-wide. This unit includes international service operations in Brussels and Nivelles, Belgium and Madrid, Spain. The organization has led the way with developments such as robotics and remotely operated tooling, advanced non-destructive examination and inspection equipment and laser-welded repair technology. In partnerships with its customers, it is driving hard to help reduce outage duration and costs, having played a key role in completing the shortest-ever, four-loop PWR refueling outage in the United States at 17 ½ days. With NRC-licensed service centres in Pennsylvania and South Carolina, it offers customers a cost-effective option for off-site repair, refurbishment, testing, and calibration of plant equipment.

The unit works closely with customers in several key areas:

Field Services — offers complete outage support for reactor systems, steam generators and training services.

Engineering Services — focuses on improving the performance of existing operating plants; concentrating on finding ways to help utilities improve plant availability, reliability, and regulatory compliance; extending plant licensing life; and reducing operation and maintenance costs.

Repair and Replacement Services — offers a vast array of services, including replacement components, equipment qualification, major electrical system upgrades, replacement motors, and electrical and instrumentation field services.

In addition to its core businesses, Nuclear Services subsidiaries offer specialized services to meet specific customer needs:

PCI Energy Services — provides field welding, machining, and remote tool delivery service vendor.

WesDyne International, Inc — specialises in the development and application of advanced non-destructive examination (NDE) inspection equipment and services for the reactor vessel, turbine generator, and related systems.

PN Services — provides chemical decontamination of BWR and PWR primary system piping, components and subsystems, and chemical cleaning of PWR steam generator secondary sides services.

Fauske and Associates, Inc. — supply testing and consulting services that support nuclear reactor safety, chemistry processing safety, and environmental safety.

Westinghouse Nuclear Services Canada Inc. — provides unique eddy current probes to operating plants, inspection companies and research organizations in nuclear and other industries for the detection and characterization of defects in metal structures.

4.2. Remote technologies for fuel assembly inspection & repair

The following table summarizes Westinghouse's fuel assembly inspection and repair technologies:

Technology	Function	Features
Vacuum Can Sipping	to detect clad penetration in one or more fuel rods	twin chambers; instrument & pumping console; detector & shielding assembly
In Mast Sipping	to detect clad penetration in one or more fuel rods	installation in any PWR refuelling machine mast; little or no impact on refuelling
Automated Fuel Inspection System (AFIS)	to pinpoint fuel rods with through wall defects	assembly suspended; underwater manipulator carrying an ultrasonic probe; electronic/ultrasonic control system
RCCA Eddy Current Inspection; (Rod Cluster Control Assemblies)	to measure cross sectional area and profile of RCCA rods	RCCA guide fixture; encircling & eddy current coils; support structure; data acquisition system
Oxide Thickness Measurement System (OTMS)	to perform oxide measurements on peripheral fuel rods, single fuel rods or fuel assembly grids	high precision three axis positioning system; eddy current probe; mounted on fuel storage rack; +/- 5µm accuracy
Fuel Assembly Repair — Multi Function Fuel Repair System (MFRS)	fuel assembly reconstitution fuel assembly reassembly	bottom nozzle removal and installation tooling; fuel rod handling tools and positioning equipment; elevator system with fuel baskets; underwater television equipment
Visual Inspection	to assess assembly condition, individual fuel rods, fuel rod to nozzle gaps and fuel rod length	fibrescope for thimble or grid; +/- 0.5mm accuracy, +/- 0.07mm repeatability visual or direct measurement
Fuel rod profilommetry	to measure fuel rod profile	performed on single rod; utilises contact measurement; obtains two diameters on each pass; +/- 0.005mm accuracy
Grid cell size	to measure grid cells	use step pins; drag force measurement to establish size; +/- 0.013mm accuracy
Grid width measurement	to measure grid widths	contact measurement; uses extreme spring slots; adjustments of measuring fingers allows precise alignment to grid; utilises two cameras to view engagement to grid +/- 0.025mm accuracy
Assembly bow	to measure assembly bow	simple tool; uses camera to make measurement; comparison of known distance to gap between f/a and cable; +/- 2.5mm accuracy
Thimble tube bow	to measure thimble tube bow	strain gauge based probe; separate probe for dashpot and upper thimble; inserted into each thimble using guide plate with built in calibration; gives magnitude and direction; +/- 0.25mm accuracy
RCCA drag	to measure RCCA drag	can be performed in containment or spent fuel pit; uses load cell to obtain drag measurement; chart recorder used to capture data
Grid vane removal	to remove grid vanes	tool grips vane to provide hinge point; vane is fatigued off of grid using air actuated cylinder; holder provided to separate individual vanes and interface with cask
Crud scraping	to collect crud samples for analysis	performed while assembly hanging from spent fuel tool; mechanical scraping by blade; suction draws off sample to collection bottle

4.3. Remote manipulator systems

Westinghouse have developed a family of manipulator systems to service the inspection requirements of PWR's and BWR's. They have been highly successful in reducing outage duration. The systems are briefly described here for information since their design could easily be adopted for other uses in spent fuel management facilities.

4.3.1. SUPREEM

SUPREEM is quick and easily deployed system for the inspection of PWR reactor vessel welds. It consists of a lightweight platform that mounts at two elevations on the vessel wall and deploys a six-axis ROSA V robot that carries out the scans required for inspection of all welds in the shell, bottom head, nozzle and nozzle safe-ends. Features of the platform include multiple radial arms that emanate from the centre of the reactor vessel and connect to support structures along the vessel circumference. These arms fold downward such that the platform can be carried in and installed in the reactor vessel with minimal use of the polar crane.

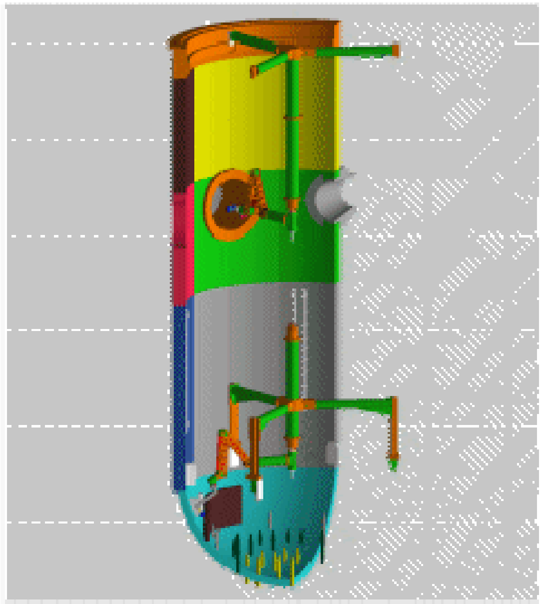

FIG. 6. SUPREEM inspection system for PWR reactor vessel welds.

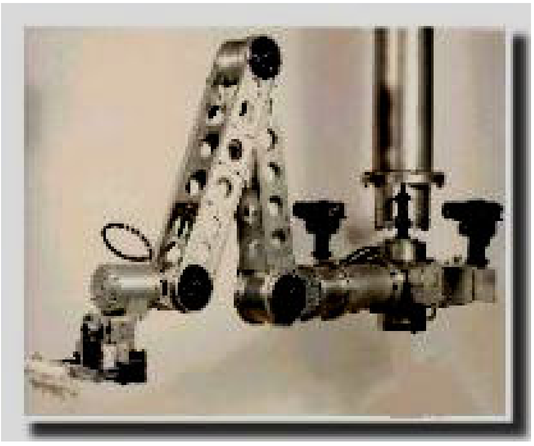

FIG. 7. ROSA V manipulator.

SUPREEM is remotely controlled and operated from a graphically programmed workstation which provides real-time 3-D computer images corresponding to the position and motion of the tooling in it's operating environment. The control station provides an operator friendly interface that allows for automatic complex surface scans, prevents collisions, and allows the flexibility to move the end effectors under manual joystick control when necessary.

The SUPREEM end effectors are compact and lightweight. They include an appropriately selected set of ultrasonic search units held with passively compliant mechanisms for following the vessel's surface during the robotic scanning. The end effectors are stored underwater on the platform storage rack for easy changeout.

4.3.2. WIRES

The WesDyne Internal Reactor Examination System (WIRES) provides BWR plant owners the capability to maximise coverage of the horizontal and vertical welds in their core shrouds in parallel with other in-vessel activities including core alterations. The WIRES consists of:

Guide Ring and Trolley. The WIRES manipulator rides on a guide ring and trolley that are mounted onto the shroud flange. The trolley, which carries the vertical mast and robotic manipulator, can be driven 360° around the shroud using a rack that is affixed to the outer diameter of the ring. A table that mounts to the trolley, moves radially with respect to the vertical centreline of the shroud, to allow the robotic manipulator access to the shroud to vessel annulus under core spray piping and feedwater spargers.

Vertical Mast and Robotic Manipulator. The vertical mast delivers the robotic manipulator to the elevation where the scanning is to be carried out. The robotic manipulator performs the motions required to get around and behind obstacles such as the jet pumps, the scan motion across a horizontal weld and the scan-index motion along a vertical weld. A telescopic arm at the end of the robotic manipulator delivers the search unit modules to the examination area.

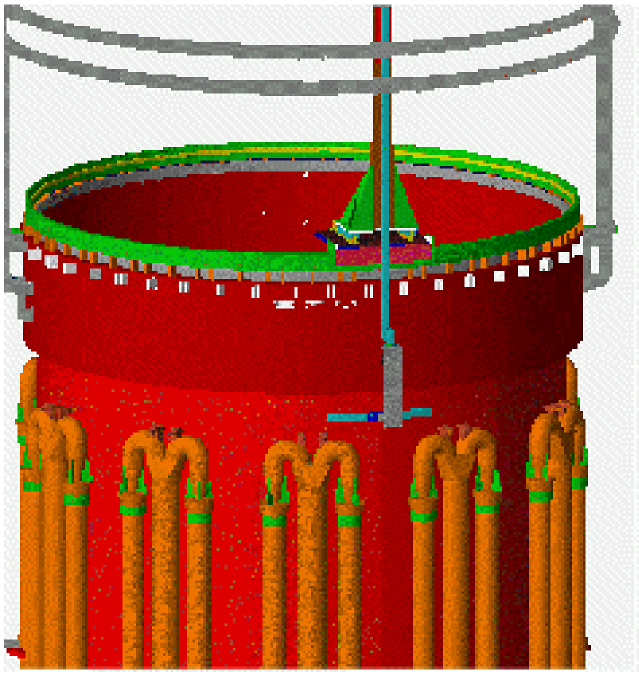

FIG. 8. WIRES BWR core shroud inspection manipulator system.

