DEVELOPMENT AND DEMONSTRATION OF PROTOTYPE TRANSPORTATION EQUIPMENT FOR EMPLACING HL VITRIFIED WASTE CANISTERS INTO SMALL DIAMETER BORED HORIZONTAL DISPOSAL CELLS

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Abstract

Over a period of 4+ years the National Radioactive Waste Management Agency (Andra), working with a variety of Contractors mostly specializing in nuclear orientated mechanical applications, successfully designed, fabricated and demonstrated 2 very different prototype high level waste transport systems. The first system, based on air cushion technology, was developed primarily for very heavy loads (17 to 45 tonnes). The results of this work are described in a separate presentation (Paper 21) at this Conference. The second system, developed by Andra within the framework of the ESDRED Project, generally referred to as the "Pushing Robot System" for vitrified waste canisters, is the subject of this paper.

The "Pushing Robot System" is a part of the French national disposal concept that is described in Andra's "Dossier 2005". The latter is a public document that can be viewed on Andra's web site (www.andra.fr). The "Pushing Robot System" system is designed for the deep geological disposal (in clay formations) of "C" type vitrified waste canisters. In its entirety the system provides for the transport, emplacement and, if necessary, the retrieval of those canisters. Nothing in the design of the Andra emplacement equipment would preclude its utilization in horizontal openings in other types of geological settings.

Over a period of some 8 years Andra has developed the"Pushing Robot System" in 3 phases. Initially there was only the "**Conceptual Design**" (Phase 1) which was incorporated in the Dossier 2005. This was followed by Phase 2 i.e. the design and fabrication of a simplified full scale prototype system hence forth referred to a **P1,** which includes a Pushing Robot, a Dummy Canister and a Test Bench. **P1** details were also incorporated in the Dossier 2005. Finally, during Phase 3, a second more comprehensive full scale prototype system **P2** has been designed and is being assembled and tested this month. This sytem includes a Transport Shuttle, a Transfer Shielding Cask, a Docking Table, the Disposal Cell Mouth equipment and a full scale (100m long) test bench, in addition to the Dummy Canister and a second generation Pushing Robot.

The successful completion of the test campaign associated with the first prototype **P1** confirmed the feasibility of emplacing 2 tonne/0.6m diameter waste packages (canisters) containing long lived HLW in 40m long horizontal bore holes (disposal cells) with only minimal annular clearance between the canister and the disposal cell liner. Preliminary testing of the second prototype P2 indicates that proper docking onto the cell mouth, followed by emplacement in 80 to 100m long disposal cells, is possible. The developed technology is considered to be mature enough for a potential industrial application.

The 2 prototypes (the 2nd and 3rd phases of the work) were executed within the framework of the ESDRED Project (Engineering Studies and Demonstration of Repository Designs) which is co-funded by the European Commission as part of the sixth Euratom Research and Training Framework Programme (FP6) on nuclear energy (2002 – 2006).

1 Introduction

The French National Radioactive Waste Management Agency, or Andra, has developed 2 Prototype Pushing Robot systems for the deep geological emplacement and potential retrieval of C type or "Vitrified Waste Canisters". The first prototype **P1** consists only of the Pushing Robot, a Dummy Canister and 13.5m of Test Bench (disposal cell mock up) – all at full scale. The second prototype **P2** consists of the entire disposal system including the Transport Shuttle, the Transfer Shielding Cask, the Docking Table, the Pushing Robot and mock ups of the Canister, the Gama Gates and the other Disposal Cell Mouth equipment. It also includes 100m of Disposal Cell mock up and a short mock up of the Access Drift, all at full scale.

Following completion of the initial conceptual design by ***SGN*** (Phase 1) Andra opted for a 2 step approach. The objective (Phase 2) was to first build a simplified but full scale version of the Pushing Robot and the Test Bench early in the ESDRED project in order to quickly, but convincingly, prove the fundamental working principles at minimum cost. This resulted in the first prototype system **P1** noted above, sometimes referred to as the ***MUSTHANE ROBOT.*** This work was the result of a cooperative effort between 2 French firms, i.e. Musthane and Creativ Alliance. Once this machine was constructed, tested and analyzed for future enhancements Andra let a Contract to ***CEGELEC*** for the design and construction of a second generation Pushing Robot System (Phase 3) which would include all of the ancillary equipment needed to demonstrate a complete transport and emplacement system in this environment. This system is now into its final assembly and testing stage. Ultimately Andra will have on display, in its technical facility and show room near the Bure URL, 2 full scale remotely operated pushing robot demonstrators capable of emplacing one (**P1**) or more (**P2**) dummy canisters having a mass and geometry identical to the real canisters.

The basic Pushing Robot System is designed for the emplacement of "C type" vitrified waste canisters (0.590m OD, 1.60m long, weighing 2 tonnes). In a first instance (**P1**) these are emplaced in 40m long horizontal bore holes (disposal cells) which have been excavated in clay host rock and outfitted with a 0.620 ID carbon steel lining. In the second generation prototype (**P2)** the length of the disposal cells is increased to 100m and the robot is designed to push up to 3 canisters at a time.

The main technological innovations applicable to **P1** and **P2** include the fabrication of a Pushing Robot which uses pneumatic toric jacks for propulsion, which is less than 1m long and which weighs less than 1 tonne, and the fabrication of dummy canisters which incorporate ceramic inserts acting as sliding runners. For **P2** only the additional technological innovations include the fabrication of a very compact Transport Shielding Cask that can concurrently house the canister and the robot and the fabrication of a single complex umbilical cord which provides for all of the operating, monitoring, control and retrieval functions in remote control mode. The latter is mounted on a winch reel that is external to the Transport Shielding Cask.

The rationale behind the pushing robot system comes from various considerations, including the need for (1) a simple and robust system, capable of moving (and potentially retrieving) 2 tonne C type canisters mounted on ceramic sliding runners over distances between 40 and 100 metres inside a carbon steel sleeve which constitutes the liner and rock support of a horizontal disposal cell, (2) having small annular clearances between the canister and the liner, (3) a compact emplacement device that can be transferred from surface to underground together with one disposal package (the canister) inside a transfer shielding cask, and (4) operations that can be remotely controlled for the sake of radioprotection.

This paper highlights the design of the 2 prototypes (**P1** and **P2**) and the evolution of the design beginning with the original concepts developed by SGN. It goes on to describe the components and the operation of the system and it provides a summary of the test work which has been concluded. The difficulties encountered from commissioning through final demonstration, together with the weak points of each system and the remedial solutions considered, are also explained. Results are discussed. The main achievements are highlighted. The paper concludes with a discussion regarding the improvement recommendations that resulted from the construction and testing of **P1** and which have been incorporated into the **P2** design. Once proven and demonstrated later this year the future prospects for an industrial application will be evaluated.

2 Summary of the French situation

2.1 The Vitrified Waste and Its Conditioning in C type Canisters

The vitrified waste (conditioned as a C type canister) to be emplaced is a High-Level and Long-Lived (HLLL) waste, which contains both short-lived radionuclides, usually in large quantities (high level), and long-lived radionuclides in medium to very large quantities.

Class C waste consists of fission products and minor actinides separated out during fuel reprocessing. This waste is conditioned by incorporating it into a glass matrix. Glass has a particularly high and long-lasting confinement capacity provided the physical-chemical properties of the environment are favorable.

Conditioning this waste involves (i) solidifying and immobilizing waste produced in dispersible form (usually liquid) and (ii) placing the waste in a container to facilitate handling and storage at industrial facilities. This first conditioning yields “primary packages”. The total volume of “primary package” C type waste to be emplaced is estimated to be 6,330 cubic metres (m^3) as per the Dossier 2005.

Before being sent underground for emplacement there is a second conditioning step. To prevent any inflow of water and subsequent leaching of the waste during the thermal phase, each primary package of vitrified waste is placed in a watertight over-pack. This over-pack is made of carbon steel with an effective thickness of 55 millimeters (mm), dimensioned very conservatively to withstand corrosion for a thousand years. The mass of the standard disposal package is approximately 2 tonnes. The result of placing a primary package inside an over-pack is a “disposal package” also referred to as C type canister in this paper.

2.2 Design Concept for the Disposal of C Type Canisters

The current base case French Disposal Concept as defined in the Dossier 2005 consists of an underground facility with shaft access; however ramp access is also being studied at the present time. Disposal areas consist of horizontal boreholes for C type waste and large caverns for B type waste. The final emplacement facilities are called disposal cells. All disposal cells are excavated in a clay formation. Disposal cells for specific types of waste are grouped in zones within specific areas.

