UPGRADE OF AN OVERHEAD CRANE IN THE CABRI NUCLEAR RESEARCH REACTOR

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This paper will present the process used to upgrade a sensitive overhead crane in a nuclear research reactor. It will focus on the nuclear safety requirements involved in such a project and how they were handled, from design to fabrication and implementation, as well as the relevant planning and operational concerns to be taken into consideration. It will conclude with general feedback on the project as a whole, both the upgrade itself and the adaptation to new equipment, its use and maintenance.

1. Introduction

The CABRI research reactor is used for nuclear safety studies looking at the behavior of nuclear fuel rods and their cladding during accidents in pressurized water reactor conditions, in particular reactivity insertion accidents. It was commissioned in December 1963, then shut down in 2003 for major refurbishment work to be performed, to comply with the new regulations, before returning to operation in 2015. CABRI, operated by the CEA, is the last remaining research reactor in service that belongs to the CEA Energy Division.

Setting up and conducting these experiments and tests requires numerous operations that involve handling heavy loads, both above and within the reactor core. For this reason, the 12-ton overhead crane at the top of the reactor is one of its key components, with stringent requirements to ensure that handling operations are performed reliably and dependably.

This presentation will deal with the upgrade of the historical overhead crane. Firstly, it will present the general context and the joint reflection with the French Nuclear Safety Authority that led to this improvement. Then, it will focus on the technical and organizational challenges involved in designing and implementing such an upgrade, in terms of safety and quality standards in a highly sensitive environment. Finally, this presentation's conclusion will expand on the commissioning of the equipment, as well as the practical feedback acquired during use of the equipment by the CEA in CABRI International Program experiments.

2. Context

2.1. CABRI - a Research Reactor for Nuclear Safety studies

In order to improve the ability to predict the consequences of a severe accident in a nuclear power plant, it is essential to be able to compare computer modelling results against real data from experiments. The CABRI nuclear research reactor has been providing such data since it was commissioned in 1963, with use of its unique reactivity injection system (transient rods containing 3He depressurized for a quick reactivity insertion) and hodoscope system (an online test-rod fuel motion detection).

CABRI is a pool-type reactor with a maximum power of 25 MW in steady-state conditions, with two separate primary coolant loops. The first of these includes the aforementioned pool, with a temperature range from 10 °C to 45 °C, and is designed to cool and operate the core reactor, specifically designed to resist the violent reactions that occur during the reactivity injection event, and intended to provide the desired neutron environment for the experimental rod. This experimental rod is contained within the second primary coolant loop, in a cavity at the center of the core reactor. This system was originally a liquid sodium loop to carry out nuclear safety studies for sodium fast reactors (SFR) such as Phénix and Superphénix, and has been replaced with a pressurized water one to simulate the thermo-hydraulic conditions existing in a PWR-type plant (see Figure 1). This replacement was part of the 12 years of major refurbishment work undergone by the reactor, with many other key renovations to comply with the new regulations as part of the CABRI International Program (CIP).

This research program brings together many French and foreign partners, representing more than ten different countries, and its objective is to study the behavior of nuclear fuel rods and their cladding during a reactivity insertion accident (RIA) in pressurized water reactor (PWR) conditions.

- Core with UO_2 fuel rods
- Initial reactor power: 0 to 100 kW
- Duration of power transient: 10 to 100 ms
- Maximum transient power: 20 GW
- Injected energy: up to 200 MJ
- Water loop characteristics: 280 °C, 155 bar, flow speed up to 4 m/s

Figure 1: Technical characteristics of a CABRI power transient

The CABRI International Program's experiments are expected to come to a close at the end of 2025, and the CEA is currently examining the different research programs that could be undertaken starting in 2026-2027.

2.2. CABRI's overhead crane

CABRI is designed as a pool reactor with removable control rod drive mechanisms. The main reason behind this choice is the need to access the center of the core, where the fuel rod being tested is located, which needs to be changed between every experimental program. These fuel rods often come from EDF's (Electricité de France) production pressurized water reactors (PWR), where they have been used intensively for about three years, before being cut and reworked for the needs of the CIP. As such, they are dangerously radioactive and contaminated. This means that heavy shielding and glove boxes are used very regularly and handled right above the core reactor.

These items weigh between two and twelve metric tons today, and the overhead crane used to handle them needs to meet stringent requirements to ensure nuclear safety – requirements that have been amended many times since the reactor was commissioned in 1964. The figure 2 shows the overhead crane as it was before the latter renovation.