Control System. All seven motorized axes of the WIRES are controlled using the ROSA control system. The system provides for complete control of the tooling from a workstation located on, or adjacent to, the refuel floor or if necessary in a trailer outside the plant. The operator is provided with a display of a 3D model of the WIRES in its environment including the reactor vessel, shroud, jet pumps, etc. Direct feedback from resolvers on each motorised axis provides the control system with real time location and orientation of the tooling within the model.

The computer control provides for collision detection based on information in the model. A self-calibration routine allows the operator to update the information in the model to the conditions found in the plant.

Camera System. The WIRES includes three independently controlled pan and tilt cameras to aid the operators during tool movements and scanning. Two of the cameras ride on vertical masts that run parallel to and on both sides of, the vertical delivery mast. The third camera is attached to the robotic manipulator near the telescopic arm. It includes an additional rotary drive so than it can look side to side and up and down. The combination of these cameras gives the operator three different views of the manipulator as it is moved around obstacles and allows for periodic checks of the system cabling to ensure it is not hanging up either during gross tool positioning or a specific scanning operation.

4.3.3. OASIS

OASIS (RCP Robotic Casing Inspection System) is a robotic delivery and control system for inspection of PWR RCP casings. The system provides the ability to inspect the pump casing ID surfaces, upper and lower casing welds, diffuser weld, crossover leg-to-pump weld, and thermal sleeve bolts.

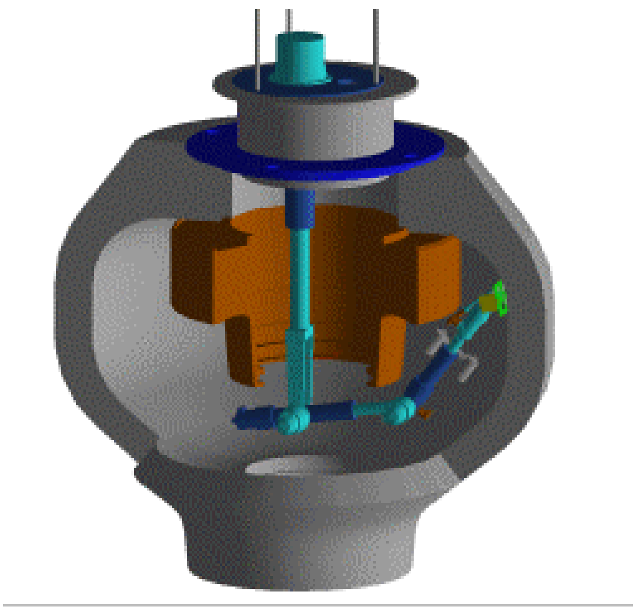

FIG. 9. OASIS RCP robotic casing inspection system.

The OASIS robotic arm is a 7-axis manipulator with three linear and four rotary joints arranged in LRRLRLR order from base to end effector mount. Actuation of all seven axes is via DC servomotors with dual resolver feedback. The dual feedback system provides accurate servo control and positioning of the actuators.

The OASIS robot is remotely controlled and operated from a graphically programmed workstation. The RCP pump casing and robot are modelled on the workstation screen allowing for simulated motion of the robotic arm or real arm motion displayed in 3D on the workstation monitor. A real time control unit provides synchronisation pulses to the data acquisition instrumentation and provides associated status information to the operator workstation. Forward kinematic manipulator arm solutions are computed in real time to provide digital pulses proportional to the distance travelled along the examination surface. Temporal as well as the spatial calculations are performed to provide a reliable data acquisition interface.

4.3.4. Bottom Head Drainline Inspection System

FIG. 10. Bottom head drainline inspection system shown in a clear pipe.

This system was developed and deployed to perform automated internal ultrasonic and eddy current inspections of the 2-inch diameter drain line in a BWR reactor vessel. The system consists of a rotating probe head containing specially designed ultrasonic and eddy current probes and a delivery system that provides the rotational and linear drive motions necessary to complete the inspection. The system is capable of delivering the probe head from a fitting in the drain line located under the reactor vessel or directly into the reactor vessel to drain line opening through the 70 feet of water that exists between the reactor vessel bottom and the refuelling bridge.

The drain lines that were inspected are approximately 18 feet long and contain up to four ninety-degree elbows. The probe head had to negotiate these elbows to inspect for the presence of stress corrosion cracking in the heat affected zones of the pipe to elbow welds and along the entire length of each elbow. The ultrasonic and eddy current data was triggered by the probe rotation and then presented in a C-Scan format that correlates the position of the eddy current and ultrasonic data display images.

4. FUTURE TRENDS

Two new reactor systems are currently being progressed which offer opportunities for the application of 21^{st} century remote technology.

The **AP600** is a Westinghouse-designed, advanced simplified 600-megawatt pressurised water reactor based on demonstrated, licensed technology with safety systems that rely on natural forces. The design is based on requirements driven by our utility customers and their extensive experience in operating nuclear stations. Current efforts are focused on AP600 design certification.

The major benefits of the AP600 design are:

- Simplifies plant systems and equipment, operation, maintenance, and quality assurance requirements by greatly reducing the amount of piping, valves, HVAC ducting, pumps, and other complex components.
- Uses experience-based power generation components that are designed to offer a high level of reliability.
- Provides a high degree of public safety and licensing certainty.
- Offers affordable electric power at competitive cost.

Westinghouse’s goals are to continue productive partnerships in passive plan programs domestically and internationally and to place the first in a series of AP600s in service shortly after the turn of the century. Westinghouse is working with the China National Nuclear Corporation (CNNC) on the CAP600, a 600-megawatt unit that combines the work of CNNC with Westinghouse's work on the AP600.

Westinghouse is also working with Japanese utilities to apply AP600's natural, passive concepts to a larger, three-loop unit rated at 1000 megawatts. This program is known as the Simplified Pressurized Water Reactor (SPWR) program. Similarly, Westinghouse is working with European utilities to develop the EP-1000, a 1000 MWe passive plant that meets European utility requirements. Another focus is to apply Westinghouse expertise to the Advanced Pressurized Water Reactor (APWR) project planned for Tsuruga, Japan.

BNFL has just invested in a significant share in a project to develop what is expected to be the safest, cleanest and most cost efficient nuclear power source option for the future, the South African Pebble Bed Modular Reactor (PBMR). The project is being led by Eskom of South Africa and the Industrial Development Corporation (IDC) of South Africa. An agreement among the three organizations has been signed.

The PBMR is a pioneering yet very simple design concept that is expected to be highly competitive with virtually all other forms of electricity generation. Each reactor will be designed to produce around 110MW of electricity and will have a 40-year life span. A single PBMR is 53 metres by 27 metres and 47 metres high, half of which would be below ground level. Four modules would fit inside a football stadium. The concept is based on prior experience in the US and particularly Germany where prototype reactors were operated for a number of years between the late 1960's and late 1980's.

The reactor is designed in a modular fashion and has a number of unique advantages. Not only is it expected to be relatively inexpensive to build compared to existing reactor designs, but as it is modular, additional units can be added to suit demand. The Reactor, which can operate in isolation anywhere, provided that there is sufficient water for cooling, also has enormous potential to significantly improve the standard of living in developing countries where rural communities are often far from the national grid.

The first phase of the project, which was given the go-ahead by the South African Government in April, involves undertaking a detailed feasibility study, an environmental impact assessment and a public participation process. This is expected to be followed, subject to Government approval, by the construction of a demonstration plant scheduled to start some time during mid-2001 with commercial operation forecasted by 2005.

Unfortunately no details of the remote technologies planned in these two designs were available at the time of writing.

In the meantime small stepwise developments are expected in the areas of waste retrieval, decommissioning and in response to plant repairs or improvements. The pace of decommissioning of redundant nuclear facilities is increasing worldwide and these projects should be monitored for the advances in the application of cost-effective remote technologies. Other industries, particularly offshore oil should is another potential source of remote technology development but it too has been subject to similar commercial pressures which have constrained the development of remote technologies to those which are guaranteed to lead to significant business benefit.

5. CONCLUSIONS

This review has confirmed that:

- The UK’s spent fuel management facilities use mature remote handling technologies which are simple and robust.
- Remote technology equipment in spent fuel facilities is often simpler and more easily maintained than in facilities which handle sheared fuel or waste streams from reprocessing operations.

This review has concluded:

The UK’s major nuclear players, British Energy and BNFL, have both embarked upon exciting strategies which have increased their international status in the nuclear field.

The Westinghouse and Magnox Business Generation Group (MGBG) technical support partnership will be responsible for the development and operation of most of the remote technology in the UK’s nuclear industry apart from in the storage, reprocessing and waste treatment facilities at Sellafield.

A number of technologies (RadScan™ 700, LIBS, Light Form Modeller and Vigilant Capacitive sensors) have been successfully used in a growing number of applications and have resulted in reduced radiation dose uptake, cost savings and improved safety.

New reactor systems (AP600 & PBMR) offer the opportunity to introduce 21st century remote technology which are likely to be simple, robust and reliable.

The pace of remote technology development has slowed due to economic pressures. The most advanced developments in the UK are for applications in reactor inspection/maintenance, waste retrieval & treatment, decommissioning and clean-up projects. Spent fuel management facilities will no doubt benefit from resultant spin-off's.

ACKNOWLEDGEMENTS

Details of RadScan™ 700 are included by kind permission of BNFL Instruments Ltd.

Details of LIBS is included by kind permission of Applied Photonics Ltd.

Details of Light Form Modeller and Vigilant capacitive sensors by kind permission of UK Robotics Ltd.

Thanks to Kenneth Quinn of Westinghouse Energy Systems for the provision of information on Westinghouse's poolside remote technology.