The Dossier 2005 architecture contains disposal cells for various categories of waste within specific repository zones. The repository zones for Class B and C waste and, if applicable, Spent Fuel (SF) are therefore physically distinct from each other.

The waste canister disposal facilities and processes are designed with the aim of simplifying any waste canister retrieval operation, which may be decided by future generations. Preference is given to using the same equipment for retrieval as is used for emplacement. As a result, clearances for handling purposes that can be durably maintained are provided between the canisters and/or between the canisters and the cell liner walls. These clearances are minimized, however, with a view to limiting future geomechanical disturbances.

The design of disposal cells C type canisters is the result of the search for a physical and chemical environment suited to the canister, and of the thermal design associated with heat dissipation by conduction through the rock. As a result, the thermal load per unit surface area is limited not only on a repository scale but also on a disposal cell scale.

Disposal cells for C type canisters are dead-end, horizontal boreholes with an excavated diameter of approximately 0.7 m. At the time of Prototype **P1** their length was limited to around 40 m, a length considered reasonable in view of construction and handling techniques. Subsequently during the preparation of the Scope of Work for the **P2** Prototype Contract this length was increased to 100m.The boreholes have a metallic liner, which supports the clay rock and facilitates the handling of the canisters during emplacement and eventually during retrieval sometime in the future. Depending primarily on the thermal characteristics of the C type canisters being emplaced (there are different types) a 40m disposal cell may contain from 6 to 22 canisters interspersed with spacers.

Figure 1 below shows the base case layout concept of such a disposal cell.

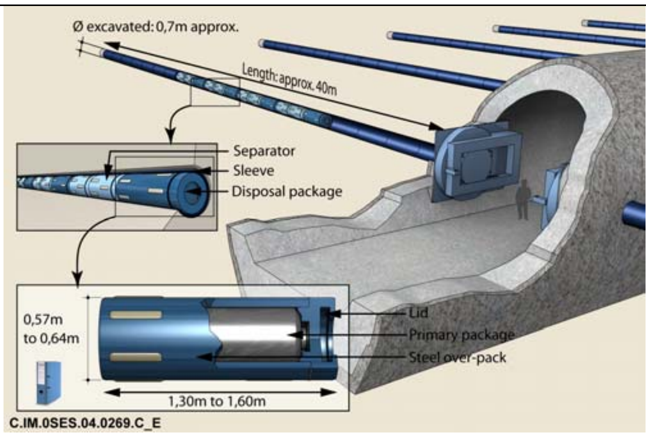


Figure 1: Disposal cell for vitrified C type Cannisters (fully filled in) before sealing operations

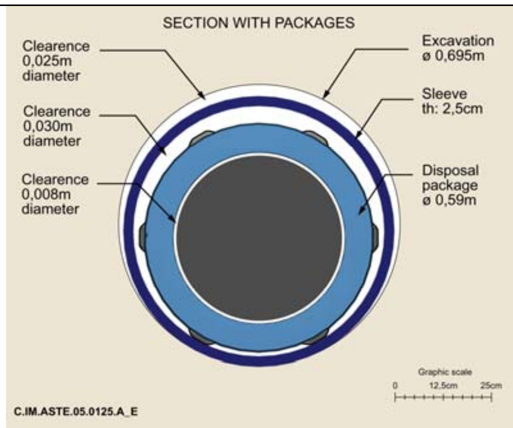


Figure 2: Cross-section of a cell for C1 to C4 vitrified waste canisters

The excavated disposal cell is physically supported by a “permanent” steel sleeve. The choice of steel is justified by its mechanical strength and the ease it offers for canister handling in the cell. The sleeve is in contact with the rock. The thickness of the sleeve must guarantee the mechanical strength of the disposal cell and support the drilling tool thrust during excavation. The strength calculations led to a pre-sizing thickness of 25 mm.

A minimum annular space is required between the sleeve and the excavated ground. The maximum value, of about one centimeter at the radius, corresponds to a conservative dimensioning and includes a margin to prevent jamming at the time of excavation and emplacement of the sleeve concurrent with the drilling operation.

Functional clearance between canister and sleeve allows waste-package handling (emplacement and retrieval) to take place. A total diameter clearance of 3 centimeters (cm) is currently used. This value is compatible with the handling of the canisters by a pushing robot. A typical disposal cell cross-section showing clearances is shown in **Figure 2** above.

A metal plug is intended to ensure radiological protection during disposal cell sealing operations, thereby eliminating the need to use the protection of the transfer cask during the installation of the swelling clay plug (hence possible with simple and reliable non-nuclear methods). Preliminary design calculations have been performed to limit the dose rate in the access drift to less than 3 micro-sieverts per hour (µSv/h). The metal plug can consist of a steel cylinder approximately 50 cm long (two thirds devoted to biological protection and one third adapted for gripping by handling tools), possibly covered with ceramic to prevent adhesion to the sleeve (under the effect of corrosion). At closure, the cell is sealed by a swelling clay plug held in place mechanically by a concrete retaining plug.

2.3 The C Type Canister Transfer from Surface to the Disposal Cell Mouth

The principle for transferring the canisters between the surface installations and the disposal cells depends mainly on radiological protection considerations. The residual rate of equivalent dose around the canisters makes it impossible to handle them without radiological protection for the personnel. The principle adopted therefore consists of putting a single canister into a Transfer Shielding Cask within the surface installations. This transfer cask is then moved to the entrance of the disposal cells where the canister is extracted and then placed into its final position in the disposal cell.

The cycle of transferring the Transfer Shielding Cask containing the canister from the surface installations to the disposal cells consists of the four following stages:

- loading the transfer cask at the surface;Transferring the transfer cask into and down the shaft;
- transferring the transfer cask through the drifts; and
- docking the transfer cask at the head of the disposal cell.

The transfer casks used for transferring the canisters are designed to contain only a single canister and of course the Pushing Robot. They must have a radiological protection function of limiting the exposure of personnel to below the Andra standard annual dose limits of (5 mSv/year).

A Transfer Shielding Cask consists of a handling frame with a shielded container on top. The container is equipped with a shielded door for loading and unloading the canisters from one end. For C type canisters the Shielding Cask is cylindrical and the door is a "sliding" type. The Transfer Shielding Cask is fitted with an on-board mechanical unit consisting of a pushing robot, used to extract the packages and place them into the disposal cell.

The Shielding Cask has walls made of Steel/ Plaster/Polyethylene with Boron addition. They are referred to as (PPB)/Steel sandwich panels. The PPB, a neutron-absorbing material, has been chosen because of the type of radiation emitted by vitrified Class C wastes and Spent Fuel. The total thickness of the side walls, bottom and the door is in the order of 400 mm for the C type canister Transfer Shielding Cask.

The loaded weight of the Transfer Shielding Cask for C type canisters is about 41 tonnes.

3 Components of C Type Canister Emplacement System

C type canisters weigh about 2 tonnes, are about 0.60 m in diameter and about 1.60 m long. Some other types of C waste canisters may have slightly different dimensions and different thermal properties. The successful emplacement of such cylindrical radioactive packages into horizontal disposal cells of circular section requires a number of fixed and mobile components which are designed to inter-lock like pieces of a jig saw puzzle and which must function in harmony with one another. In all there are 8 main components, 6 of which were considered during the initial Conceptual Evaluation. Only the first 2 and the second last items were included as part of Prototype **P1**. Although all the components are essential it is the remote-controlled robot and the docking system which have provided the most important contribution to the body of knowledge in this area.

The equipment studied, designed, fabricated and demonstrated includes the following main components:

- a **Dummy Canister** housed inside the transfer cask until the emplacement begins;
- a mobile **Pushing Robot** also housed inside the transfer cask until the emplacement process begins;
- a **Transfer Shielding Cask** which sits on the docking table;
- a mobile **Transfer Shuttle** which supports the docking table;
- a **Docking Table** which is fixed to the transfer shuttle and which supports the transfer cask;
- the **Disposal Cell Mouth** equipment which is fixed to the cell mouth;
- a **Test Bench** which simulates from 40 to 100m of disposal cell liner (depending if **P1** or **P2)**;

- an **Access Drift Mock-up** to simulate the access way to the **Cell Mouth.**

3.1 The Dummy Canister

3.1.1 Description

The 2 tonnes C type canister shown in **Figure 3** below consists of 4 parts: the primary package, the body of the overpack, the overpack cover and the ceramic sliding runners. These are described in the next sections. As part of the ESDRED Project essentially identical dummy canisters were fabricated for both the **P1** and the **P2** prototypes.