Figure 2: CABRI’s overhead crane in 2021

Indeed, the original overhead crane installed sixty years ago only had a capacity of six metric tons, sufficient for the requirements of that time, as the shielding was allowed to be a lot thinner. The safety standards and technology for overhead cranes were also different to those of today, with fewer redundancies and safety features.

There have been several updates and checks performed over the years, in particular with modifications to increase the capacity to 10 and then 12 metric tons, reinforcements to meet changing requirements regarding earthquake resistance and checks on the integrity of components and welds, up until the upgrade performed in 2022, the subject of this paper.

2.3. Origin of the need for an upgrade

Every ten years, every nuclear facility in France submits to an extensive review by the relevant French Nuclear Safety Authority, in most cases the Auotorité de Sûreté Nucléaire (ASN) and their technical experts the Institut de Radioprotection et de Sûreté Nucléaire (IRSN). This ré-examen de sûreté (safety reappraisal) entails the ASN interrogating and evaluating every sensitive system, leading to studies and checks and renovations to ensure that a facility is compliant with the current safety standards. Aging considerations are evaluated, but it is usually advances in technology and safety requirements that make this an important and comprehensive event in the life of a nuclear reactor.

During CABRI’s previous safety reappraisal, the ASN voiced the concern that the loads being handled for operation of the reactor were growing heavier, and that some components had not been upgraded to bear them because of technical issues (size and position incompatible with the new systems). A Failure Mode Effects and Criticality Analysis was performed, concluding that the reliability of the overhead crane was high enough for the recommissioning of the reactor, but also identifying the critical components and major failure modes.

Parallel with the recommissioning and the start of the CABRI International Program, the CEA continued their discussions with manufacturers and monitoring of the general technological advances made on overhead cranes, undertaking regular design studies to look for ways to improve any areas highlighted by the FMECA. About five years later, a design was produced that made use of recent more compact solutions for hydraulic brakes and some clever component positioning.

3. The upgrade

3.1. Technical description and joint reflection with the ASN

In order to address the major failure modes highlighted by the FMECA, the upgrade needed to implement three things, depicted on figure 3 and described thereafter:

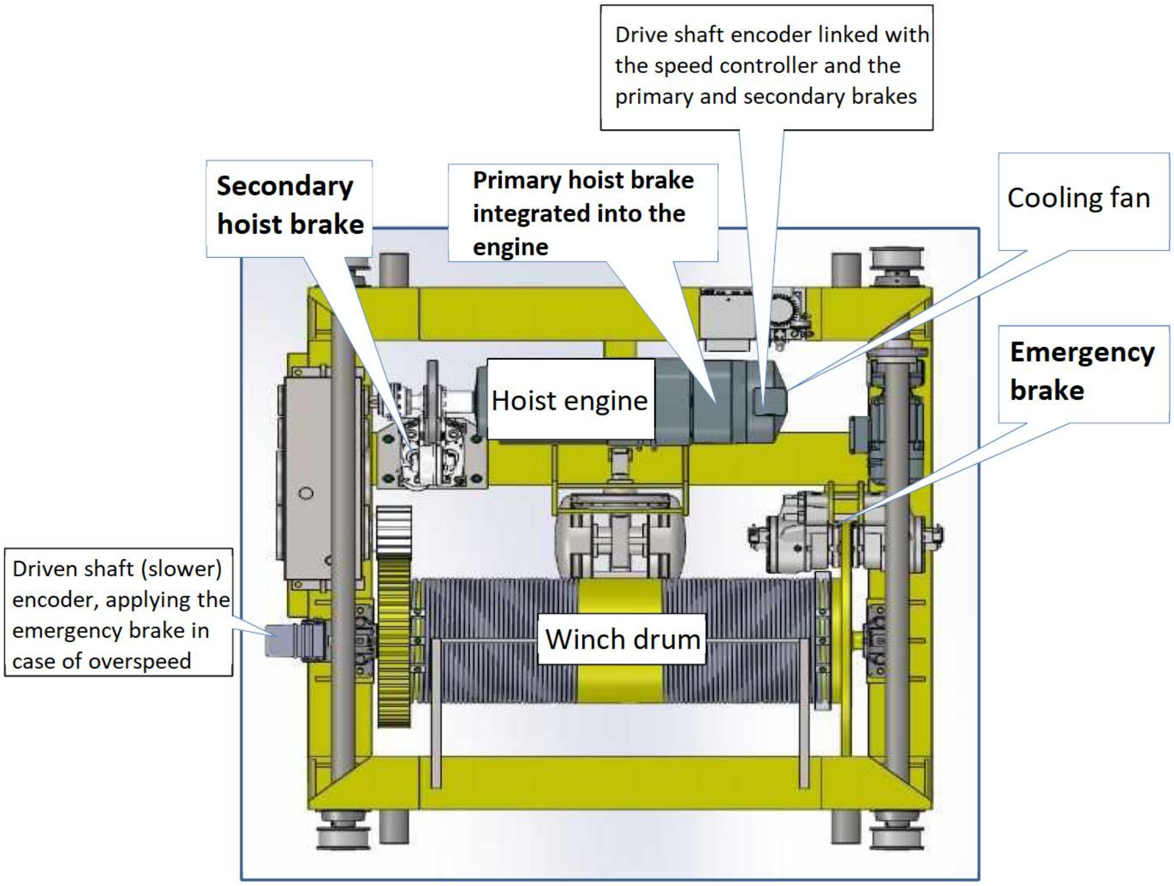

Figure 3: layout of the major components being upgraded

- Upgrading the 10-ton emergency brake to a 12-ton emergency brake.
  The emergency brake is the one that stops the load from falling down completely after it has already started to fall – i.e. when the hoist brake has already failed. On bridge cranes there is usually a hydraulic caliper disc brake set up on the winch at the end of the kinematic chain, close to the load.
  This was the most important part of the upgrade, which was not possible when the overhead crane capacity changed from 10 tons to 12 tons because of available room on the crane. Operating precautions were taken when handling 12-ton loads with the crane to ensure proper respect of nuclear safety, but the low reliability of the emergency brake for actually stopping the load in case of failure of the 12-ton hoist brake was the single point that led to the upgrade.

- The addition of a secondary hoist brake.
  Nowadays, the primary hoist brake is integrated into the engine: it keeps the engine in place when the load is not being taken up or down from the beginning of the kinematic chain, so that the load at the end of it is also kept in place.
  A secondary hoist brake does the same thing, but is positioned right after the motor, usually as a brake on a disc located there specifically for this purpose. It is designed to close automatically, right after the primary hoist brake does (or receives the order to close), so that in case of failure of the latter the load is still stopped and held in place before it can gain speed. This avoids activation of the emergency brake, which only closes when it detects that the load is travelling faster than it is supposed to, violently stopping the momentum and damaging the crane.
  It is relatively recent in standards for overhead cranes in Europe, and provides a significant improvement to their overall reliability.

- Renovation of the electrical components
  The electrical components, from circuit breakers to engines via speed variators and sensors, were changed and replaced with new ones, more up-to-date and adapted to the low speed that is the current standard in handling heavy loads in the CABRI context, as well as providing speeds proportional to the operator's input on the new radio control for easier and finer accuracy.
  This was an upgrade in terms of nuclear safety, especially as the previous engines and frequency changers were not designed for the speeds at which loads are currently handled, which caused some heating in the systems and affected their reliability.

Comprehensive studies were performed for the overhead crane with these modifications, modeling mechanical constraints and acceptability in operating at max capacity over time, the capacity to keep the load in place in case of an earthquake of significant magnitude (revised after the events of Fukushima Daiichi) as well as a new Failure Mode Effects and Criticality Analysis to evaluate the impact of these modifications.

It is interesting to note that CABRI was (and still is) between two major safety reappraisals, and this was not something required of the CEA by the ASN. Yet it was anticipated that the overhead crane would be an important point for the next one, and these steps were taken to ensure that the nuclear reactor would not have to be stopped then and wait until this major operation was performed.

For this reason, the CEA contacted the ASN, presented the project and studies that had been performed and entered into a phase of discussions with the safety authority. Numerous questions were asked, some easily answerable in session and others necessitating new studies and modelizations. In the end, no amendment was made to the new overhead crane design, but some special attention was paid to the way the CEA would lead and oversee the fabrication and implementation process, within and outside of its nuclear reactor.

3.2. Fabrication

An overhead crane consists of two parallel rails seated on longitudinal I-beams attached to opposite steel columns by means of brackets. The traveling bridge spans the gap. A hoist, the lifting component of the crane, travels along the bridge. This hoist can be as simple as a winch and an engine for some low-risk utilizations but, in the CABRI case, where it is supposed to lift and carry loads above the reactor core, the different safety and redundancy features make it vastly more complex.