Annex VI

APPLICATION OF REMOTE TECHNOLOGY FOR SPENT FUEL MANAGEMENT AS PROPOSED FOR A POTENTIAL REPOSITORY AT YUCCA MOUNTAIN

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ABSTRACT

The Yucca Mountain site in southern Nevada in the western United States is currently being characterized for its suitability as a site for a repository for spent nuclear fuel and high level waste. The information contained herein represents the current approach to surface and subsurface facility design for the potential repository at Yucca Mountain. These design concepts will continue to be assessed and modified as appropriate, so the design concepts described in this paper will evolve in the future. The Waste Handling Building will integrate the five primary systems that receive, lift, unload, handle, reload, package, and deliver high-level radioactive waste to subsurface waste handling systems. The Waste Handling Building will have one canister transfer line that moves the disposable fuel canisters through the building to prepare the waste for emplacement in the repository. The Waste Handling Building will have two assembly transfer lines. The disposal container handling system will receive loaded disposal containers from both the canister transfer system and the assembly transfer system. Each disposal container will again be purged with inert gas, after which the container’s lids will be welded and the welds inspected. If the welds meet inspection criteria, the sealed disposal container will be reclassified as a waste package. A crane will transfer the waste package to the transporter loading area, where it will be decontaminated and placed on a transporter for emplacement in the subsurface repository.

1. OVERVIEW

The Yucca Mountain site in southern Nevada in the western United States is currently being characterized for its suitability as a site for a repository for spent nuclear fuel and high level waste. The information contained herein represents the current approach to surface and subsurface facility design for the potential repository at Yucca Mountain. These design concepts will continue to be assessed and modified as appropriate, so the design concepts described in this paper will evolve in the future.

2. WASTE HANDLING OPERATIONS OVERVIEW

The Waste Handling Building will integrate the five primary systems that receive, lift, unload, handle, reload, package, and deliver high-level radioactive waste to subsurface waste handling systems. These primary systems in the building are:

- Carrier/cask handling system
- Assembly transfer system
- Canister transfer system
- Disposal container handling system
- Waste package remediation system.

At the carrier bay, the carrier/cask handling system will lift the transportation cask to a vertical position and place it on a cask transfer cart. Depending upon the cask's contents, the cart will move to one of two transfer systems. Casks that contain disposable fuel canisters with DOE spent nuclear fuel, vitrified high-level radioactive waste, or naval spent nuclear fuel will go to the canister transfer system. Casks that contain spent nuclear fuel in dual-purpose canisters or individual fuel assemblies will go to the assembly transfer system.

The Waste Handling Building will have one canister transfer line that moves the disposable fuel canisters through the building to prepare the waste for emplacement in the repository. The system will move arriving casks through an air lock into a cask preparation area. Once a cask arrives inside the cask preparation area, workers will use remotely operated equipment to vent gases from the cask, purge it with inert gas, remove the lid bolts, and then open the cask. An overhead crane will move the cask to a transfer cart, which will take the cask to a shielded transfer area. Inside the transfer area, machines will remove the canister from the cask. The canister may go directly into a disposal container for repository emplacement, or to a staging rack for later placement in a disposal container. Another transfer cart will move loaded disposal containers to the disposal container handling system. The transfer cart will move the empty transportation casks back to the carrier/cask handling system, which will place them back on a transporter. The empty cask and cask transporter will return to the Carrier Preparation Building to be readied for offsite shipment.

The Waste Handling Building will have two assembly transfer lines. Each line will operate independently to handle waste throughput and support maintenance operations. The assembly transfer process begins by moving the cask on a transfer cart through the airlock into the cask preparation area. Once inside the cask preparation area, workers will use remotely operated equipment to inspect, vent, and cool the cask and remove the cask lid bolts. A large overhead crane will lift the casks and place them in a cask unloading pool, where machines will open the casks and dual-purpose containers and unload the fuel assemblies. The system will move the empty casks and dual-purpose containers back out through the cask decontamination area. A transfer cart will move the fuel assemblies underwater from the cask unloading pool to an assembly staging pool, where a crane will place the assemblies in assembly baskets. A transfer cart will move the baskets containing the fuel assemblies underwater from the assembly staging pool through a transfer canal to a fuel inventory pool. When a fuel assembly is selected from the fuel inventory pool for packaging, a transport cart will move it underwater through an inclined transfer canal to the assembly drying area.

After fuel assemblies arrive at the assembly drying area, an overhead crane will set them into one of two vacuum drying vessels. After drying, the system will retrieve the assemblies and transfer them through a loading port to a disposal container loading area. The empty assembly baskets will be returned to the pool area for reuse. Inside the disposal container loading area, machines will load the fuel assemblies into disposal containers. After loading, workers will purge the disposal container with inert gas and temporarily seal it for transfer to the disposal container handling system.

The disposal container handling system will receive loaded disposal containers from both the canister transfer system and the assembly transfer system. Each disposal container will again be purged with inert gas, after which the container's lids will be welded and the welds inspected. If the welds meet inspection criteria, the sealed disposal container will be reclassified as a waste package. A crane will transfer the waste package to the transporter loading area, where it will be decontaminated and placed on a transporter for emplacement in the subsurface repository.

3. CARRIER/CASK HANDLING SYSTEM

The Waste Handling Building carrier/cask handling system will receive rail and truck carriers containing transportation casks from the carrier/cask transport system, unload the casks, and reload the empty casks back onto the carriers for shipment offsite. Loaded casks will be transferred to the assembly transfer system or the canister transfer system.

The carrier/cask handling system will also receive dual-purpose canister overpacks from the carrier/cask transport system, unload them, transfer them to the assembly transfer system, receive the overpacks with the empty dual-purpose canisters back from the assembly transfer system, and reload the empty dual-purpose canisters onto carriers for shipment offsite.

4. CANISTER TRANSFER SYSTEM

The Waste Handling Building will house the canister transfer system, which will receive rail and truck transportation casks from the carrier/cask handling system and empty disposal containers from the disposal container handling system. One canister transfer line will handle canister waste and support maintenance of the system. The line will be configured to handle disposable canisters of DOE high-level radioactive waste or spent nuclear fuel, ultimately loading them into disposal containers. The canister transfer line will also have an air lock, a cask preparation and decontamination area, a canister transfer cell, an off-normal canister handling cell, and a transfer tunnel connecting these two cells.

A transportation cask containing canisters of DOE high-level radioactive waste or spent nuclear fuel will be unloaded in the Waste Handling Building's carrier bay, then transferred to a cask transfer cart and secured against overturning. The cask transfer cart will move through a transfer corridor into a canister transfer system air lock, which will have isolation doors at both ends to maintain a negative air pressure in the canister transfer work areas relative to the carrier bay. The cart will take the cask through the air lock to the cask preparation area.

The cask preparation area will include a preparation station and a decontamination station. Remote handling equipment will consist of a cask transfer cart, cask preparation manipulator, and tools required to perform cask unbolting, venting, lid removal, and decontamination. Workers preparing a cask will sample the cask's vent ports, vent the cask and purge the cavity gas to atmosphere through a high-efficiency particulate air filtration system, loosen the outer lid bolts, and secure a lifting fixture to the outer lid. The outer lid will then be removed and staged in the cask preparation area. Workers will repeat this process before removing the cask's inner lid in the canister transfer cell. A special lifting fixture will be installed on naval spent nuclear fuel canisters, using the hoist and the manipulator. The cask transfer cart will then move the cask to the canister transfer cell.

Once the canisters are removed from the transportation cask, the empty cask will be prepared for shipment back to a transportation contractor for reuse. The cask transfer cart will move the cask to the decontamination area, where workers will remove the inner lid lifting fixture, install and tighten the inner lid bolts, install and tighten the outer lid bolts, remove the outer lid lifting fixture, perform a radiation survey on the empty cask, and decontaminate the cask, if required. After the cask has been prepared, it will be moved to the carrier bay for loading onto a rail or truck carrier.

All canister transfer operations will be performed remotely in shielded canister transfer or off-normal canister handling cells. The canister transfer cell will consist of upper and lower transfer rooms, a cask unloading port, a disposal container loading port where canisters will be loaded, an off-normal canister transfer port, a small canister staging area, and a crane maintenance area. Small canisters will either be loaded directly into a disposal container or staged in the canister transfer cell until enough canisters are available to fill a disposal container. Large canisters of naval spent nuclear fuel will be loaded directly into a disposal container. The canister transfer system will then deliver the loaded disposal containers to the disposal container handling system. Any canisters that are damaged during handling or received in a condition that does not meet acceptance criteria will be considered off-normal. Off-normal canisters will be transferred to the off-normal canister handling cell for corrective action.

The canister transfer cell will be divided into lower and upper rooms, as previously described, with transfer ports between the rooms to allow vertical lifting of a canister from its transportation cask to its disposal container, to the staging area, or to the off-normal transfer tunnel. The upper room will include a port for unloading transportation casks, a port for loading disposal containers, a transfer port for off-normal canisters, ports to the staging area for canisters, and a maintenance bay. The lower room will include a station for unloading casks and a station for loading disposal containers, the staging area, and a transfer tunnel and cart for off-normal canisters. A rack will accommodate temporary staging of 20 small canisters in a shielded area. This arrangement will reduce the height of any potential canister drop during transfers.

The canisters will be removed from a transportation cask one at a time by remote equipment and placed in a disposal container, taken to the staging area, or moved through the port for off-normal canisters to the off-normal canister handling cell. Remote handling equipment in the transfer cell will include a 65–ton overhead bridge crane (sized to handle large naval canisters), an electromechanical manipulator, and a suite of small canister-lifting fixtures. The remote equipment will be designed to facilitate in-cell operations, maintenance, and recovery from off-normal events. A maintenance bay inside the cell will facilitate in-cell maintenance. Interchangeable components will facilitate maintenance, repair, and replacement of equipment. Lay-down areas will be provided, as required, for fixtures, tooling, and canister grapples. If in-cell equipment fails, the crane and manipulator can be remotely withdrawn to the maintenance bay by using off-normal and recovery operations. Once a disposal container has been loaded, it will be moved to the disposal container handling system.

A separate off-normal handling cell will be located next to the canister transfer cell, connected by the off-normal canister transfer tunnel. Special equipment will receive, handle and, if necessary, repackage off-normal canisters before final disposal in the repository. The cell's equipment will include a small overhead crane, a bridge-mounted electromechanical manipulator, and two overpack loading and welding stations (for canisters with different diameters and heights). The loading and welding stations will be located in a pit to reduce the height above the floor that a canister must be lifted for placement into an overpack. At both the loading and welding stations, special fixtures will be used to properly position, load, and weld the overpacks. A robotic welding machine, positioned between the pits, will remotely weld a loaded overpack in either station. The cell (off-normal canister handling cell) will also have a canister transfer cart, racks for staging 20 small canisters, a canister repair station, canister overpacks, remote-handling fixtures, a decontamination station, strategically located closed-circuit television systems, and shield windows.

