

# MINOR ACTINIDE BEARING BLANKET MANUFACTURING PRESS

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## ABSTRACT

This study concerns the Advanced Processes of Conversion and Manufacturing of fuels for transmutation (APCM). One of the fuel manufacturing processes arises from the conventional process of the powder metallurgy industry and enables pellet shaping in dies and sintering. The shaping of the Minor Actinide Bearing Blanket (MABB) pellets is currently done manually in hot cells. In this study, automation for this manufacturing and a better control of the shaping parameters were tested in order to prepare the way for a new automatic nuclear press. Collaboration has been set up between the CEA (ATOMIC ENERGY COMMISSION) and CHAMPALLE<sup>ALCEN</sup> for the construction of the new press. The minimization of criticality risks is an important goal for MABB pellet manufacturing, and is the main reason why the press is being built to operate without oil and is completely electromechanical. It is a uni-axial automatic mono-punch single effect press, with a displacement-piloted die. Its capacity is 10 tons, the maximum height is limited to 1200 mm and the production rate is 1 to 5 cylindrical annular pellets per minute. Installing the apparatus in an existing hot cell for nuclear fuel production required modular conception and simulation studies, which were carried out using a 3D software to show the entry of all modules through the airlock. The objective was to validate the modular units' ability to be assembled, dismantled and maintained by remote handling techniques. The thirty separate units making up the press had to go through a 240 mm diameter air-lock to enter the hot cell. To be sure the remote handling scenarios were appropriate, virtual reality simulation studies were carried out, taking into account force feedback and inter-connectability between the different units. In parallel, different radiological software checked that the press components' radiological dimensioning would ensure its radiation resistance during operation in a hostile environment. A mock-up simulating the future hot cell and equipped with the real remote handling was built in the CEA/Marcoule HERA facility technological platform in order to physically test press unit assembly by remote handling, and the apparatus operations. This press, adapted to nuclear conditions, is patented. The press will be showed for a sale at the World Nuclear Exhibition (WNE).

## 1. Context

The electronuclear closed fuel cycle chosen by France plans the reprocessing of spent fuel and enables natural uranium resource saving, and a reduction in the volume of wastes and their toxicity compared with the choice of a direct storage (open cycle). The nuclear waste from spent fuel is classified depending on its activity and half-life. The High Activity (HA) waste represents more than 95% of the total radioactivity of French nuclear waste. The liquid extraction process

called PUREX enables the Minor Actinides (MAs) to be separated from the Fission Products (FP) in HA waste. The advanced management of the MAs is a goal for the transmutation envisaged in 4th generation reactors or in the specially-dedicated reactors. Two ways of MA transmutation in fast breeder reactors (FBRs) are envisaged, homogeneous and heterogeneous recycling. The heterogeneous mode consists in concentrating the MAs in special assemblies located in the periphery of the reactor core. The neutronic impact on the core limits the introduction of a higher quantity of MAs, restricted to 10 to 20%. Materials including Americium (Am) and located around the reactor core can be of target type if the MA support an inert matrix, or else part of a Blanket Loaded in Minor Actinides (AMBB) if the MAs are directly incorporated into fertile UO<sub>2</sub> fuels.