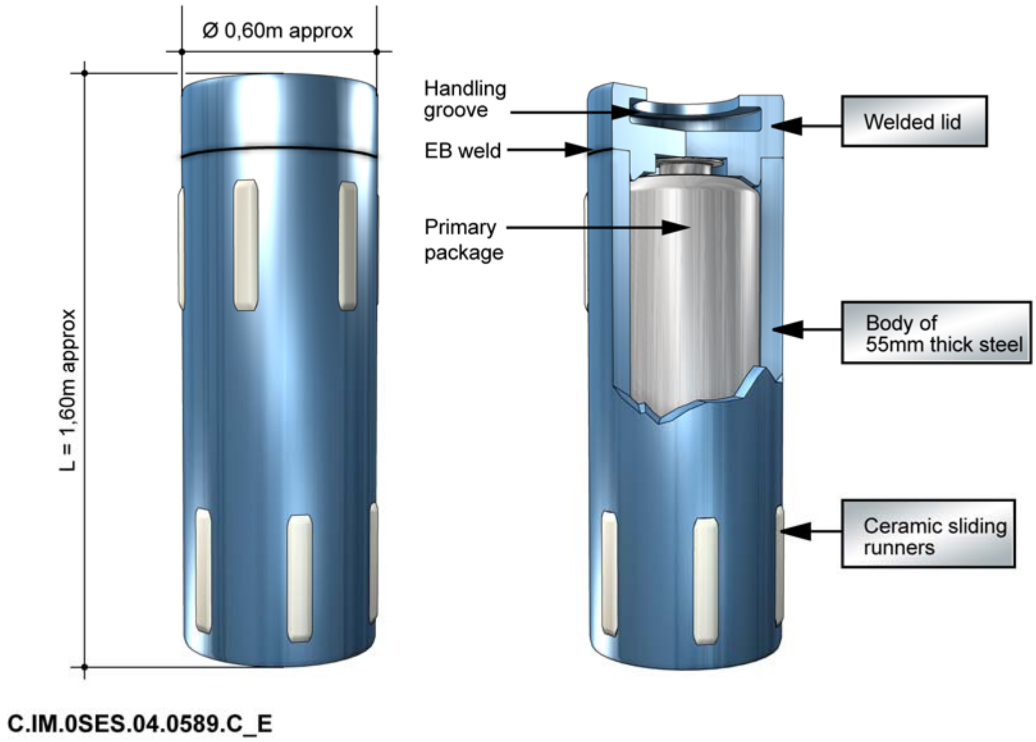


Figure 3: Principle of the C Waste Over-pack

3.1.2 The Primary Package

Following retreatment of Spent Fuel at La Hague a glass-waste mixture is poured into a stainless steel canister called the Primary Package. The common R7T7 reference canister is made of 5 mm thick stainless steel. Its weight is 94 kg before filling and approximately 500 kg after filling. Its height is 1338 mm (lid included), for an OD of 430 mm. The external total volume of the canister is 175 l.
The lid is welded after filling using the electron beam welding technique.

3.1.3 The Body of the Overpack

The body of the overpack consists of a cylindrical shell with an effective thickness of 55 millimeters; this envelope is fitted with ceramic sliding runners. Where the sliding runners are embedded, the thickness of the envelope is increased by ± 10 millimeters, to avoid degrading the integrity of the effective thickness. The base has an effective thickness of 77 or 83 millimeters depending on the type of package. It can be manufactured in a single piece, without welding, so that the body has a built-in base. For **P1** the dummy was made of cast pig iron whereas the real one would likely be made of non-alloy type P235 steel. Research is on-going at Andra in order to optimize the dimensions of the overpack especially where the ceramic sliding runners are to be mounted and to optimize the fastening system for these runners.

3.1.4 The Overpack Lid

The lid is made of the same grade of steel as the body. It is thicker than the base because its effective thickness is increased by about 100 millimeters to create a handling interface. This handling interface consists of a machined groove to enable the over-pack to be gripped by a grab thus facilitating retrieval of the package. A hollow shape provides a greater weight-bearing area and consequently a better load distribution than a "mushroom" type protruding shape. The internal shape of the lid matches the upper profile of the primary package to help limit the void fraction.

3.1.5 The Sliding Runners

The overpack is fitted with 12 ceramic sliding runners (20mm thick and 20cm long) installed longitudinally. The sliding runners are fitted to the overpack in two sets of six. Each set has an angular offset of 30 degrees relative to the other. The sliding runners are mounted so that when there is pressure on the disposal cell liner intrados, three sliding runners are always in direct contact with the cell liner. Each sliding runner is a solid ceramic block. Research is on-going at Andra in order to optimize the shape and mounting of the ceramic runners.

3.2 The Pushing Robot

3.2.1 Physical Description

This key component enables the emplacement of the canister inside the horizontal disposal cell liner. It is characterized by its small dimensions (1m long and 0.55m diameter), its light weight (0.4T) and its powerful pushing force (up to 5 tonnes with version **P2**). At the beginning of the emplacement cycle it is located, together with the canister, inside the Transfer Shielding Cask and it goes back inside this Cask at the end of each emplacement cycle.

There are 3 versions of the Pushing Robot:

- the conceptual Dossier 2005 version (left side of **Figure 4**) which was never built,
- the Prototype **P1** version (right side of **Figure 4**, built within ESDRED in 2005),
- the current Prototype **P2** version illustrated in **Figure 5**.

Initially the Pushing Robot concept was developed in Andra’s Dossier 2005 as a device activated by means of various hydraulic jacks (acting horizontally or radially). This conceptual design was changed when the first Pushing Robot Prototype **P1** was designed for fabrication & testing. **Figure 4** shows the evolution from the Dossier 2005 conceptual design to the **P1** prototype as eventually built.

The final **P1** design of the pushing robot (on right) shows a number of significant differences in comparison with the original conceptual design (on left). Those differences are summarized below.

- The original gripping supports (typical of tunnel boring machines and actuated by hydraulic jacks) designed to resist the thrust on the canister are replaced by a unique “inflatable toric jack” at the back of the robot.
- Similarly the return gripping supports (also actuated by hydraulic jacks) are replaced by a unique “inflatable” toric jack to the front of the robot.
- The conceptual canister retrieval system made up of 3 small longitudinal hydraulic jacks and a locking jack are replaced by a single central jack combined with 3 fingers (with return springs) actuated by an inflatable bag.

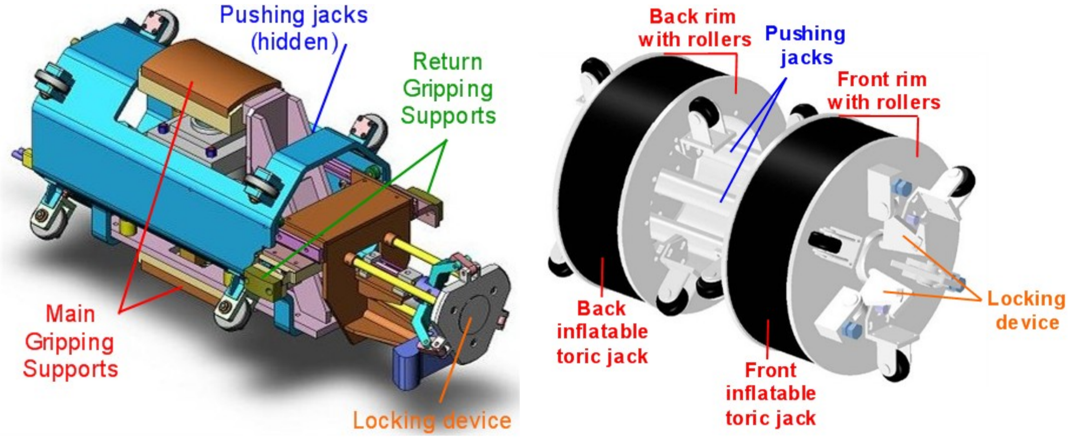


Figure 4: Evolution of the Design of the Pushing Robot from Conceptual Stage (left) to the **P1** Prototype as built (right)

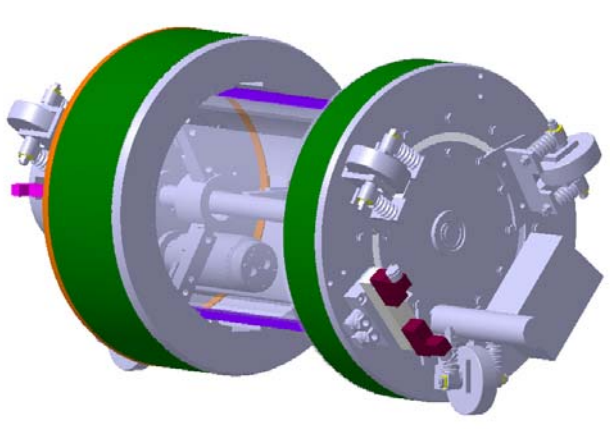
The 3 main reasons for replacing the radially actuated hydraulic jacks by inflatable toric jacks are the following:

- substituting pneumatic jacks for hydraulic oil jacks reduces the potential for pollution;
- thrust stresses are applied evenly on cell walls, therefore avoiding risks of out of round wear of the tube;
- the mechanism is simplified, thereby making it more robust.