5. ASSEMBLY TRANSFER SYSTEM

5.1. System overview

The assembly transfer system will include the equipment, facilities, workers, and processes for preparing individual spent nuclear fuel assemblies for disposal in the repository.

Two nearly identical assembly transfer system lines will be housed in the Waste Handling Building. Each will operate independently to handle waste throughput and support maintenance operations. Each will include a cask unloading area and a transfer cell area. The cask unloading area will contain an air lock, a cask preparation and decontamination area, and a pool area. The pool area will contain a cask unloading pool and an assembly staging pool. A single transfer canal will connect the two pools. An incline transfer canal will be used for moving the spent nuclear fuel assemblies from the staging pool to the assembly handling cell. The assembly transfer will include an assembly handling cell, a disposal container loading cell, and a disposal container decontamination cell. The assembly transfer system will also include fuel blending inventory pools and a special pool for nonstandard fuel, which will be located in an annex to the Waste Handling Building.

The process begins with the receipt of transportation casks from the carrier/cask handling system and the receipt of empty disposal containers from the disposal container handling system. The casks are prepared for unloading, cooled, and filled with water. The system will then transfer the rail and truck transportation casks to the cask unloading pools. In the pool, the system will remove the inner cask lid and unload individual spent nuclear fuel assemblies, single-element canisters, and dual-purpose canisters from the transportation casks. Dual-purpose canisters will be opened in the pool using remote underwater tools. The system will then stage or store the assemblies in pools, transfer the assemblies to transfer cells, dry the assemblies, load them into disposal containers, temporarily fill the containers with inert gas, install a lid sealing device, and decontaminate the lid area. Next, the system will transfer the loaded disposal containers from the cell area to the disposal container handling system. The system will also repackage nonstandard fuel assemblies in a special nonstandard fuel pool to meet waste package criteria and prepare empty transportation casks and dual-purpose canister overpacks for offsite shipment.

5.2. Cask preparation and handling

A transportation cask enters a cask preparation area on a cask transfer cart. The cask preparation and decontamination area will include two cask preparation and decontamination rooms. Each room will contain a station for unloading and loading transportation casks from the cask transfer cart to a cask preparation pit. These stations will also be used to transfer empty transportation casks and dual-purpose container overpacks on transfer carts to the decontamination area. Each cask preparation pit will contain access platforms that can be adjusted for various cask sizes. The pit will also include a cask preparation manipulator and hoist that will be operated remotely. The manipulator and hoist will mount on a gantry and straddle the pit and access platforms. The system will contain a variety of remotely operated tools and accessories for preparing and decontaminating casks using the cask-preparation manipulator and hoist. Each assembly transfer system line will include a large overhead bridge crane. The cask preparation area will also include a maintenance bay where workers can perform maintenance on the bridge crane.

The cask preparation and handling area equipment will include a cask transfer cart, a bridge crane that serves the cask unloading area, and two cask preparation manipulators with hoists mounted on gantries. The equipment will also include yokes for lifting casks and dual-purpose canister overpacks, handling fixtures, and remotely operated tools and accessories. The cask unloading and staging pools will be equipped with remotely operated assembly transfer machines mounted on the pool deck, grapples for lifting fuel assemblies, and cutting tools for removing lids from dual-purpose canisters. The cask unloading and assembly staging pools will contain dual-purpose canister overpacks, assembly baskets, basket staging racks, and transfer carts.

The assembly transfer process begins when the carrier/cask handling system unloads a transportation cask from a truck or rail carrier. A crane will lift the cask vertically and transfer it to a cart at the entrance to an assembly transfer system line. The cask will be secured against overturning. The transfer cart will move the cask into an air lock, which will control air movement between the carrier bay and the cask preparation and decontamination area for contamination protection. The air lock will have isolation doors at both ends to maintain a slightly negative air pressure in the radiation work areas relative to the carrier bay. The transfer cart will then move the transportation cask to one of two rooms for preparing and decontaminating casks.

The cask preparation and decontamination rooms will have equipment for both remote and manual operations. A dry cask lifting yoke will lift the cask from the transfer cart, then the large bridge crane in the unloading area will move and lower it into a cask preparation pit. Access platforms will adjust to the size of the cask.

Cask preparation activities will require both remote and manual operations using the crane, manipulator, and associated tools. All cask preparation activities will be performed in a dry environment, but the casks must be prepared for direct transfer to the cask unloading pools. Cask preparation will involve casks with and without dual-purpose canisters. Casks without canisters will have an outer lid or lids, and an inner lid with a built-in shield plug to provide radiation protection for manual operations. Casks with dual-purpose canisters will have a shield plug built inside the top of the canister.

Remote or manual cask preparation operations consist of gas sampling, venting, lid unbolting and removal, gas and water cool-down, shield plug unbolting, and attachment of the shield-plug lifting fixture. Gas sampling and venting operations are performed by the cask prep/purge system, which vents to the atmosphere through a high-efficiency particulate air filtration system. If the cask contains individual spent fuel assemblies with no dual-purpose canister, it will be filled with water in the preparation pit and transferred to the cask unloading pool.

If the cask contains a dual-purpose canister, workers will remove the outer lid while the cask is in the preparation pit. Using remotely operated and manual tools, workers will then open the vent valves on the dual purpose canister; sample, vent, and cool the interior cavity; attach a lifting fixture to the canister; and fill the canister with water. The bridge crane and lifting yoke will transfer the cask containing the dual-purpose canister to the cask unloading pool.

5.3. Cask unloading pool

The pool area will contain a cask unloading pool and an assembly staging pool connected by a transfer canal. Another inclined transfer canal will connect the assembly staging pool to a handling area. Transfer canals that contain transfer carts for fuel baskets will connect both staging pools to fuel blending inventory pools. Another transfer canal will connect the cask unloading pool and the nonstandard fuel pool.

If a cask contains individual spent fuel assemblies, the bridge crane, cask shield plug fixture, and wet lifting yoke will be used to remove its shield plug underwater in the cask unloading pool. If the cask contains a dual-purpose canister, the bridge crane, canister lifting fixture, and wet lifting yoke will be used to lift the canister from the cask and place it in a dual-purpose canister overpack. Using remote cutting tools, workers will then sever and remove the dual-purpose canister lid. All of these activities will take place underwater in the cask unloading pool.

A wet assembly transfer machine will remove the individual fuel assemblies from the opened shipping casks and dual-purpose canisters and load them into assembly baskets in the staging pool. The fuel will remain in these baskets until it is dried and placed in inspected and approved disposal containers. The fuel baskets will contain either four fuel assemblies from pressurized-water reactors or eight fuel assemblies from boiling-water reactors. The staging pool can hold a maximum of sixteen fuel baskets at any one time. When the assembly baskets in the staging pool are full, the wet assembly transfer machine will move the baskets to a transfer cart, which, in turn, will move the loaded fuel baskets to a fuel blending inventory pool or the assembly handling transfer cell for disposal container loading.

The pool area bridge crane and wet handling tools will return the empty transportation casks, and the canister overpacks containing empty dual-purpose canisters and lids, to the cask preparation and decontamination area. The cask preparation and decontamination process will include replacing and bolting down the lids on the empty transportation casks and dual-purpose container overpacks. Workers will decontaminate and dry the casks and containers and then survey them for remaining contamination. Following decontamination, workers will transfer empty casks and containers to the carrier/cask handling system for shipment offsite and reuse.

5.4. Fuel blending inventory

The fuel blending inventory area, located in an annex to the Waste Handling Building, will contain four modular inventory pools for spent nuclear fuel and one pool for nonstandard fuel. Each modular pool will have inventory a maximum of 750 fuel baskets loaded with spent nuclear fuel. Transfer canals from the assembly staging pool in each assembly transfer line will connect the modular inventory pools. The pools will have isolation gates so that, if necessary, one pool can be isolated from the other pools. The fuel inventory area will also have a separate pool for handling nonstandard and defective fuel in single-element canisters. All spent fuel and basket-handing operations will be conducted under water.

5.5. Dry assembly handling

A fuel assembly is selected for a disposal container according to the heat generation of the assemblies planned for placement in the disposal container. Assembly baskets and fuel will be transferred from the fuel blending inventory pools. The basket transfer machine will lift and place the fuel basket on a transfer cart, which will take the basket back to the assembly staging pool. The wet assembly transfer machine will move the assembly basket to another transfer cart for the inclined transfer canal. This cart will transport the assembly basket up the inclined canal, out of the pool water, and into the dry assembly handling transfer cell.

The dry assembly handling transfer cell will contain a disposal container loading port, an assembly transfer machine, an in-cell manipulator, two drying vessels, an in-cell service crane, and a maintenance bay. A dry assembly transfer machine will move the assembly basket into one of two drying vessels. It will be necessary to dry the fuel assemblies to meet repository waste package performance criteria. After drying the assemblies, the machine will remove them from the drying vessel and load them into a disposal container. The disposal container will be joined to the disposal container loading port below the assembly transfer cell. The dry assembly transfer machine will install the sealing device and the disposal container's inner lid. The transfer cart will then transfer the disposal container to the decontamination cell, where the top lid area and the inner-lid sealing device will be decontaminated. The system will then evacuate the disposal container internal cavity and fill it with nitrogen gas. Finally, the transfer cart will transfer the disposal container to the disposal container handling system for lid welding and inspection.

5.6. Disposal container loading

An empty disposal container equipped with a lifting collar, a base collar, and an inner lid sealing device will be transferred into the disposal container loading cell and mated with the disposal container loading port. The dry assembly transfer machine will remove the disposal container loading port lid and the inner lid-sealing device. After the fuel assemblies are dry, the dry assembly transfer machine will remove fuel assemblies, one at a time, from the baskets in the drying vessel and load them into the disposal container, positioned below the disposal container loading port. When the disposal container is loaded, the inner lid sealing device and the loading port lid will be reinstalled using the assembly transfer machine. The disposal container will be disengaged from the loading port and transferred to the decontamination cell using the transfer cart. The empty assembly baskets will be returned to the pools.