## **2. Objective**

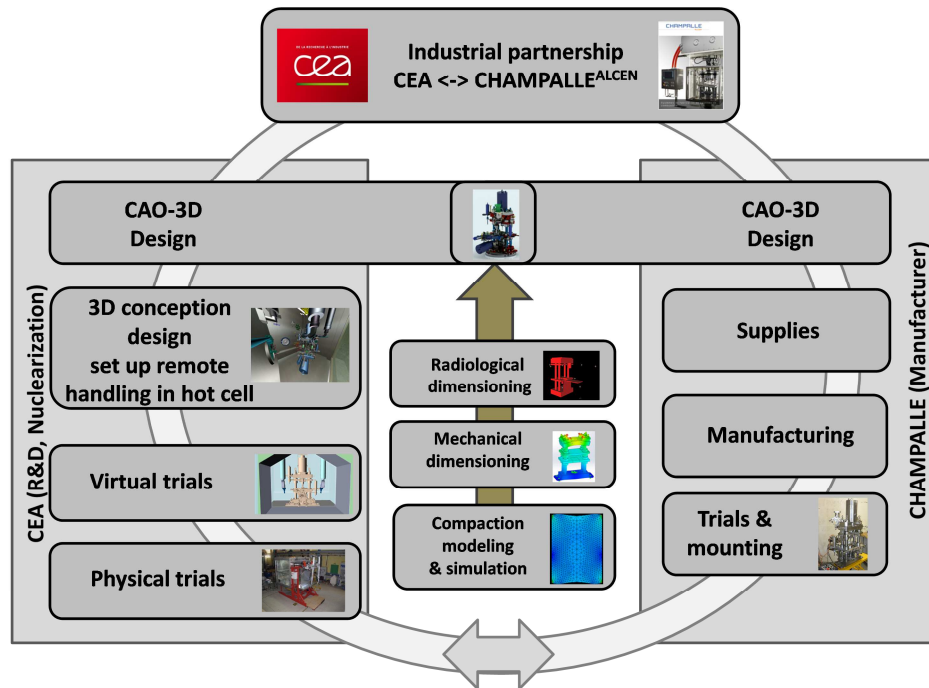
The APCM project consists in defining the Advanced Processes of Conversion and Manufacturing of fuels for transmutation. One of the fuel manufacturing processes comes from the conventional process of the powder metallurgy industry and enables pellet shaping in dies, and sintering. The shaping of the MABB pellets is currently done manually in hot cells. In this study, manufacturing automation and a better control of the shaping parameters were tested in order to prepare the way for a new automatic nuclear press. A collaboration was set up between the CEA (ATOMIC ENERGY COMMISSION) and the CHAMPALLE<sup>ALCEN</sup> for the construction of the new press. The minimization of criticality risks is an important goal for the manufacturing of MABB pellets, and is the main reason why the press is designed to run oil-free and is completely electromechanical.

The study was carried out to develop a remote handling press for hot cell use. It needed to be as small as possible and to improve the current MABB manufacturing process, to pass from a unitary production to a continuous automated batch production of approximately 100 pellets at a time, with a central hole and without grinding. The output rate needed to be 1 pellet per minute, while respecting the criteria for fast reactor fuel manufacturing. The press had to be completely assembled, dismantled or maintained by remote handling techniques. For access, all parts had to go through the hot cell entrance airlock, with a maximal diameter of 240 mm.

The remote handling equipment was chosen taking into account the hot cell volume, and the height of the press had to be reduced. The capacity of the overhead travelling crane is about 80 kg. For reasons of criticality, waste release, degradation of liquids hydrogenated under irradiation and to avoid any contamination of hydraulic systems, oil could not be present. The press module had to be radiologically dimensioned according to two scenarios for powder load, either with a full jar (capacity = 1300 g, theoretical density = 10.73 g / cm<sup>3</sup>), or for the same capacity, the distribution of the powder in the jar, in the column, in the filling shoe and in the die. For the gamma and neutron activity calculations, two reference spectra were taken into account and the composition considered consisted of 70% Uranium from reprocessing and 30% Americium. The press had to allow powder loading operations, pellet unloading, external surface tool lubrication, and cleaning, in order to minimize any pellet damage as well as powder retention or hold-ups.

## **3. Project road map**

To make a nuclearized MABB manufacturing press, the CEA and CHAMPALLE combined their knowledge under the terms of a collaboration agreement. The CEA contributed knowledge for equipment nuclearization in hot cell, and compaction research and development. CHAMPALLE has skills concerning nuclear fuel press manufacturing, and is a supplier of presses for nuclear and non-nuclear applications. The methodology implemented for the project is defined in the plan below, *Fig 1*.



**Fig 1: Methodology implemented for the project**

Transverse conception studies enabled the first version of the press specifications to be prepared, taking into account the product manufacturing constraints imposed by the CEA. CHAMPALLE was in charge of supplying the specific press equipment (motors, sensors ...etc.), as well as the actual manufacturing, assembly and trials before transfer to the CEA Marcoule center.

Based on the final version, a first CAD-3D study placed the press in the hot cell environment, to define the best possible set-up. The best hot cell location had to take into account all module routing operations through the equipment entrance airlock, as well as their remotely-handled assembly, dismantling, and maintenance.

The accessibilities of different units were approved with the elaboration of specific tools. A new version of the press was then able to be proposed. The results of the mechanical and radiological sizing have shown respectively the good mechanical of the system proposed under static requests and the dose rate will receive different units of the press during the batch of manufacturing.