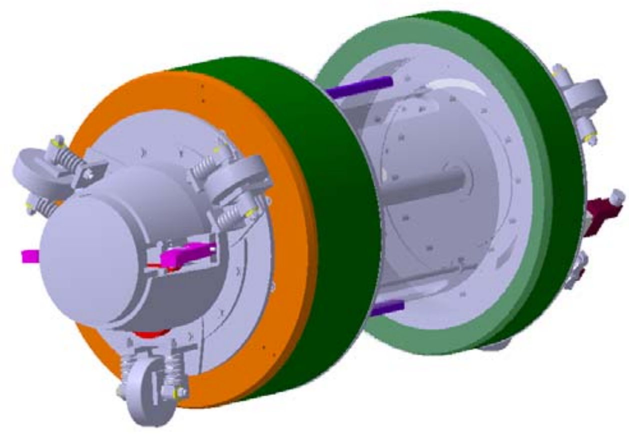
As for the canister retrieval system, the concept selected is simpler and therefore more cost effective and more reliable. It is also pneumatic, therefore avoiding risks of pollution due to hydraulic oil leakage. Thus, the general principle of having an intrinsically safe ("fail safe") system is achieved.

The current **P2** design of the Pushing Robot is illustrated in **Figure 5**. There have been a number of important design evolutions from **P1** to **P2**. These are summarised and justified below:

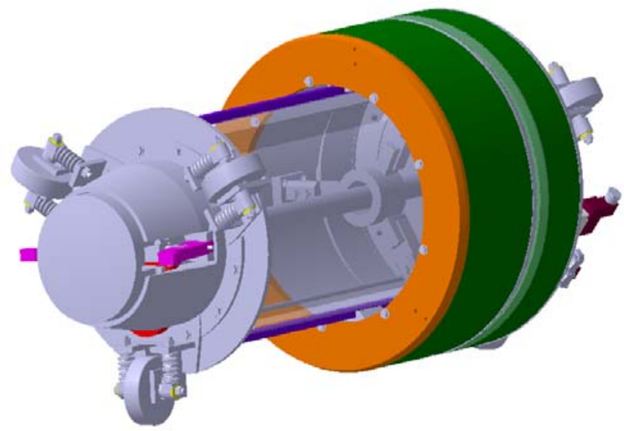
- the 2 inflatable (pneumatic) toric jacks have now been sized differently. The bigger one is activated when pushing the canisters. The smaller one which is only used to move the robot body has a reduced width, since the horizontal pushing force exerted on it is not bigger that half the weight of the Robot (0.4 t). This helps reduce the overall size of the robot by 20cm, and consequently the overall length and weight of the Shielding Cask can also be reduced;
- the 3 hydraulic horizontal pushing jacks in **P1** have been replaced in **P2** by a single horizontal screw jack activated by a pneumatic motor, so that the robot body is much stiffer. Since compressed air is now the only energy source **P2** has only a single (composite) umbilical; a solution compatible with potentially increasing the length of the Disposal Cell from 40m in **P1** to 100m in **P2**;
- the canister locking system in **P2** is a totally fail safe 2 finger (instead of 3) device which, when retracted, is totally flush with the robot head. The previous **P1** device was prone to accidental gripping of the canister by one finger;
- All the connections between the **P2** Pushing Robot and the single composite umbilical are protected, since the umbilical is located inside the Robot body, and
- finally the **P2** guiding trolley wheels are bigger, harder and mounted on a stiffer support than the previous version.



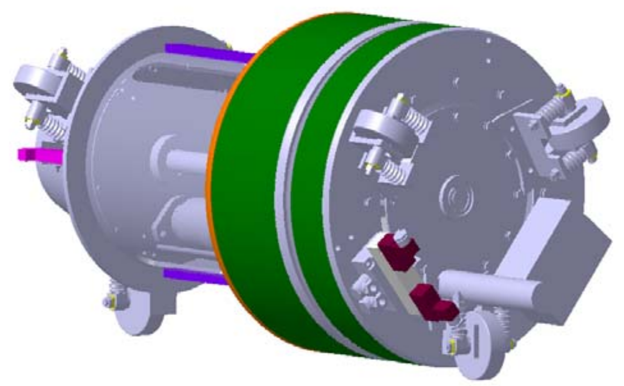
1. Pushing Robot – Extended – Rear view



2. Pushing Robot – Extended – Front view



3. Pushing Robot – Retracted – Front view



4. Pushing Robot – Retracted – Rear view

Figure 5: New **P2** design of the Industrial Pushing Robot at basic design stage

3.3 Transfer Shielding Cask

No prototype was built before the current **P2** development; however a Conceptual Design was developed for Dossier 2005. As with all the other components that make up the **P2** demonstrator, the Transfer Shielding Cask is also being fabricated and assembled at the present time.

Compared to the initial Dossier 2005 Conceptual Design the main **P2** evolutions are:

- the suppression of the mobile sleeve used to cover the gate track slots (thanks to a modification of the shielding gates), i.e. the ones mounted on the Transfer Shielding Cask and on the disposal Cell Mouth base plate;
- an optimized Transfer Shielding Cask body (reduction in its overall length and a change in the shape of the rear of the cask from cylindrical to conical) which resulted in a 20% or 15t reduction of the total weight.

The inside of the cask is designed to house, in line, the Pushing Robot and one Dummy Canister. As well it contains a manually operated compact pusher rod to be used in the event that there is any kind of system failure just as the canister is located in the gate travel way thus preventing the gates from closing. In the event that the Pushing Robot is impeding the closure of the gates it can be pulled back into the cask via the umbilical. In order to ensure that the **P2** Pushing Robot can operate successfully in 100m long Disposal Cells, it was decided to simplify as much as possible the problematic of separate umbilicals / wires / cables attached at the rear of the Robot. This issue was solved by:

- choosing only air as the single energy source used to move the Pushing Robot (i.e. elimination of all hydraulic fluids);
- choosing a composite umbilical incorporating the air conduit, the retraction cable and the control & monitoring signal cables.

The umbilical that has been selected is shown in **Figure 7** below. It is reeled (in one layer only) on the drum of a motorized winch mounted on the same frame as the Transfer Shielding Cask. This winch is also equipped with a spooling system to avoid incorrect winding, which is more likely to occur during reeling operations over long distances.