5.7. Disposal container decontamination and inerting

In the decontamination cell, the lid of the disposal container and the inner lid sealing device will be decontaminated. The disposal container will be evacuated and filled with nitrogen gas using an inerting manipulator. The disposal container will then be transferred to the disposal container handling system on the transfer cart for lid welding, inspection, and emplacement in the repository.

A transfer cart will transfer disposal containers between the disposal container handling cell, the decontamination cell, and the loading cell. An isolation door will separate the loading cell and the decontamination cell, and a shield door will separate the decontamination cell and the handling cell. A loading port mating device in the loading cell will provide a contamination barrier between the assembly handling cell, the disposal container loading port, and the disposal container during transfer of spent nuclear fuel. The decontamination cell will be equipped with a bridge-mounted inerting manipulator, a bridge-mounted decontamination manipulator, a decontamination tool, and a contamination sample pass-through glove box. Contamination survey samples will be transferred using the pass-through glove box into an adjacent operating gallery for counting.

All assembly transfer system remote operations will be controlled from operating galleries next to each assembly transfer cell. Strategically located closed-circuit television systems and shield windows will monitor remote operations. All transfer cell area equipment will be designed to facilitate remote operation and removal for contact decontamination and maintenance. Interchangeable components will be provided where appropriate. The assembly transfer system will also be designed to provide safe and efficient recovery from equipment failures and malfunctions.

5.8. Handling nonstandard fuel

One assembly transfer system line will be specifically designed and equipped for processing spent nuclear fuel that does not meet the standard loading criteria for disposal containers. This nonstandard fuel would not meet the loading criteria because, for example, it is in an irregular size single or multiple-element canister, it is not intact, or it contains failed fuel. The Waste Handling Building will include a handling room for nonstandard fuel in the fuel blending inventory pool annex. The assembly transfer system line cask unloading pool will connect to the fuel handling room through an underwater transfer canal equipped with isolation gates and a transfer cart. To meet disposal container loading criteria, the nonstandard fuel canister may undergo cutting, unloading, and repackaging operations. All will take place underwater in the nonstandard fuel pool.

Any cask containing nonstandard spent nuclear fuel will be directed to the appropriate transfer line. After the cask has been prepared, it will be placed in the cask unloading pool. The cask will be opened and the isolation gates between the cask unloading pool and the nonstandard fuel pool opened. The wet assembly transfer machine will unload the fuel assemblies or canisters from the cask and place them in assembly baskets in the nonstandard assembly basket transfer cart. The transfer cart will then be moved to the nonstandard fuel pool. Once the fuel has been unloaded and transferred, the isolation gates between the two pools will be closed. Using an overhead bridge crane, the assembly baskets will be removed from the transfer cart and placed into the nonstandard fuel pool basket staging rack. After the fuel has been repackaged, it will be loaded into the assembly basket again and sent back to the cask unloading pool by reversing the above steps. Once in the cask unloading pool, the loaded fuel baskets will be directed either to the fuel blending inventory pools or to the assembly handling transfer cell.

6. DISPOSAL CONTAINER HANDLING SYSTEM

6.1. System overview

The disposal container will consist of two concentric metal cylinders: an inner cylinder made from stainless steel and an outer cylinder made of a high-nickel alloy (Alloy 22). The bottom end of each cylinder will be closed with inner and outer lids made of the same materials used to make the cylinder itself. The upper end of each cylinder will be used for final closure lid welds, one for the inner cylinder and two for the outer cylinder. The disposal container arrives without any waste forms inside and is subsequently loaded. After the radioactive waste is loaded, the disposal container design does not provide radiation shielding for operating personnel. The lids for the upper end of the disposal container will be fabricated, but not welded and inspected until after waste is loaded into the container. The three top lids will be installed and welded inside the Waste Handling Building. Once the disposal container is loaded, and its inner and outer top lids are welded, inspected, and accepted, the disposal container is called a waste package.

The system receives loaded disposal containers from the assembly and canister transfer systems, as well as empty disposal containers from the carrier/cask transport system. The system, located in the Waste Handling Building, includes areas for preparing empty disposal containers, welding disposal container lids, staging loaded disposal containers, docking and loading the waste package transporter, and maintaining equipment used in handling the disposal containers/waste packages.

Once loaded, the container will be returned to the disposal container handling cell for welding. A number of welding stations will be provided to receive loaded containers from the assembly or canister transfer system lines. The welding operations include mounting the container on a turntable, removing temporary lid sealing devices, and installing and welding the lids. The welding process includes nondestructive examination and post-weld heat treatment. Following the nondestructive examination and acceptance of the weld, the container will be certified as a waste package and either staged or transferred to a tilting station for transport to the underground repository. Any disposal container that does not meet the weld examination criteria will be transferred to the waste package remediation system for repair or corrective action. A suite of handling fixtures, including yokes, lift beams, collars, grapples, and attachments, will support the operations of the disposal container handling system. The remote equipment will be designed to facilitate decontamination, maintenance, and use of interchangeable components, where appropriate. Set-aside areas will be included, as required, for fixtures and tooling to support off-normal and recovery operations. Semiautomatic, remote, manual, and backup control methods will be used to support normal, maintenance, and recovery operations.

6.2. Disposal container handling

The disposal container handling cell will be a large, shielded structure containing areas for several welding and inspection stations, staging of loaded containers, transfer cart operations, tilting the waste package to a horizontal position, and maintenance of the overhead cranes. Handling operations for disposal containers will involve two remotely operated bridge cranes and hoists, as well as peripheral equipment. An empty disposal container will be lifted by one of the cranes. The container will either be staged or directly transferred to a transfer cart servicing one of the two assembly transfer system lines or canister transfer system line for loading. The outer lids for the disposal container will be staged near the welding stations for sealing after the container is loaded. The empty container will be taken into either the assembly transfer system or the canister transfer system for loading. When loaded, the disposal container will be returned to either the staging area or to one of eight welding stations. Each welding station will be equipped with a robotic gantry, a turntable, and multiple sealing tools.

Following examination and certification of the welds, the waste package will be prepared for transport underground to the repository. A completed waste package will be moved either to the staging area for loaded disposal containers, or to the waste package tilting area, where the waste package will be rotated to a horizontal position resting on a horizontal transfer cart. This cart will transfer the waste package to the transporter’s loading cell.

Equipment for the disposal container handling system will be designed to facilitate remote retrieval for manual decontamination, maintenance, and component replacement, as required. All handling operations will be supported by a variety of remote handling fixtures, including disposal container lifting and base collars, lifting trunnions, lifting yokes, lifting beams, tilting fixtures, staging fixtures, and lid sealing devices. A crane maintenance bay at the far end of the handling cell will allow for contact maintenance and testing of the cranes in the cell.

6.3. Empty disposal container preparation

Special fixtures have been developed for the disposal containers to simplify handling operations. In the empty disposal container preparation area, a standard set of disposal container lifting collars and base collars for the different size disposal containers will be installed on each container. The collars will facilitate remote handling operations in the transfer cells using the in-cell cranes and transfer equipment. The collars, which will be attached and secured to the disposal container, will be equipped with trunnions for lifting, positioning, aligning, tilting, and securing the container during handling operations. The benefits of using the collars include a standard lifting interface for all disposal containers, a simple and visually verifiable lift attachment, and a safe and proven approach for lifting, tilting, aligning, and securing heavy loads. The base collar will secure and protect the disposal container against tipping over when it is placed on carts, staging fixtures, and welding station turntables; the collar will secure and stabilize the container as it is rotated and its lids are welded. The collars will also serve in supporting and lifting the disposal container when it is in a horizontal position.

The area for preparing empty disposal containers will be located in an unshielded structure next to the disposal container handling cell (not shown). This area will provide adequate space for staging 20 empty containers and their lids, handling collars, and inner lid sealing devices. The disposal container handling system is configured so that empty containers can be brought into the disposal container handling cell ready for handling and loading. This will permit manual handling of each empty container before it is transferred into the handling cell. Preparing an empty disposal container includes unloading the container from a carrier, staging the empty container, tilting it for vertical handling, outfitting it with lids and fixtures, setting the empty container onto a transfer cart, and transferring it through an air lock to the handling cell. The handling equipment in the preparation area for empty disposal containers includes a bridge crane, lifting yokes, lifting beams, collar installation tools, staging racks, a tilting station, the transfer cart, and the handling fixtures described above. In this area, an empty disposal container will be received, inspected, fitted with handling collars, positioned vertically, and prepared for loading by installing fuel assembly spacers, inner and outer lids, and inner lid sealing devices. The disposal container will then be placed on the transfer cart to await transfer into the handling cell.

The air lock from the preparation area will consist of a shielded room through which the empty disposal container will be transferred into the handling cell. The air lock will prevent airborne contamination that may be present in the handling cell from entering the empty container preparation area. The shield walls and doors at the air lock will also provide protection from radioactive waste inside the handling cell.

6.4. Disposal container sealing and closure

The disposal container handling system will receive a loaded and temporarily sealed disposal container from the assembly transfer system or the canister transfer system, then transfer it to a staging area or a welding station. Sealing and closure will include a number of steps and remote equipment operations. Additional steps and remote equipment will also be required to conduct weld inspections and post-weld heat treatment operations. Following weld inspection and weld certification, the container will either be staged or prepared for transfer to the subsurface repository. A loaded, closed, welded, inspected, and certified disposal container is called a waste package.

The cranes in the disposal container handling cell will be used to lift and transfer a loaded container to one of the eight independent lid-welding stations. A remotely controlled robotic gantry will set up, prepare, weld, and backfill the container with inert gas. The gantry will also serve as the remote handling platform to inspect the sealing operations, which will include securing the disposal container to the welding station's turntable, removing temporary sealing devices, purging the lid with inert gases for welding, backfilling the container with helium prior to closure, turning the container, welding the inner lid, installing the outer lids, and welding the outer lids. Welding will be performed using automatic welders deployed from the robotic gantry platform such that they can be remotely removed from the cell for retooling, testing, adjustments, and maintenance. This feature eliminates the need for personnel to enter the radiation environment in the handling cell. Future welding considerations will include review of laser peening and annealing processes.

One air lock will be provided for each of the eight welders. The welder air locks will provide access to the robotic gantry, remote welder, nondestructive examining equipment, and post-weld heat-treating equipment. Access and service work on the equipment will be possible in these rooms without exposing the workers to the atmosphere and radiation sources in the disposal container handling cell.