From then on, the ultimate version of the press was able to be confirmed, what enable the CHAMPALLE supply and manufacture launching. To perfect the studies of setting-up and remote handling, another really virtual study enables the immersion a little more the press in its working environment. Situated between the simulations CAD 3D study and the physical trials with the attempts in feigned box, this crucial stage allows to validate even more the nuclearization of the press.

To completely validate the press nuclearization, press handling trials of assembly/dismantling, maintenance and operation planned in a hot cell simulation with Lacalhene MT200 remote handling. Finally, based on CEA manufacturing criteria, regulation and optimization of the press cycle operations are essential to obtain products meeting the specifications (size, shape, crack damage etc.).

To do this, Finite Element Method (FEM) simulation studies with the compaction model identification coefficients is in progress. The final objective for a given powder batch will be to be able to adjust the press settings to guarantee the most constant possible product quality. To better understand the importance of the stages which marked out this project, a later chapter will

discuss some crucial passages which stood out. For the moment, a technical description of the press will be given, to understand better the issues.

#### 4. Technical details of new press

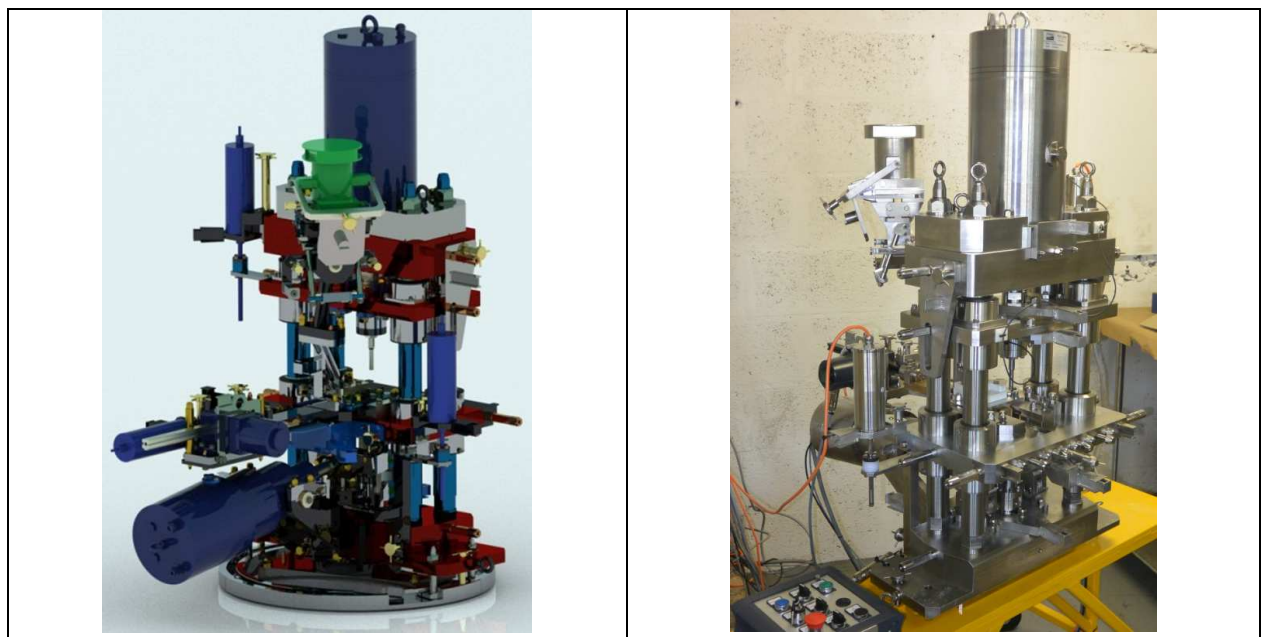
The press [1] is a uniaxial mono punch press, with a single compaction cycle. The upper punch and die are mobile at different velocities and the lower punch is fixed. The die is used for the ejection step with an upper punch pressure support.

The press hot cell integration imposed the use of an existing hot cell (without modifications and external motors being possible). A transfer of the module units through the 240 mm diameter of the Lacalhene Leaktight Transfer Double Door had to be carried out. To minimize the criticality impact, the use of hydrogenated liquids is not permitted in the hot cell.

This is the main reason why the choice was made of electric motors with transmission systems with a minimum gap, combining rotary and translatory mechanisms for the upper punch and the die. To decrease the height needed, the die motorization was placed to one side and the effort transmitted via a toggle joint to the die plate.