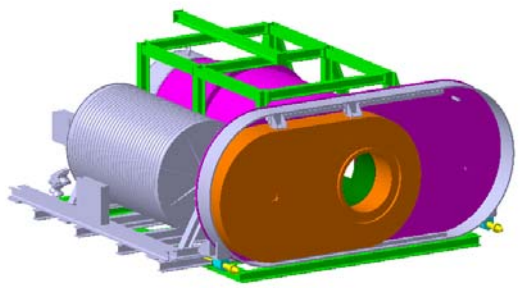
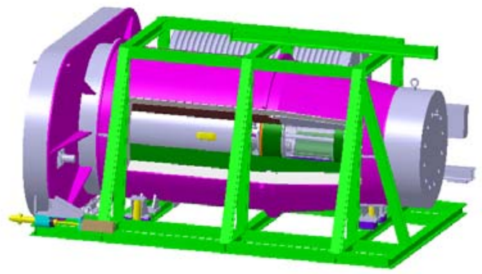
	
1. Front view showing the shielding gate open and the motorized winch	2. Longitudinal view showing the Canister & Robot through the Plexiglass

Figure 6: Sketches of the Transfer Shielding Cask of the Industrial version at basic design stage

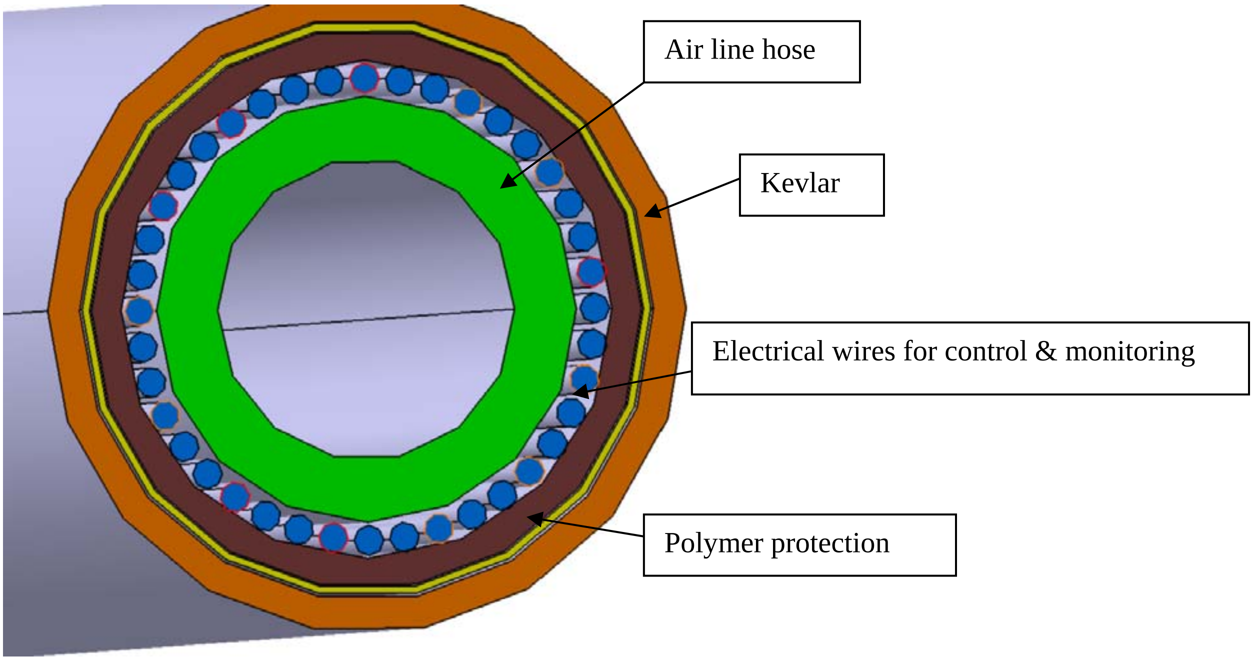


Figure 7: Cut section view of the composite umbilical

3.4 Transfer Shuttle

This vehicle is used to transport the Transfer Shielding Cask from a transfer facility located near the Waste Shaft Repository level Station to the disposal Cell Mouth, via a network of Connection and Access Drifts. No prototype of this component of the emplacement system was ever designed or built prior to the development of the current **P2** version.

The current **P2** design (see **Figure 8**) is significantly simpler than the original Conceptual Design included in Andra's Dossier 2005, for various reasons. These include:

- currently only one pair of wheels is motorized and only the front axle can pivot. This is due to budget reasons (in order to stay as close as possible to the initial ESDRED budget which has already overrun) and due to the fact that this Transfer Shuttle (within the framework of the planned testing and Demonstration) will only move longitudinally (along the Access Drift) so as to pre-position itself in front of the disposal Cell Mouth, whereas the real shuttle will have to travel through 90° curves at crossings between Access Drifts and Connection Drifts with very limited clearances on either side of the vehicle;
- the required elevation of the Transfer Shielding Cask in front of the disposal Cell Mouth is now assured by the Docking Table (via electrical screw jacks extended to the drift floor) while in the original conceptual design hydraulic jacks mounted next to each pair of Transfer Shuttle wheels were used to raise the entire Transfer Shuttle body (and the Transfer Shielding Cask).

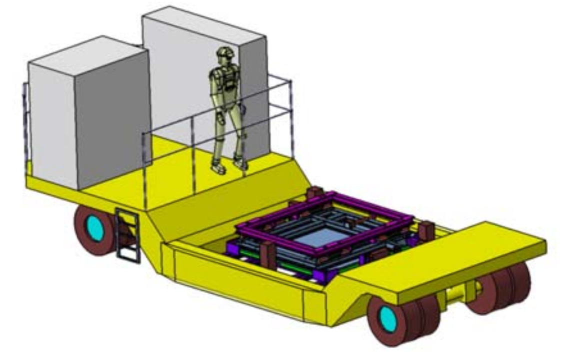
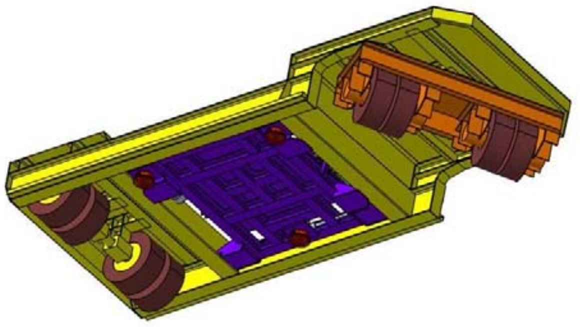
	
The Shuttle with the docking table integrated in the chassis	The Shuttle with its pivoting front axle

Figure 8: The Transfer Shuttle

3.5 Docking Table

No prototype of this component was ever designed or built before the current **P2** development. In fact this component of the system was not even studied in the Dossier 2005 Conceptual Design. As with all the other components that make up the **P2** demonstrator the Docking Table is also being fabricated and assembled at the present time.

The current design is fairly complicated with a number of interconnected parts performing specific functions. The initial coarse elevation adjustment (independent of the Transfer Shuttle elevation) is assured by the 3 electric elevating screw jacks (shown in red in **Figure 9** below), whose articulated feet compensate for any Access Drift concrete slab geometrical defects (slope, planarity). The smooth docking of the Shielding Cask gate onto the Disposal Cell Mouth gate is achieved via an air cushion system (shown in green), while the fine tuning and ultimate positioning is provided via dash pot hydraulic jacks.

Even before testing, this unit already seems clear that future designs of the Docking Table might be even simpler, possibly involving more laser assisted positioning.

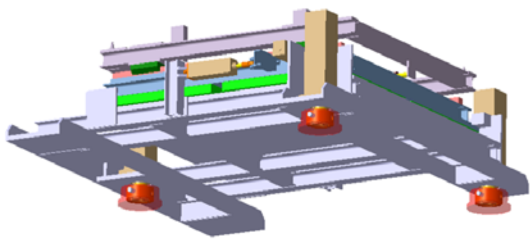
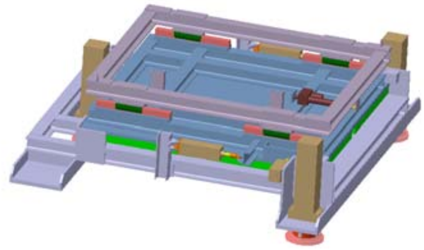
	
1. Bottom view showing the feet (in red) of the 3 electrical elevating jacks	2. Top view showing the dash pot jacks

Figure 9: Sketches of the **P2** Docking Table at Basic Design Stage

3.6 Disposal Cell Mouth

For the **P2** demonstrator only (see **Figure 10** below) this component includes a base plate which is physically attached to the host rock at the cell mouth, and a passive Shielding Gate onto which the active Shielding Transport Cask gate is locked during the emplacement process. The 2 gates behave in a master/slave relationship.

Compared to the original Dossier 2005 concept the main difference relates to the design of the passive Shielding Gate which was redesigned to be compatible with the active Transfer Shielding Cask gate (see Chapter 3.3). For operational safety reasons the Cell Mouth gate is positively locked at all times and can only be opened when the Transfer Shielding Cask gate is connected to the Cell Mouth frame.

For demonstration purposes, the base plate support is equipped with devices to simulate the geometrical construction defects likely to be encountered in a real underground repository.