6.5. Waste package staging

The staging area for loaded disposal containers will be used to stow loaded disposal containers or waste packages awaiting transfer to the waste package transporter's loading cell. To reduce radiation levels in the crane maintenance bay, loaded disposal containers will be staged in a separate area inside the disposal container handling cell. This area will have partial walls and an access door to facilitate transfers of disposal containers to and from staging locations. The partial walls will provide shielding for the main portions of the cell and the maintenance bay, where protection of equipment and personnel is required. The design configuration incorporates both distance and shielding by isolating radiation sources to one area of the transfer cell and adding a wall separating the staged disposal containers from the welding, handling, and crane maintenance areas. This will significantly reduce radiation doses to equipment during normal operations, while also reducing radiation levels during manned entry into the cell for periodic maintenance and test operations.

6.6. Waste package transporter loading

The final handling sequence for the surface facilities involves repositioning the waste package to a horizontal position, transferring the sealed waste package to a decontamination and transporter loading cell, and loading the waste package onto a pallet and then onto the transporter. These operations include lifting, transferring, final decontamination, final inspection, certification, and tagging of waste packages. The operations will be performed using a remotely operated horizontal transfer cart, a waste package horizontal lifting machine, decontamination and inspection manipulators, and the waste package transporter.

Only one transporter loading line will be available for the final decontamination, inspection, transfer, and loading of waste packages onto a transporter. The waste package, once it is moved into the transporter loading cell from the disposal container handling cell, will be lifted off the horizontal transfer cart by the lifting collar, the base collar, and the horizontal lifting machine. While suspended, the waste package will be decontaminated, inspected, and certified. Important data needed for repository recordkeeping will be recorded. The mobile pallet of the transporter will then move into the cell, and the waste package will be lowered onto the pallet. The handling collars will then be remotely removed and taken out of the waste package transporter loading cell for reuse. Any contamination picked up during disposal container sealing will be manually removed in rooms for equipment contamination before the collars are transferred to the empty disposal container preparation area for reuse.

A transporter air lock will be provided at the Waste Handling Building exit of the transporter loading line so that the waste package transporter vehicle may enter and be docked for loading. The air lock will prevent movement of air between the transporter loading cell and the outside atmosphere. In the final surface waste handling steps, the waste package pallet and rolling bed plate will be pulled into the shielded waste package transporter, the transporter shield doors will be closed, and the waste package transporter will be disengaged from the loading cell dock. Then the waste package will be transported to the subsurface repository.

6.7. Waste package remediation system

When a waste package is found to be abnormal or damaged, workers will transfer it from the disposal container handling system to the waste package remediation system. This system will be housed in a multipurpose cell inside the Waste Handling Building.

The waste package remediation system will receive disposal containers and waste packages that have failed the weld inspection processes, that have been selected for retrieval from the repository for performance confirmation examinations, and that are defective or abnormal. Workers will repair the abnormal or damaged waste packages (or disposal containers, if they are not correctly sealed and inspected). After workers have examined, repaired, or, if necessary, unsealed and repackaged the damaged disposal containers or waste packages, the remediation system will deliver them back to the disposal container handling system.

The processes for opening a waste package or disposal container will include remotely cutting the closure weld, collecting and processing the cutting fines, removing and disposing of the cutting waste, and installing a temporary seal to confine contamination to the inside of the container.

All remediation operations on radioactive waste packages or disposal containers will be performed remotely in a dedicated, shielded cell accessible directly from the large handling cell inside the disposal container handling system. The remediation cell will accommodate one waste package or disposal container at a time. A shield door will open to allow the transfer cart to enter. After the transfer cart enters the remediation cell, the damaged container will be positioned at one of two work stations in the remediation cell, and will exit the cell without being removed from the cart. The two remotely operated work stations will accommodate different repair tasks. One workstation will facilitate the cutting, removal, and staging of the container lids. The other will allow remote inspection, examination, and purging of the container, as well as backfilling it with inert gas, temporarily sealing it, and decontaminating it.

The remediation system will use a variety of remotely operated equipment, including an overhead bridge crane, an in-cell multipurpose manipulator, a lid-cutting machine, and closed-circuit television viewing systems. System operations will all be performed remotely using equipment designed to facilitate decontamination, maintenance, and replacement of interchangeable components, as required.

Opening a sealed container will require remotely cutting the closure welds of the inner and outer lids, removing and staging the lids, collecting and processing cutting fines, removing and disposing of cutting waste, and installing a temporary seal to confine contamination to the inside of the container. Following remediation, the container will be inspected for contamination and remotely decontaminated, as required. The container will then be returned to the disposal container handling system for rewelding, transferred to the assembly transfer system for unloading of fuel assemblies, or transferred to the canister transfer system for unloading of canisters.

7. REPOSITORY OPERATIONS MONITORING AND CONTROL SYSTEM

Two central control centers will be established in the Geologic Repository Operations Area to monitor and control repository surface operations and perform emergency command functions. The control centers will be located in the Waste Handling Building and the Administration Building.

Operators in the Waste Handling Building control center will monitor and control specific operations in the Waste Handling Building and throughout the plant: for example, track all radioactive material in the building, operate building utilities, and control radiation containment doors. The control system will include local consoles at various locations, including the operating galleries where workers will control the remote waste handling operations while watching the mechanical operations. Operators at the main control center will monitor the gallery console operations and respond to emergency and off-normal events. If a gallery console malfunctions or a gallery becomes uninhabitable, the main control center will perform any necessary emergency response functions. Gallery console operators will communicate with main control center operators via secured communication lines. A separate emergency control panel will serve as a backup to the main control center system. If the main system fails, this panel will be able to bring waste handling systems and other systems that are important to safety to a safe operating or shutdown condition.

8. RADIOLOGICAL SAFETY SYSTEM

The radiological safety system will ensure that activities associated with operating, monitoring, and closing a repository will not expose workers or the public to radiation doses above applicable regulatory limits. Moreover, the DOE will implement its policy of keeping both occupational doses and possible doses to the public as low as is reasonably achievable.

The radiological safety system will establish the controls for assuring that the repository and its operations will have appropriate and sufficient radiation protection features. The system will cover such aspects as facility designs, operational activities, and facility policies to assure radiation safety. The radiological safety system is part of the overall formal radiation protection program for controlling radiological areas, approving radiological work, and monitoring worker exposures.

9. WASTE PACKAGE TRANSPORTER

The waste package transporter selected for the repository consists of a flat railroad car 22 m (72.4 ft) in length, with a waste package shielding structure at one end and an open deck at the other end. Ancillary equipment installed on the transporter includes mechanisms for opening and closing the shielded doors; a bed plate supported on rollers; and a semirigid chain mechanism and tracks for rolling the bed plate in and out of the shielded enclosure.

This waste package transporter design with an integrated transfer deck eliminates the complexities of aligning several separate components at the waste package transfer locations.

The integrated transporter design with the shielded enclosure located toward one end of the flat deck car allows the open deck area to extend adequately beyond the shielding structure, which permits the waste package and pallet to be moved together out of the enclosure and positioned for access by the emplacement gantry. The waste package transporter is docked between the rails of the emplacement gantry in the emplacement drift, enabling the emplacement gantry to straddle the transfer deck to pick up the waste package and pallet.

A bed plate sized to contain and restrain the pallet has four low-profile, heavy-duty rollers affixed to its underside to aid movement of the waste package out of the shielded enclosure. After the emplacement gantry engages the pallet and raises the loaded pallet high enough to clear the bed plate, the bed plate is retracted back into the shielded enclosure. This transporter design eliminates the need for precise alignment of tracks between the transporter and the emplacement drift, and it diminishes the possibilities for waste package mishandling and dropping incidents. The gantry lifting screw limits the maximum height the waste package can be lifted to less than 1 m above the deck of the transporter. To eliminate the risk of dropping a waste package in the docking area, the transporter remains in the area until the loaded gantry moves back into the emplacement drift.

The shielded enclosure is designed to meet the radiation dose rate limit of 100 mrem/hr on the transporter surface, which is accomplished with an A–516 steel enclosure wall with a thickness of 171.5 mm (6.75 in.) in the radial direction and a wall thickness of 196.9 mm (7.75 in.) in the axial direction. An A–516 steel thickness of 152.4 mm (6 in.) provides sufficient shielding for nonaccessible areas (i.e., the deck floor below the shielded enclosure) during normal operations. In addition to the A–516 steel, the shielded enclosure has a borated polyethylene layer for neutron shielding.

Emplacement Gantry

The gantry designed to handle the waste package and pallet is called the bottom/side lift gantry. The gantry has been designed so it will not drop a waste package or become inoperable as a result of a seismic Category 1 design basis event.

The gantry is designed to operate in the elevated-temperature, high-radiation environment inside the emplacement drifts. Its operation only involves moving forward and backward on the rails and moving the lifting hooks up and down. This simple operation reduces the complexity of the gantry’s mechanical, electrical, and control systems, which makes the gantry inherently reliable. The incorporation of high-quality hardware and software components further enhances control system reliability. These components mainly include redundant programmable control computers, instruments, and communications equipment. Fault-tolerant operation is ensured by physically separating the redundant components, providing backup electrical power and data communication systems, and employing diverse technologies that will not be susceptible to similar failures from a single cause. Shielded and insulated cabinets protect the heat- and radiation-sensitive instrumentation, and solid-state air conditioning units regulate the temperature. Built-in fire detection will automatically activate fire suppression systems should an onboard fire be detected. At this point, the gantry would be retrieved from the drift for repairs.

The video system of the gantry will provide operators at the remote control center with real-time visual information about the operating environment and vehicle performance. This system will consist of several onboard high-resolution, articulated, closed-circuit television cameras and a series of high-intensity lights. Thermal and radiological sensing instrumentation will provide the remote control center with real-time status on these two environmental conditions of the emplacement drift.

The emplacement gantry will not be left inside an emplacement drift for extended idle periods because of the potential detrimental effects of heat and radiation on the gantry sensors and instruments. An emplacement gantry carrier, which is a flatbed railroad car with on-deck rail tracks that mate the drift tracks, moves the gantry from drift to drift, or to a staging area.