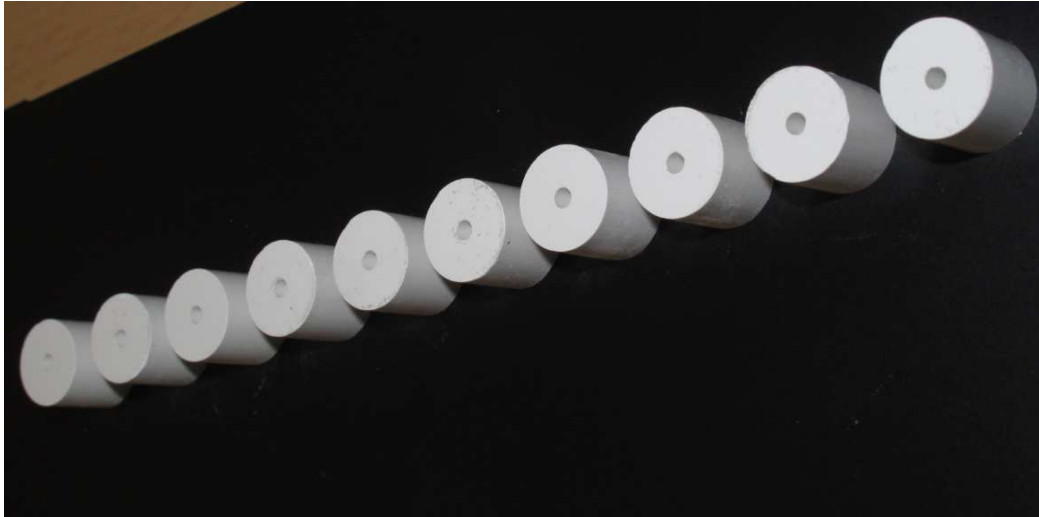
The press production rate is about 1 pellet per minute and its capacity is 10 tons. The base structure has one lower plate, see **Fig 2**. This plate is fixed to a circular rail built into the hot cell floor. The press can therefore be rotated in order to access any of the five main parts as required. These parts are described below.

The first part includes the rigid frame of the press, consisting of the lower and upper plates connected by 4 guide columns. The plates support respectively the motors of the die and of the upper punch. The lower plate holds the fixed lower punch equipped with a displacement sensor. Between these two plates, the upper punch and the die plates (parts 2 and 3) slide up and down. Plate displacements are monitored by sensors, and the mobile upper punch is also fitted with a force sensor. The powder load system and displacement motor of the filling shoe are set up on the mobile die plate. The filling shoe is moved laterally by an electric motor and a rack system. The powder load system has a tippable powder transfer jar which can be completely connected using remote handling.



**Fig 2 : Left, 3D view of the press and right, picture of the press during first trials to CHAMPALLE**

The **Fig 3** show the alumina pellets manufactured by the press during the first CHAMPALLE trials. Velocity of the upper punch was 15 mm/s and 10 mm/s for the die. The main difficulty was to put the force containment during the ejection but the regulation parameters enabled the pellet ejection without damages.



**Fig 3:** Alumina pellets manufactured by the press during the first CHAMPALLE trials

## 5. Radiological sizing

To calculate the dose rate [2] received by the different press modules, in particular by the sensitive electronic components, a radiological dimensioning study was carried out by the CEA with the Mercurad 1.04 [3] and MCNP 5 [4] calculation codes. This was done to quantify the life span of different apparatus, but their true radiation resistance is not yet known. However, suitable module positioning or radiological shielding could extend their life span. A special effort should be made to ensure spare parts are kept available to facilitate any unplanned maintenance, as that show in a previous study [5].

For the calculations, two cases were taken into account. The first considered the powder jar as full (maxi jar), with 1300 g of powder, while the second (mini jar) considered that the 1300 g of powder were divided among the jar (533 g), the powder column (731 g), the filling shoe (23 g) and the die (10 g). Four source terms were then identified, the jar with maxi or mini powder, the column of powder, the filling shoe and the die. Six powder compositions may be used, and for each composition, the percentage of each radioelement (reprocessed Uranium, Plutonium, Americium, Neptunium, Curium) is variable.