The CEA studied two options early in the project timeline: either using the current hoist mechanical structure, by taking it down, refurbishing it and equipping it with new components before putting it back up, or making a new hoist from scratch and using it to replace the current one. The former option would have been less expensive and resulted in slightly less radioactive waste needing to be processed, but the latter offered a more reliable and maintainable design as well as a shorter delivery time. For both of these reasons, fabricating a new hoist was the end decision.

The company REEL, with 75 years' experience in manufacture and implementation of lifting and handling in highly sensitive environments, as well as an involvement with the French nuclear sector in particular since its earliest days, was chosen to carry out the upgrade. The CEA inspected their quality system, from the standards for validation of documents to the overseeing of their suppliers, and the different checks carried out in their operational process, and approved it as appropriate, requesting only a few supplementary points – in particular the traceability of the materials as well as regular meetings to talk about the project's development and to solve potential issues.

During the manufacturing process, particular attention was paid to quality control of the critical components (brakes and kinematic chain in general) as well as the welding. The CEA carried out several unexpected inspections as it took place, making sure each time that the welders had a Welder Performance Qualification (WPQ) and were in possession of the correct Welding Procedure Specification (WPS), approved by the CEA and that they were executing it in a satisfactory way. It is pleasing to note that this was the case on every inspection.

At the end of the fabrication, a Factory Acceptance Test (FAT) took place with REEL and the CEA, testing all functionalities and electrical components and their characteristics. Everything was wired specifically for the FAT and unwired afterwards, as it was necessary for implementation on-site, but this made it possible to ensure that everything worked as intended and to highlight and solve a couple of issues when it was still relatively easy to do so (in factory conditions as opposed to nuclear facility conditions).

3.3. Implementation

Before implementing the modification, a last verification was performed with the French Nuclear Authority, who checked that the manufacturing had been performed and overseen in a satisfactory manner and asked the CEA to expound on how they would lead the implementation.

The ASN's principal concern on this point was respect for nuclear safety: CABRI is a very compact nuclear facility (the reactor building is about 10m x 20m), full of pipes and tanks and other items containing or having contained substantial quantities of radioactive fluids at one point or another, and most of the work on the overhead crane upgrade takes place about 10 meters above ground. Consequently, in most phases, but especially when taking the old hoist down and hoisting the new one up, it was essential to prevent the possibility of a heavy load falling down and potentially breaking containment, or even worse damaging the nuclear core.

For this purpose, a physical zone was precisely defined, selected for the absence of more sensitive system equipment in its immediate vicinity, and for its resilience to the potential fall of a 2-ton metallic object. The winches and steel structure fabricated specifically for this operation were, of course, also designed and checked – by means of modeling as well as stress testing – to prevent occurrence of a failure. Furthermore, several protective systems were created and implemented to protect less critical systems from impacts with a smaller magnitude (items propelled indirectly by the falling hoist or by general falling of lighter items – whether they are other components or tools carried by the workers) so everything sensitive would be covered during the hoisting of the now hoist, an operation seen on figure 4.

Figure 4: hoisting of the new hoist in 2022

It is interesting to note that the only position available in terms of nuclear safety concerns made the initial design of the steel structure (in red on figure 5) impossible, due to unforeseen interference from the beams supporting CABRI's ceiling, and this was observed during an on-site inspection intended to simulate the operation. This allowed REEL and the CEA to anticipate the problem and change the design, avoiding the delay that would have resulted from new fabrication and more testing.