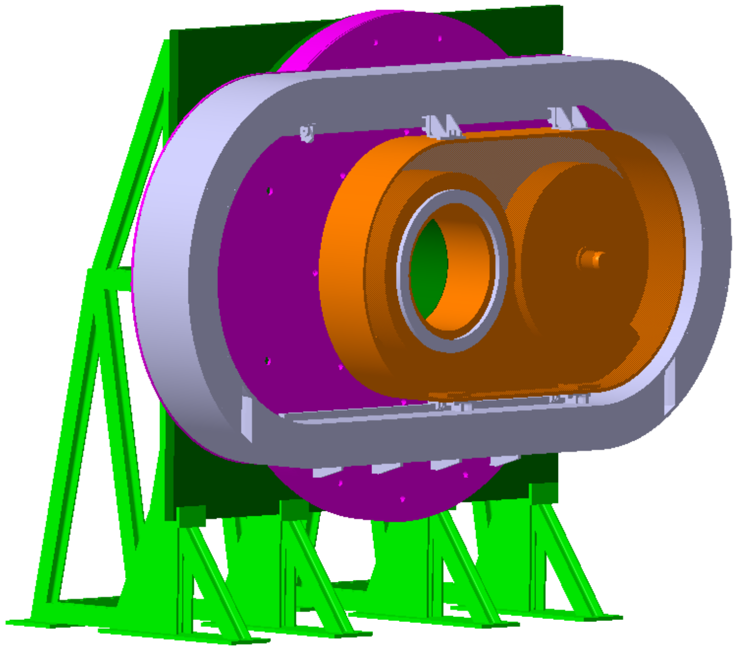


Figure 10: Sketch of the **P2** Cell Mouth Shielding Gate (orange) and the Base Plate (purple) attached to the Supporting Frame (green)

3.7 Test Bench

3.7.1 P1 Test Bench

The Prototype **P1** test bench used for demonstrating and testing the **P1** Pushing Robot can be seen in **Figure 11** below. These 2 components, as well as the Dummy Canister, are presently stored at Andra's temporary showroom in Limay near Paris. Towards the end of 2008 the entire demonstrator will be moved to Andra's permanent showroom and technology centre (CTe) which is presently under construction next door to Andra's URL in Bure, France. The **P1** Test Bench consists of the following components:

- two 4.50-m sections of pipe, one as a mock up of the shielding cask and the other a mock up of the disposal cell liner;
- two 1-m-long central observation sections (picture windows) fitted with a system for creating a step in the middle of the bench (simulating the gaps and steps likely to be encountered at the docking of the Shielding Transport Cask with the Disposal Cell Mouth); and
- a 2.50-m launch table for initial positioning of the Dummy Canister and the Pushing Robot on the Test Bench.

The unit is mounted on feet that are adjustable in the X, Y and Z directions. The height adjustment (Z) of the mobile parts is made with a manual hydraulic jack and locked into place with jack screws. X-Y adjustments are made with screws and locking nuts. An optical ray (laser), combined with targets at the ends of the two halves of the bench, is used to assist in configuring and simulating various disposal cell geometrical imperfections (defects) for testing purposes.

Figure 11: General view of the **P1** Test Bench, also showing the Prototype Pushing Robot and the Control Panel

3.7.2 P2 Test Bench & Access Drift Mock-up

The **P2** Test Bench is presently in the fabrication and assembly stage. It is similar in design but at 100m it is considerably longer. The reader will recall that the **P1** system was designed for 40m long disposal cells whereas the **P2** system is intended to prove that pushing robot system is practical in 100m long disposal cells. Also, a post ESDRED phase of endurance testing is included in the **P2** work only. Because the **P2** system includes the transport Shuttle and various docking components it was decided to attach a short (full scale) section of Access Drift mock-up installed at right angles to the Test Bench i.e. to the cell liner mock-up. All of this is shown in **Figure 12** and **Figure 13** below.

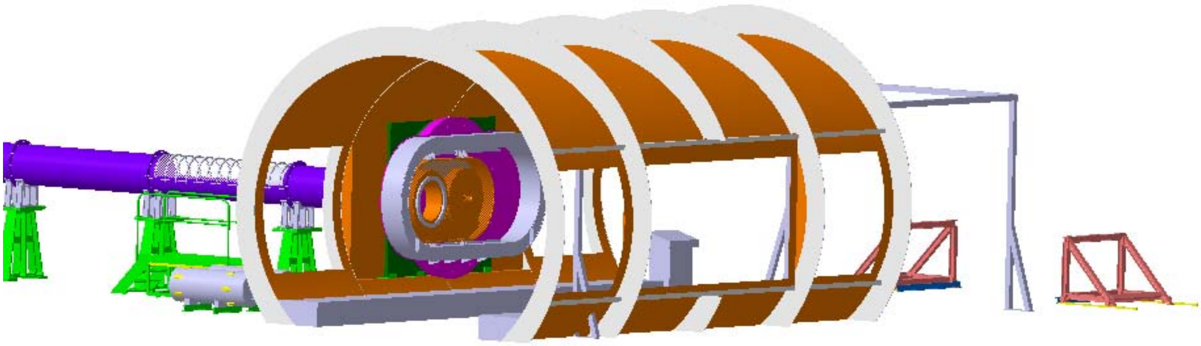


Figure 12: General View Showing **P2** Mock-ups of the Disposal Cell (purple), the Access Gallery (brown) as well as the Disposal Cell Mouth (orange)

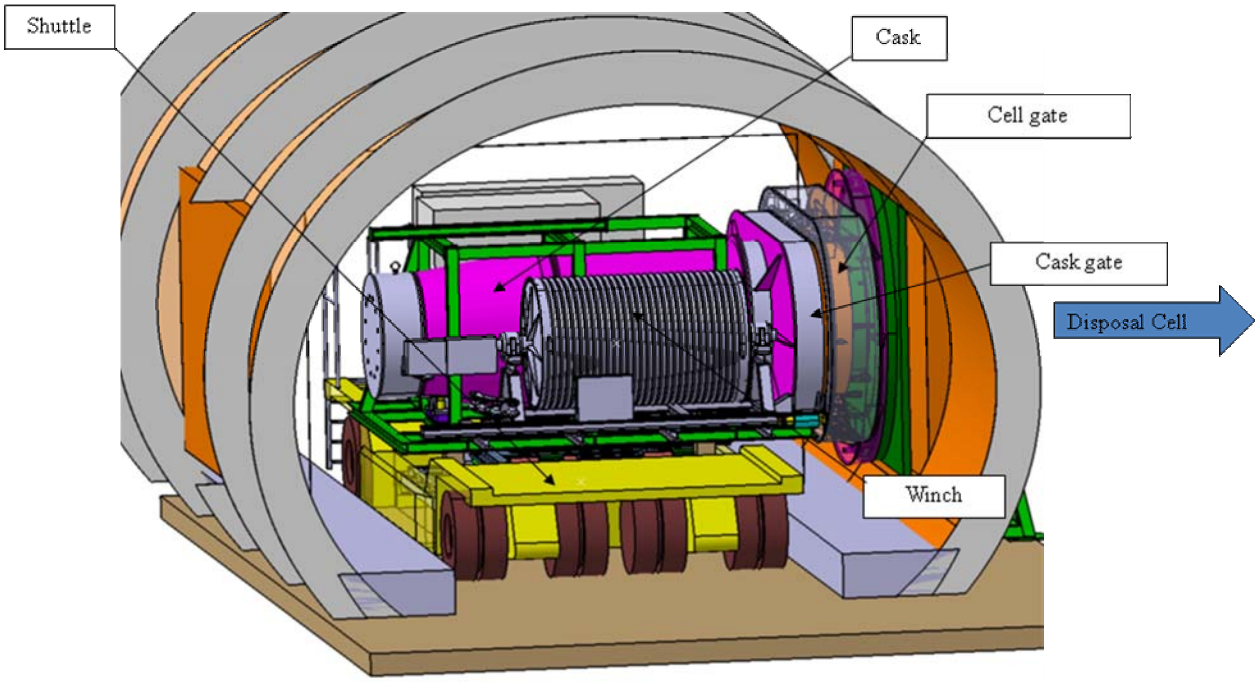


Figure 13: P2 Full scale demonstrator

3.7.3 Registration of Parameters, Control system and Control Panel

For the **P1** Prototype a system to record the main operating settings for the robot is provided with the unit. For this purpose, all sensors and measuring equipment data are digitalized for the transfer of data to a laptop. A symbolic representation of the robot on the screen is used to remotely monitor the various operations and a number of time related curves can be directly displayed during testing (hydraulic & pneumatic pressure, calculated thrust and pulling, measured thrust, travel of the canister and robot, etc).