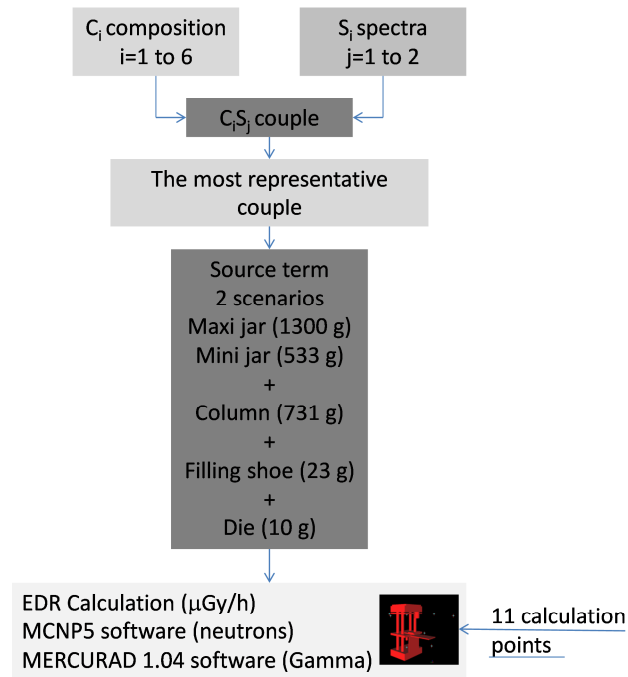
These 6 different compositions are neutronic (by ( $\alpha$ , n) reactions and spontaneous fission) and gamma emission sources. The spectral distributions and the activities of the different sources are given in **Tab 1** below. Only two spectra (Si)) giving the probability of neutronic emission as a function of the energy in MeV, were considered. To define the most radiologically restrictive pair Ci/Si, an activity calculation was made for a compacted pellet.

This calculation showed that the most restrictive pair was C4S1, remembering that Curium was not taken into account. The isotopic distribution of the C4S1 spectrum is given in Table 3, for 70% of reprocessed Uranium and 30% of Americium (UOX3 60-5). The total equivalent dose rate (total EDR) calculations, for a detection 1 to 5 centimeters from the pellets, give 7 288  $\mu\text{Sv/hour}$  compared to 7 263  $\mu\text{Sv/hour}$  for the C4S2 pair.

Reprocessed Uranium	% mass	Mass (g)	Activity 1 pellet (Bq)
U234	0.072	7.56E-04	1.74E+05
U235	3.956	4.15E-02	2.95E+03
U236	0.896	9.41E-03	2.27E+04
U238	95.076	9.98E-01	1.24E+04
<b>UOX (60-5)</b>			
Am241	63.08	2.84E-01	3.60E+10
Am242m	0.20	9.00E-04	3.49E+08
Am243	36.72	1.65E-01	1.22E+09

**Tab 1: C4S1pair isotopic distribution**

The calculations were then made for each case as shown in **Fig 3**. For all sources considered, a succession of 11 sensors was taken into account to determine the dose rate received by the sensitive components of the press.



**Fig 3: Radiological dimensioning approach**

The calculation results given in **Tab 2** show that the Mini jar case is the most damaging for the press equipment. The extreme values of 1368 and 1655  $\mu\text{Gy}$  per hour must be noted respectively for the filling shoe motor and for the applied force sensor. The component most impacted is the applied force sensor, located between the upper punch and the plate. However, as the protection

around the sensor was not taken into account, the calculation value is probably higher than the reality.

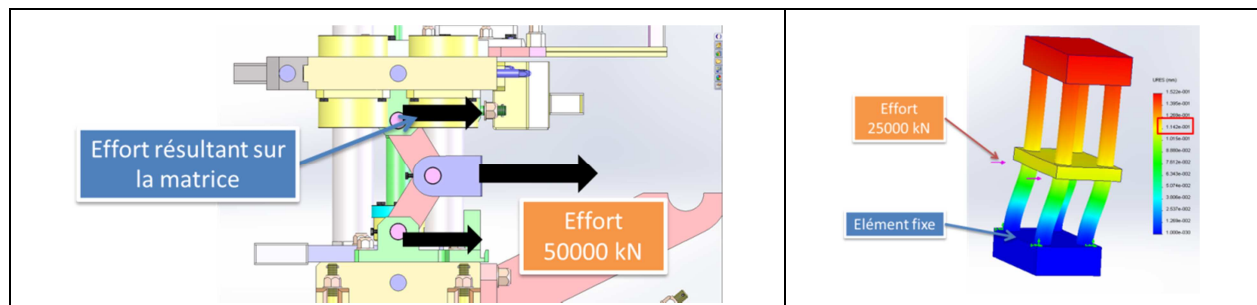
In the Maxi jar case, the total EDR value for the filling shoe motor is 465  $\mu\text{Gy}$  per hour, and 681  $\mu\text{Gy}$  per hour for the applied force sensor. The lesson learned is therefore to avoid holding up the powder during the manufacturing step and to drain out remaining powder as quickly as possible afterwards. Other calculations were carried out for a more advanced version of the press. Given that the distance between the center of the jar and that of the press is greater, and that the size of the jar decreased, the previous values gave a wider range, within which the new values are located.