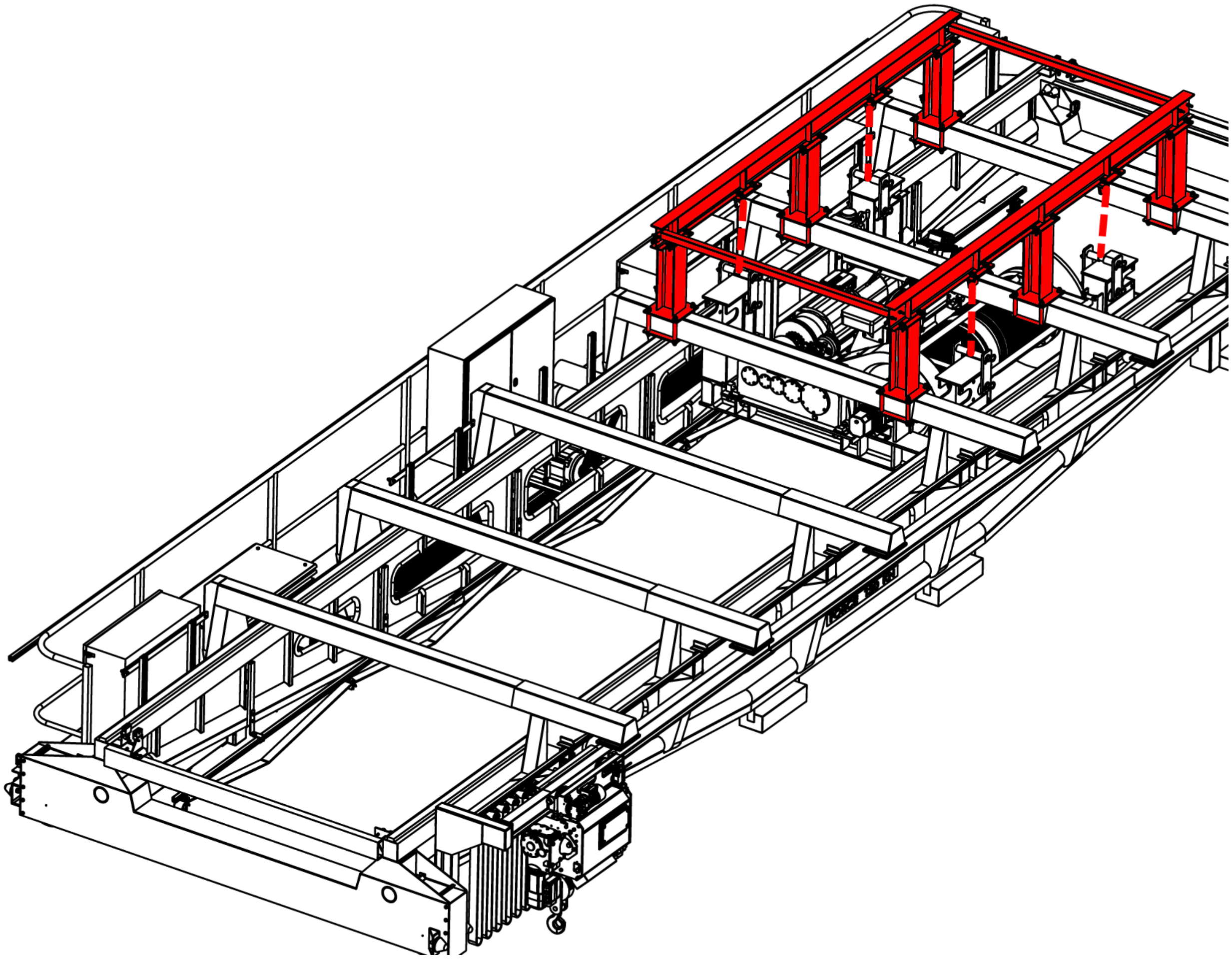

Figure 5: steel structure allowing the hoisting of the hoists in place on the overhead crane

The other notable on-site issues in the upgrade of the overhead crane included:

- Protecting the workers from the radioactive elements present on the hoist and its components, as well as the paint. This was a concern for the whole operation but in particular for the dismantling operations needed for handling the old hoist as waste.
    - To resolve this issue, the CEA radiation protection specialists were constantly on-site, working with the technician to check the radioactive contamination levels and instruct them on the relevant protective actions.

- Protecting the reactor pools from the different types of dust produced by the work. The overhead crane was stationed opposite the pools and reactors for its upgrade, but since it was also ten meters high in a small building some of the dust was bound to travel that far. This is a problem with all kinds of dust, which can affect the properties of the water used as a coolant and moderator, or its turbidity and the general capacity to verify water and system integrity, but it is especially true for metallic dust produced by cutting and welding on-site. Whenever possible, such operations were performed elsewhere, but some needed to take place in the reactor building, for technical reasons, and there was a concern that carbon steel particles would fall on the stainless steel present everywhere in the reactor pool and lead to corrosion.
    - Several tarps and strong ventilation systems were installed and monitored, both at the immediate cutting and welding point and above the pools, to prevent this risk.

- General protection of the workers for work at height.
    - The standard measures for this kind of work, which REEL has a lot of experience with, were put into place, including use of a mobile elevating work platform and some scaffolding where possible, and specially adapted procedures and wearing of a safety harness otherwise.