Settings saved in a database are used to create (using Excel) curves based on observations made during the tests, including progress curves based on thrust. In order to be able to observe, with a delay, all the reactions of the robot and the canister with its runners in the test bench, it was decided to record all measurable parameters at a frequency in the order of one tenth of a second. All test information was recorded and displayed either on the control panel or on the monitor screen.

The control panel face displays the following three types of information:

- actions, which can be controlled by the operator;
- feedback from some of the sensors; and
- status of different parts of the system.

The control panel and control functions of the **P2** system will be similar to what has been described for **P1.**

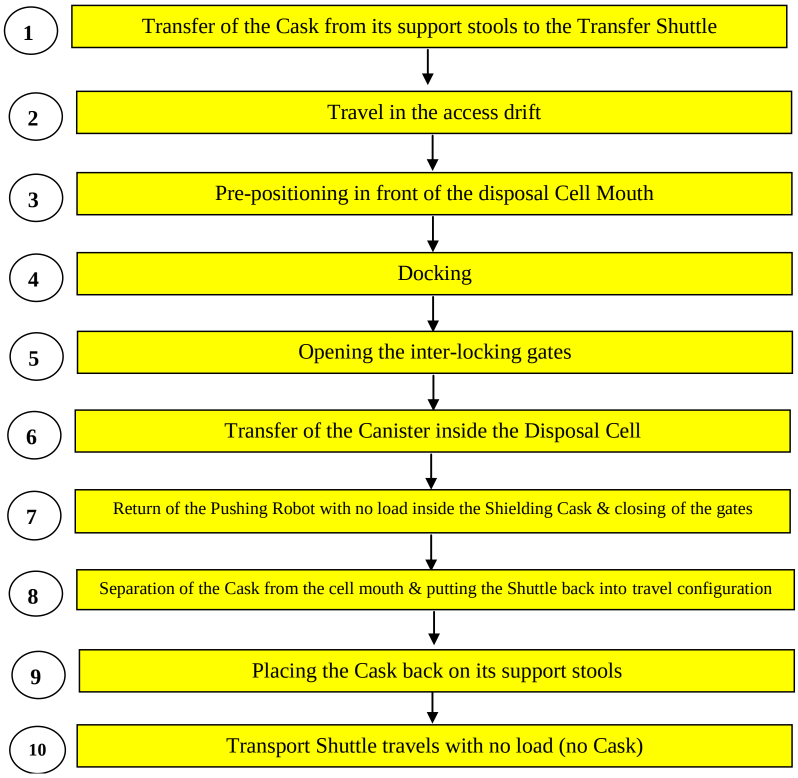
4 Operation – Emplacement Sequence

4.1 Emplacement Sequence

As part of the much more complicated **P2** Prototype demonstration a synoptic (shown below) of all the basic operations to be carried out has been established for each stage of the emplacement process. Among other things:

- at each stage of the process the operating dimensions have been detailed (length of movements, clearances, position in the 3 dimensions, etc.) to confirm that the system functions properly and to determine its limits,
- the control and monitoring devices (e.g. jacks, sensors, lasers, etc.) needed to operate the system have been detailed.

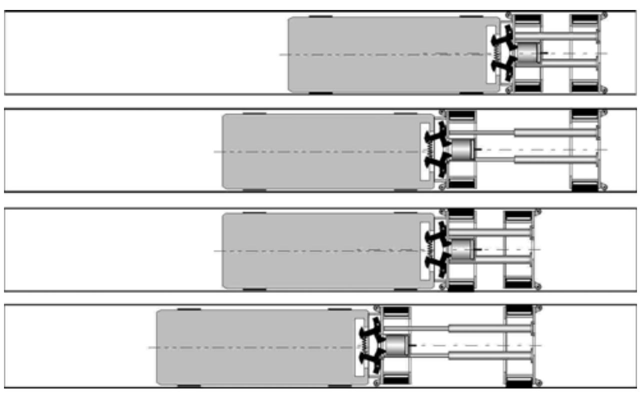
The 10 main steps for which a synoptic of operations has been detailed are:



4.2 Emplacement Kinetics

Notwithstanding various design evolutions between **P1** and **P2** the fundamental operating sequence has remained unchanged. The Pushing Robot moves in 0.5m increments or steps and each 0.5m step forwards involves two main operations: (1) pushing the package(s); and (2) moving the robot body. As can be seen in the schematic below (developed for **P1**) the first operation is to inflate the rear radial toric jack (thus locking the rear of the robot in place) and to advance the canister and the front of the robot by extending the 3 longitudinal pushing jacks. Thereafter the front radial toric jack is inflated (thus locking the front of the robot in place), the rear radial toric jack is deflated and the extended pushing jacks are retracted thus advancing the rear of the robot. Then the entire process is repeated. To retrieve a canister the entire procedure is reversed after a gripper situated at the head of the robot has locked onto the canister to be removed.

The kinetics of the Pusher Robot is illustrated in **Figure 14** below.



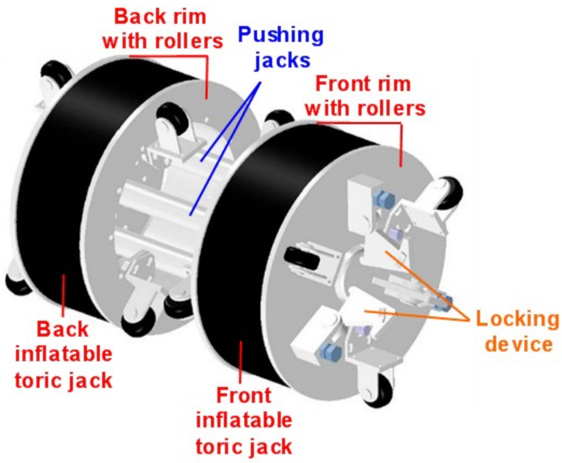


Figure 14: Illustration of the principle of the **P1** Pushing Robot operation

For **P1** the time to complete a full cycle of pushing a package over a distance of about 40 m inside the disposal cell and returning the Pushing Robot to the Shielding Transfer Cask is estimated to be about 2 hours based on the test work conducted. In **P2** the total cycle time starting with the arrival of the Transfer Shuttle at the Cell Mouth and ending after 3 canisters have been placed approximately 90m into the disposal cell and the undocking of the Shielding Transfer Cask is complete is roughly estimated to be ± 3 hours. A better feeling for this number will only be available after the system has been fabricated and tested towards the end of 2008.

5 The Test Programme

5.1 P1 Test Programme

This Chapter 5 provides an overview of the purpose of the test programme developed and executed once the **P1** Prototype system was commissioned. It also describes the types of tests executed and the observations and conclusions that resulted from these tests. Brief comments related to Prototype **P2** are provided in Chapter 5.2.

5.1.1 Purposes of the Test Programme

In order of priority the purpose of the **P1** test programme was to:

- verify that the overall pushing robot system ran correctly according to the design specifications, which were proposed by the Contractor (Musthane) as a Technical Variant, and accepted by Andra;
- confirm the suitability of the sliding runner design choices made by Andra as the result of a stand alone development project which included a separate test bench facility. Among other things this project defined the selected ceramic material (alumina), the shape of the runner and the type of mounting;
- assess the required pulling and pushing forces for a reliable operation of the overall system (for the mock up used in the feasibility tests and by extrapolation for an industrial scale demonstrator);
- determine the required operating parameters (air pressure, hydraulic pressure, speed of translation, etc);
- check that the overall emplacement performance (average speed in automatic mode for a 6-m travel) was equal to or better than the specified one;

- characterize the capability of the overall system to tolerate operational “anomalies” (e.g., air loss or hydraulic pressure drop);
- determine the capability of the system to deal with geometric irregularities, such as bumps or steps along the robot’s travel path. This included also worst case test that combined the various potential geometric defaults to simulate what was assumed to be the most critical combination; and
- provide operational parameters with a precision of ±5% and tolerance margins for geometrical/construction defects with a precision of ±10%.

5.1.2 Main Tests Carried Out

The list of the main tests, which have been carried out, is provided below. For a given geometrical configuration of the test bench, most of the tests were run successively in manual and automatic modes, and with a hydraulic flow (from the hydraulic unit) varying between 12 litres per minute and 36 litres per minute. The hydraulic pressure variation had a direct impact on the instantaneous and average travelling speed of the robot. The simulated geometrical defaults had an impact on the functioning of the system and helped the assessment of the Robot’s robustness. Following is a listing and concise description of the tests conducted:

1. Properly aligned test bench:

- manual mode test at 12 l/min flow rate;
- automatic mode test at 12 l/min flow rate;
- return trip test in manual mode at 36 l/min flow rate;
- return trip test in automatic mode at 36 l/min flow rate;
- return trip test with and without load in automatic mode at 36 l/min flow rate; and
- manual mode test at 36 l/min flow rate (maximum speed).