REMOTE HANDLING OF SPENT NUCLEAR FUEL IN THE MODULAR DRY STORE DESIGN CONCEPT

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ABSTRACT

Principal features for the remote handling of spent nuclear fuel in the modular dry storage design concept are presented and discussed. The modular design concept has been successfully applied in several locations worldwide and offers particularly attractive remote handling options that ensure safe operations. Emphasis in this paper is on new facilities in the United States of America based on this design concept that are or will be licensed by the U.S. Nuclear Regulatory Commission.

1. INTRODUCTION

The Modular Vault Dry Store (MVDS) design concept is a licensed, dry spent (irradiated) nuclear fuel storage technology that has been applied internationally for the storage of a wide range of different types of fuel. A critical part of the operation for transferring fuel from the reactor pool to the MVDS storage position requires the use of a fuel handling machine. In each facility, the fuel handling Machine is designed to perform a number of specific remote handling functions, as well as to withstand a variety of fault or off-normal conditions. This paper reviews some of the design and remote handling operational requirements that have been incorporated into the MVDS fuel handling machine.

2. EXAMPLE INSTALLATION UTILIZING THE MODULAR VAULT DRY STORE DESIGN

A number of installations utilizing the MVDS design are in operation worldwide. One such installation was constructed at the Fort St. Vrain nuclear facility in Colorado in response to the needs of the nuclear power generating utilities who require a safe and cost-effective solution for the interim at-reactor storage of irradiated fuel assemblies. This MVDS storage facility is shown in Fig. 1.

FIG. 1. The Fort St. Vrain modular vault dry store facility in Colorado.

The MVDS is designed to operate separately from existing reactor facilities and, as demonstrated at Fort St Vrain, it can operate in a self- sufficient manner, even after the reactor is decommissioned. The MVDS is equally suitable for at-reactor (AR), or away-from-reactor (AFR) applications. The MVDS represents a comprehensive spent fuel management system for which various handling, packaging, and storage operations can be conducted.

The Fuel Handling Machines designed for the MVDS operations have evolved from the reactor refuelling machines that have been used in the British gas-cooled reactor programs. The British gas-cooled reactors are routinely refuelled under load conditions (i.e., while the reactor is pressurized and operating at full power) and therefore the designs of the reactor refuelling machines have had to take account of very arduous safety requirements. For the dry store Fuel Handling Machines, the design requirements are far simpler, as there are no high pressure, high temperature or gas flow conditions to contend with. The design features to maintain shielding, confinement, cooling and sub-criticality are, however, a fundamental requirement that must be implemented and maintained in a safe and cost-effective manner.

Since there are typically a wide range of spent fuel types (and associated canisters) to be stored, each with unique or special design and safety requirements for dry storage, there are a range of designs and functional requirements for the Fuel Handling Machines needed to transfer spent fuel into (and ultimately out of) an MVDS. The Fuel Handling Machine used at Fort St Vrain is shown in Fig. 2.

FIG. 2. Fort St Vrain fuel handling machine.

The MVDS Fuel Handling Machine, as shown in Fig. 2, is designed to carry out a number of relatively simple tasks:

- At the start of the fuel storage period, the Fuel Handling Machine has to remove or pick up the irradiated fuel assembly or canister containing fuel elements from the Transfer Cask at the Transfer Cask Reception Bay and then to transfer it to the appropriate storage position in the Vault Module.

- The Fuel Handling Machine has to provide the required shielding, confinement and cooling features needed to ensure the safe and secure transfer of the irradiated fuel assembly or canister.

- At the end of the fuel storage period, the Fuel Handling Machine has to remove or pick up the irradiated fuel assembly or canister from its storage position in the Vault Module and then transfer it for inspection into the off-site Transport Cask at the Transfer Cask Reception Bay.

3. DESCRIPTION OF THE MVDS CANISTER HANDLING MACHINE

The Fuel Handling Machine is located in the MVDS Charge Hall, above the Charge Face through which fuel or canisters are transferred into the Storage Vault. When designed and used for handling canisters, the Fuel Handling Machine will be referred to as a 'Canister Handling Machine'.

The Fuel Handling Machine consists of a bridge and trolley that carries a shielded cask/turret assembly. The Fuel Handling Machine runs on rails that allow it to travel the full length of the storage vaults. A single failure-proof wire rope hoist and grapple system is mounted at the top of the turret assembly. The hoist and grapple assembly handles the loaded canisters. The total weight of a Fuel Handling Machine assembly is typically 200 - 500 tons depending on the size of the fuel assembly or canister that is being handled.

A single operator uses the trolley-mounted control desk to operate the Fuel Handling Machine. Operations for positioning the Fuel Handling Machine and handling the canisters are performed remotely at the control desk. Drive control interlocks prevent the possibility of a canister being trapped inside the nose cavity of the Fuel Handling Machine by inadvertent activation of any of the travel drives or the turret rotate drive when the canister is being raised or lowered.

The Fuel Handling Machine is held in a locked position during canister raising/lowering operations. This avoids the potential for trapping and damaging a canister if the uncontrolled movement of the Fuel Handling Machine should occur with the canister partially inserted into a storage tube. A seismic event could lead to such an occurrence, so the Fuel Handling Machine locking system is designed primarily to withstand seismic forces. To ensure that an uncontrolled motion of the Fuel Handling Machine does not occur, substantial clamps lock the bridge to the long travel rail system, the trolley to the bridge, and the rotating parts of the turret to the trolley and the non-rotating base casting.

The turret is fully shielded and provides protection from gamma and neutron radiation that is emitted by the spent nuclear fuel during transfer operations.

The major subassemblies of the Fuel Handling Machine are:

- A bridge assembly including girders, cross travel rails, end trucks, long travel drive, wheels, seismic locks, and the power supply collecting system.
- A trolley assembly with structural steel frame, cross travel drive unit, wheels, seismic locks, power supply collecting system, operator control desk, instrumentation and control cubicles, and a turret rotate festoon system used to convey power and control between the trolley and the rotating turret.
- A turret assembly that incorporates three operational cavities:

  1) A canister cavity inside the main cask body together with a dedicated single failure proof canister hoist and grapple for raising and lowering the canisters containing spent nuclear fuel.
  2) A storage tube plug cavity with its dedicated plug hoist and grapple system that is used for handling tube plugs.
  3) A navigation cavity with its CCTV system that is used to accurately position the Fuel Handling Machine over the storage tubes or other stations and for viewing the canister identification numbers.

The MCO Handling Machine that is in operation at the Hanford Canister Storage Building (see Fig. 3) is a typical example of a MVDS Canister Handling Machine.

FIG. 3. Hanford canister handling machine.

4. REMOTE HANDLING REQUIREMENTS AND FEATURES OF THE MVDS FUEL HANDLING MACHINES

Spent fuel can be transferred into storage either as bare fuel assemblies, or as canistered fuel. However, due to the intense radiation source of the fuel, the Fuel Handling Machine has to make the transfer into storage by remote operation – direct contact with the spent fuel assembly or canister is not possible. Remote handling of spent fuel in a MVDS requires the following technical issues to be addressed in the design of the Fuel Handling Machine and the associated vault structure:

- ***Remote Handling of the Fuel or Canister***

The successful remote handling of spent fuel in a MVDS requires a lifting feature on the fuel assembly or canister that can be automatically engaged by the lifting grapples without having direct viewing or manipulation. The grapple lifting interface has to consider the geometry of the tube or cask basket into which the fuel is to be placed or removed, taking account of the possible radial and azimuth misalignments that can occur. Lead-in features on the grapple are often required to assure correct line up prior to attempting to engage the fuel or canister.

The route through which the fuel or canister is moved is designed to prevent load hang-up or snagging. This requires changes in the section to be chamfered so that ledges cannot be formed. If a load is being lowered and it ledges in the route, by the time that the hoisting system has detected that the load has stopped moving, it will have paid out an amount of slack rope or chain. If the load subsequently falls off the ledge, then the load will drop by the distance allowed by the slack rope and be abruptly arrested as the rope goes tight. This accident is known as the hang-man's drop and it can lead to very high loads being induced in the hoisting system. Although hoists may be designed to be high integrity and with high factors of safety, the loads that can be imparted from a 'hang-man' drop are generally far higher than those specified in the design codes. Therefore, the design approach is to ensure that load hang up is not credible. If load hang up is considered credible, then it is necessary to provide energy absorbing features in the hoisting system that will absorb the potential energy of the dropped load without exceeding the code specified factors of safety.

Similarly if the load is being raised and it ledges in the route, then the hoist system loads will increase as the hoist motor reacts to the stuck load. If the hoist system does not have weight sensing features built into the control system, then the load could increase to the point where the hoist system fails. The main cause of hoist system failure in a stuck load condition is due to the motor torque load added to loads induced by the rotating kinetic energy of the drive motor and drive system as the speed is reduced to zero.

When spent nuclear fuel is being handled within a pool environment, the operators have the benefit of direct viewing to assist with controlling the operation. In a fuel handling machine environment, handling operations take place without the benefit of direct vision and therefore the fuel handling machine must provide signals that give the operator information as to what is happening during the handling operations. Control signals will be incorporated with appropriate logic to give an operating system with in built safety interlocks that prevent incorrect operation of the fuel handling machine. Typical signals that will be provided to the fuel handling machine control and interlock system are:

- Fuel hoist: raising, or lowering
- The load on the fuel hoist, including overload or underload conditions
- The position (depth) of the fuel hoist
- Fuel grapple jaws: open or closed, locked or unlocked
- Fuel grapple jaws: engaged on the fuel or canister
- Crane bridge and trolley travel: end stop positions

Maximum operator flexibility is provided by allowing any drive motion to be selected at any time, but the conditions of the interlock decide whether that drive will be permitted to operate or not. Use of PLCs or other automatic sequencing systems is minimized.

The Fuel Handling Machine used at Wylfa is shown in Fig. 4.

FIG. 4. Wylfa dry store fuel handling machine.

All of the main drive systems will have a method for manual operation and recovery for use in case of loss of power. Typically, this is achieved by the addition of a hand-wind facility on the drive system, or by the use of a secondary hand wound system. The objective of the manual system is to be able to drive the machine into a safe condition where it can be left – with fuel on board – for as long as it takes for electrical power to be restored. As the heat rejection and shielding are provided by passive systems there are no time restrictions for how long fuel can reside in the fuel handling machine. When the machine handles bare fuel assemblies, then there will be an on-board extract system and HEPA filters, and this system will utilize on board batteries to keep the system operating should the main power be disrupted.