- Minimising the period of unavailability of the overhead crane, given its central role for CABRI, so that most of the facility continued to be able to perform experiments as much as possible. A universal concern for nuclear reactors and industrial installations in general, as time spent on maintaining and improving the facility, despite being useful and necessary, is time not spent on fulfilling the facility's main purpose.
    - In addition to the decision to work on the basis of a completely new hoist rather than modifying the old one, the schedule was planned to optimize the sequence of operations and to perform as many tasks in parallel as was reasonably achievable. This schedule was then examined using a critical eye and experience gained from operating nuclear facilities and overseeing operations at similar scales, in order to achieve the best compromise between efficiency and needing to deal with unavoidable setbacks, which were handled at mandatory weekly meetings between the CEA and REEL. Finally, many items were prepared, realized and checked in advance outside of the facility, to end up with the least possible entropy.

4. Commissioning

The commissioning took place with a final performance test, which consisted in handling 150% of the maximum authorized capacity. Every direction and command was tested with this configuration, and every brake tested separately. This test proved tremendously important when it became apparent that the emergency brake had been loosened as a consequence of the taking down and setting up of nearby components, and was not able to hold the load. The test weight ended up sliding to the ground, harmlessly, as the test took place about 2-3 cm above ground and at the same secure location mentioned previously, to limit the consequence of failure. The emergency brake was tightened and tested again and the way that it had been loosened was analyzed and recorded. Moreover, the CEA made the decision to continue testing every brake separately as part of annual testing of the overhead crane rather than the single global test that was the norm, and to check the emergency brake's setting itself during half-yearly maintenance.

The acceptance test also included retesting of each electric component and its characteristics, as well as another check on the wiring that had been removed and reinstalled since the factory test. The overhead crane was only supplied with power after everything was confirmed to be in operational order (or brought into operational order where applicable), and the final functional tests were then performed. The latter focused on the safety systems, speeds and their responsivity and range of movements of the new hoist, which needed to accurately reproduce the performance of the previous one.

Once every test was performed and the criteria met, the CEA checked and signed the testing documentation, and sent it to the ASN. This mailing process, as it consisted of checking and confirmation of every criteria and requirement that had previously been agreed upon by the French Nuclear Authority, constituted the acceptance of the definitive upgrade and allowed the CEA to begin normal operation of CABRI again.

5. Feedback

Commissioning of the CABRI bridge crane occurred in June 2022, almost a year before the time of writing this paper. The feedback on the upgrade has been overwhelmingly positive.

No component failures have been reported. The brakes hold perfectly well and the half-yearly maintenance found no change in their tuning nor wear and tear. Thankfully, the situation was similar with the overhead crane pre-upgrade, but combined with the new FMECA and its conclusion of reliability this gives a sense of security to the operators. The precautions that existed before to deal with the risk of brake failure are still being followed: they have become standard for the facility and only serve to improve nuclear safety.

The electric components are in perfect condition too. No abnormal heating has been observed and no circuit break happened even when the crane was used at maximum capacity for several hours. This is an improvement for the general operation of the reactor and for the reliability and life-expectancy of the engines, now functioning at the standard RPM.

The new range of movements is satisfactory, and the new speeds and the option of proportional speeds gives the operators better control of the load. There is an option on the radio control unit to set the same lower limit cap on the speed as was used for the previous hoist, regardless of input. This is used for the most sensitive loads, and several general “quality of life” features (tracking load position by coordinates, displaying weight being handled on the radio control unit as well as on the bridge itself, etc.) have been greatly appreciated in carrying out day-to-day operations.

This upgraded overhead crane has been used to perform two of the six experiments of the CABRI International Program in the past year, as well as several smaller scale experiments. Built to last twenty years at the current intensive level of use before there will be any need to check on its structural integrity and potential obsolescence, we expect that it will perform its role flawlessly in carrying out the remaining part of the CIP as well as whatever comes after that.

Acknowledgements

The author wishes to thank:

- Vincent Roux and Fanny Jallu for their support to CABRI in general and this presentation,
- Manuel Saez for his help in the writing of this paper,
- The whole operational team of the CABRI nuclear reactor, the LEXIC, past and current members, for their general help and investment in carrying out the upgrade of the overhead crane and everything that contributes to the experiments conducted in the facility.

References

No quotable reference.