2. Misaligned test bench:

- test with 2 mm step (mixed automatic one-way trip / manual return);
- test with 7 mm step (Manual or Auto mode); and
- test at 12 l/min flow rate with 7 mm step and relative alignment defect of 1% (manual mode).

3. Retrieval of Canister

- tested in manual and automatic mode.

5.1.3 Observations and Conclusions from the Test Campaign

The experiences and lessons learned from the **P1** test campaign are summarized below.

Successes:

- excellent behavior of the robot per se and of the toric jacks;
- no difficulties of any type with the ceramic sliding runners as then designed;
- excellent capabilities of robot and canister to pass over specified defects;
- retrievability of canister with robot checked; and

- average traveling speed in automatic mode measured on an outward trip with full hydraulic power (36 l/min flow for the hydraulic unit) = 1.1 m/min (versus the 0.5 m/min specified in the Scope of Work).

Difficulties encountered:

- Jamming occurred (on return trip of robot) when passing the polycarbonate window connection. This type of incident was due to the relative flexibility of this material versus the rigid carbon steel that it was attached to. Such a case should not be encountered in the real repository situation where only carbon steel material is employed. The problem was solved on the test bench by adding extra steel flanges between the large windows in order to reinforce them.

Main achievements:

- The P1 Contract was carried out starting late April 2005 and successfully completed by mid February 2006. The selected Contractor (MUSTHANE/CREATIV ALLIANCE) was responsive and complied with the requirements (performance specifications) contained in the Scope of Work.
- The Prototype Pushing Robot system design turned out to be very rugged and efficient. The ceramic sliding runners also resisted very well to all the shocks induced by the back and forth movements of the canister (including when sliding over “steps”). No significant wear on the sliding runners could be noticed, while the alteration of the slide track was considered as normal and of little impact to an industrial application.
- Overall, the test programme ran as initially planned and the most representative tests specified in the Scope of Work were successfully implemented. The functional parameters for the nominal operating case were determined and registered, and the tolerances and limitations of the system, relative to geometrical anomalies, were observed.
- The only minor operational problem encountered was due to the difficulty associated with determining the effective pushing/pulling forces applied by the robot when moving the canister. The initial method of determination (a computation based on the longitudinal hydraulic jack pressure measurement was deemed unreliable and was replaced by a direct measurement of the pushing force value via a load cell which was installed between the canister and the robot. The test campaign was completed with a 1.5 month delay.
- Some recommendations for improvements/adaptations of the system design regarding the subsequent P2 Demonstrator were proposed by the Contractor. These recommendations and the lessons learned by Andra were taken into account when the Scope of Work for P2 was developed.
- The basic concerns raised by external Experts during Andra’s technical review in December 2003, regarding SGN’s Conceptual Design (i.e. Phase 1 of this 3 Phase R&D undertaking) were successfully addressed by the P1 Prototype. By showing that emplacement based on Pushing Robot Technology, and the associated use of ceramic sliding runners attached onto the shell of the canister, was feasible, the way was paved for launching the much more comprehensive P2 Demonstrator which will be completed by the end of 2008 and fully tested before the end of Q1 2009.
- The numerous pictures taken and the various videos made during the experiment were extensively used to support technical presentations made by Andra in front of the main French evaluator the “Commission Nationale d’Evaluation” and other stakeholders. Some of these media materials are already available to the Public at large on the ESDRED website – more will be added once P2 is completed.

5.2 P2 Test Programme

For reference the P2 Contract (to CEGELEC) was awarded in July 2007 and is expected to be completed during Q1 2009. The test programme for **P2,** to be carried out by CEGELEC, has not yet been fully detailed at time of writing. In any case it will be similar but more extensive than the **P1** tests. Unlike the **P1** test programme it will of course include substantial docking and undocking tests and will try to simulate the various construction defects that may be encountered in the vicinity of the Cell Mouth. There will also be considerably more operational deficiencies/break downs to simulate. Finally there will be a 1.5 month endurance test scheduled to begin early 2009 and which was not included in the **P1** tests.

6 Outlook

6.1 Conclusion

The successful completion of the **P1** Pushing Robot Prototype Test Campaign is a valid confirmation, and a practical justification, for the technical choices made within the framework of the French repository concept for emplacement of C type canisters into horizontal disposal cells. The suitability of a ceramic material such as alumina for the sliding runners, as well as their geometrical shape, was also confirmed.

The performance achieved with the **P1** prototype emplacement system is in line with the pre-established specifications. **P1** already represents a significant simplification relative to the original Phase 1 Conceptual Design. Further simplifications have been integrated into the design that has already been produced for **P2**, notwithstanding that this is a much more elaborate and comprehensive project. In addition to having more components than **P1**, the **P2** project now under development involves 100m long disposal cells that are 2.5 times longer than those considered for **P1** and the robot is designed to push as many as three canisters at one time. All the preliminary results so far suggest that **P2** should also be a success.

6.2 Improvement Recommendations Based the P1 Demonstrator

Two categories of improvements were foreseen. The first category relates to the ones which, even without any further technical evolution of the pushing robot design per se, should be integrated into the existing **P1** system if it were to be adapted for industrial operations. The second category relates to those improvements that offer a further simplification and an optimization of the existing design and which should therefore be included in **P2**. The main points considered for improvement are listed below:

- All the sensors and as much as possible all the wiring/hose/cable bundles and their related connections should be integrated into the body of the robot in order to maximize the protection of these parts, to give an industrial finish to the equipment and to improve the overall ruggedness (operational reliability) of the robot. This has been achieved in the **P2** current design.
- The **P1** weak elements (such as the trolley supports and the hydraulic jack fittings) should be reinforced, while the rim shoulders of the toric jacks have to be chamfered for a smoother travel over any obstacles/steps encountered during the robot's travel. This has been achieved in the **P2** design and the hydraulic fittings have been eliminated altogether.
- The pushing robot's compactness should also be improved: the preliminary prototype robot is built with two toric jacks with a similar annular contact area, while the front one could be significantly reduced, since the retaining force necessary for moving the robot alone (on its trolleys) is less than 100 kg. This adaptation could reduce the overall length of the robot and

therefore could have a favorable impact on the overall length and weight of the future real transport shielding cask. Everything has now been achieved in the **P2** design.

- The 3 hydraulic pushing jacks in **P1** are potential sources of hazard (leakage of fluid) and their use implies the need for two hydraulic hoses and for a hydraulic unit (installed on the transport shuttle in a real underground repository). Their replacement by screw type pushing jack(s) would: i) enable a reduction in the number of umbilicals / hoses following the Robot as it pushes the canister forward inside the tube and ii) facilitate the design and fabrication of a composite (integrated) feed line mounted on a controlled feed reel compatible with the potential extension of the disposal cell length from 40 m up to 60 m or more. All of this has been achieved in the **P2** design.

6.3 Perspectives for the Next Generation (P2) Full Scale Demonstrator

Based on the lessons learned by Andra during the **P1** Prototype Pushing Robot project, a new Scope of Work was written for the **P2** Demonstrator Contract. This pushing robot based emplacement system should be completed by the end of the 2008 and fully tested and demonstrated by the end of Q1 2009. The objectives established for **P2** include all of the improvements noted above and in particular:

- an overall reduction in the number of moving parts that make up the robot;
- the design and fabrication of the Transfer Shielding Cask with all its functionalities;
- the design and fabrication of a Transfer Shuttle for delivering the Transfer Shielding Cask to the Cell Mouth;
- the design and fabrication of a dynamic docking system between the Transfer Shielding Cask and Disposal Cell Mouth complete with the Docking Table and the corresponding Gamma gates;
- the design and fabrication of a single umbilical providing a power source, monitoring conduits and Kevlar retraction cable in case the robot and/or the canister need to be pulled back to the cell mouth;
- the design and fabrication of a cable reel with spooling device for holding a single composite umbilical compatible with a disposal cell length of approximately 100 m (by comparison with a 40-m length in the reference repository design);
- the design and fabrication of two separate recovery systems, one for the robot in the cell, and one for the canister when passing from the cask into the disposal cell;
- long term tests to assess the reliability and ruggedness of the various components over an extended period of time;
- additional simulation of the constrained underground working environment by incorporating a mockup section of the Access Drift as part of the Test Bench.