- ***Radiological Safety Features During Fuel Handling***

The MVDS Fuel Handling Machine must ensure the safety of the spent fuel assemblies, or canisters, during the remote transfer operation from the Transfer Cask into the vault storage position. There are four fundamental radiological safety concerns that the design of the MVDS dry store facility, including the transient residence in the Fuel Handling Machine, must address. These are:

- ➢ Confinement of the irradiated fuel assemblies
- ➢ Shielding of the irradiated fuel assemblies
- ➢ Cooling of the irradiated fuel assemblies
- ➢ Sub-Criticality of the irradiated fuel assemblies

These four fundamental safety issues are addressed in the Fuel Handling Machine by a number of alternative methods depending on the type of fuel being handled.

- ***Confinement of the irradiated fuel assemblies***

The irradiated fuel assembly can be transferred as an un-canistered (i.e., 'bare') fuel assembly within the Transfer Cask and Fuel Handling Machine, before being posted into its storage position in the vault. Alternatively, the irradiated fuel assembly can be canistered at the reactor pool and transferred within that canister to its storage position within the vault. Both the canistered and non-canistered design options have already been license approved.

The canistered fuel transfer route has the advantage that the Fuel Handling Machine remains clean of contamination during all normal operations. The canister is the confinement barrier for the irradiated fuel assembly and therefore it is not necessary to have a sealed Fuel Handling Machine. The Fort St Vrain Fuel Handling Machine, as shown in Fig. 2, was designed to handle canistered fuel.

For the Fuel Handling Machine that is designed to handled un-canistered fuel on a routine basis, the design must recognise the need for continuous confinement. The un-canistered Fuel Handling Machines are designed with on-board HEPA ventilation systems that run continuously while the fuel transfer operations are taking place.

In the event of there being non-canistered fuel that could not be transferred in an air environment (due to either high heat loading, chemical reactivity, damaged or exposed fuel, etc) then the MVDS Fuel Handling Machine can be designed as a totally sealed machine with the ability to introduce an inert atmosphere within the machine for the transfer operations. Machines of this design allow that type of fuel transfer to take place every day during the normal refuelling operations at the UK gas cooled reactors.

- ***Shielding of the irradiated fuel assemblies***

The amount of shielding needed at a dry storage facility is determined by three separate parameters:

- ➢ The radiological characteristics of the fuel being handled and stored.
- ➢ The allowable on-site operational dose rates and the allowable off-site dose rates to the critical public group.
- ➢ The dose rates coming from the existing nuclear facilities on the site that reduce the contribution to the total allowable dose rates from the dry store facility.

This means that it is not possible to have a truly standard design of (any type) dry store as the shielding design must always review what pre-existing radiation sources exist on the site. Failure to carry out this review can lead to operating staff receiving higher annual doses than are acceptable, or more likely is that the off-site dose rates will exceed the annual limits.

The Idaho Handling Machine and Storage Vault are shown in Fig. 5.

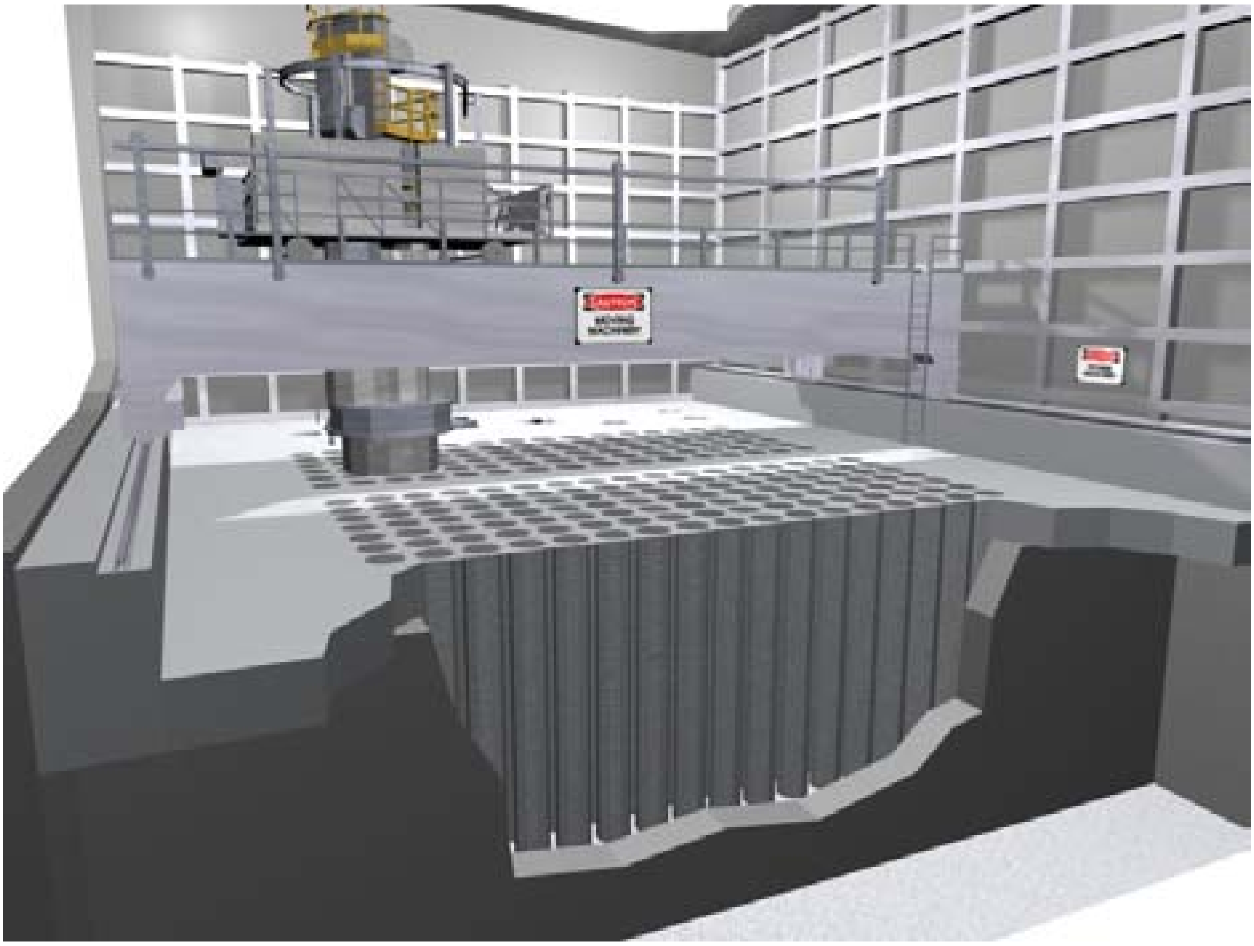

FIG. 5. Idaho spent fuel project canister handling machine and storage vault.

The shielding on the Fuel Handling Machine must provide attenuation of gamma and neutron radiation. Some fuel types, especially if they have been recently discharged from the reactor, will emit significant neutron radiation that requires a significant amount of shielding. The materials used for the shielding on the Fuel Handling Machine are:

- Steel, cast iron or cast lead - for gamma radiation attenuation.
- Concrete - for gamma and neutron radiation attenuation.
- Polythene - for neutron shielding attenuation.

- ***Cooling of the irradiated fuel assemblies***

The method of cooling the fuel in the MVDS vault is by a naturally induced cooling air flow. While the irradiated fuel assembly is in transit inside the Fuel Handling Machine it is not possible to have such an efficient convective cooling mechanism due to the need to confine the irradiated fuel assembly within the body of the Fuel Handling Machine. The method of cooling the irradiated fuel assembly inside the Fuel Handling Machine relies primarily upon direct radiation of the decay heat of the fuel assembly to the body of the Fuel Handling Machine. The Fuel Handling Machine body absorbs this decay heat which is then dissipated by radiation (and convection) from the external surface of the Fuel Handling Machine to the Charge Hall environment.

Because the Fuel Handling Machine carries a limited number of fuel assemblies within its body cavity, the heat loads are very manageable. Even if the fuel were to be kept within the body of the Fuel Handling Machine for an extended period (due to an off-normal event that prevented the fuel from being moved) then the thermal inertia and heat rejection capabilities of the Fuel Handling Machine will maintain acceptable fuel pin temperatures for an indefinite period.

- ***Sub-Criticality of the irradiated fuel assemblies***

The criticality analysis for the MVDS considers the fuel assemblies in an infinite vault array and during the reactor pool loading operations. The criticality analysis also considers the possibility of a fully and partially flooded vault. The fuel array (including the case of the transfer cask being loaded in the pool) is always shown to be non-critical for all the above criticality analysis design conditions.

The conditions found within the Fuel Handling Machine handling operations are not as onerous as either the reactor pool operations or the vault storage conditions, and therefore it is a relatively simple calculation to demonstrate the non-criticality of the fuel assemblies during the transfer in the Fuel Handling Machine.

5. REVIEW OF FUEL HANDLING MACHINE DESIGN PARAMETERS

The principal features that have to be considered in the design and application of a Fuel Handling Machine vary from facility to facility. Example facilities include the following:

- Fort St Vrain MVDS — refer to Fig. 1 and 2.
- Hanford CSB — refer to Fig. 3.
- Wylfa Cells 4 and 5 — refer to Fig. 4.
- Idaho Spent Fuel Project — refer to Fig. 5.
- Torness (Scottish Nuclear) MVDS FHM.
- Paks MVDS.

At these facilities, the differing types of fuel have led to development of different types of Fuel Handling Machines to ensure safe operations. The Fuel Handling Machines for the Torness and Paks facilities provide an additional fuel inspection capability. For these two stores, the operators have specified that the Fuel Handling Machine must be able to carry out visual inspection of the fuel. This is achieved by the use of CCTV cameras mounted within the body of the Fuel Handling Machine.

6. CONCLUSION

The MVDS Fuel Handling Machine has evolved from reactor refuelling machines that were designed for far more arduous duties. The dry store Fuel Handling Machine design has therefore taken advantage of the inherent safety and operational margins in its predecessors to provide a very high degree of design flexibility and reliability that is used to ensure the safe and secure transfer of the many varying type of fuel materials being placed into dry storage.

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