Sensor	Location	Dose rate $\text{EDR}_{\text{total}}$ ( $\mu\text{Gy/h}$ )	
		Mini jar case	Maxi jar case
1	Upper punch motor	57	95
2	Die motor	97	62
3	Filling shoe motor	1368	465
4	Transmitted force sensor (*)	28	5
5	Die displacement sensor	16	13
6	Punch displacement sensor	118	3
7	Applied force sensor (*)	1655	681
8	South side of the press (30 cm)	246	60
9	North side of the press (30 cm)	154	148
10	East side of the press (30 cm)	242	184
11	West side of the press (30 cm)	238	184

**Tab 2: Estimated dose rate calculations ( $\text{EDR}_{\text{total}}$ ) depending on the sensor positions for Mini jar (column, filling shoe, and pellet) scenario and for Maxi jar (\*without sensor shielding)**

## 6. Mechanical sizing

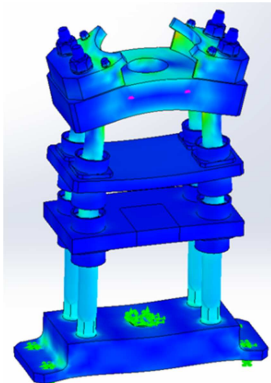
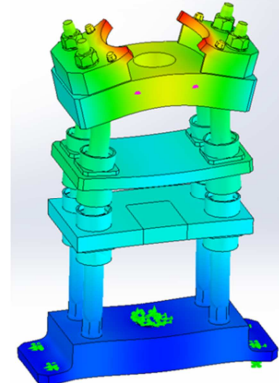

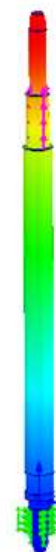
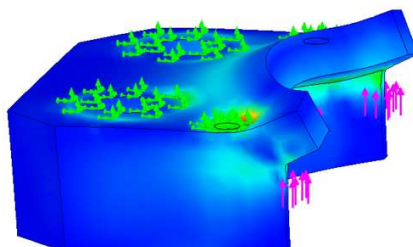
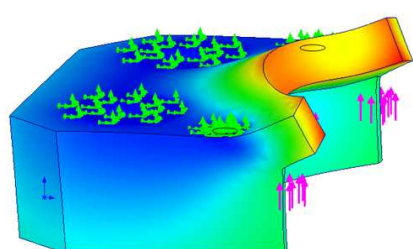
FEM Calculations [6] were used to verify the press sizing and to make sure the equipment was sufficiently rigid (frame distortion, strain concentrations at the tungsten carbide punches, plate distortions, column friction, etc). The example in **Fig 4** enabled improvement of the toggle joint effort transmission to the die plate.



**Fig 4: Toggle joint mechanical dimensioning calculation results**



Also, the die plate motor was re-examined and the capacity changed from 5 to 3 tons, which seems clearly sufficient for the necessary force. **Tab 3** gives some results concerning the mechanical resistance of the frame, the column and the mounting flange of the upper punch motor. Note the safety factors respectively of 5, 22.5 and 11.5.

Materials and boundary conditions	Maximal Von Mises stresses (daN/mm <sup>2</sup> )		Maximal displacements (mm)	
<p>Frame</p> <p>(Yield stress = 20 daN/mm<sup>2</sup>)</p> <p>Load = 10 t</p>				
<p>Columns</p> <p>(Yield stress = 90 daN/mm<sup>2</sup>)</p> <p>Load = 2,5 t</p>				
<p>Upper punch motor flanges</p> <p>(Yield stress = 90 daN/mm<sup>2</sup>)</p> <p>Load = 5 t</p>				

**Tab 3: FEM simulation calculation results for the frame, column and upper motor flange in the case of maximum loading**

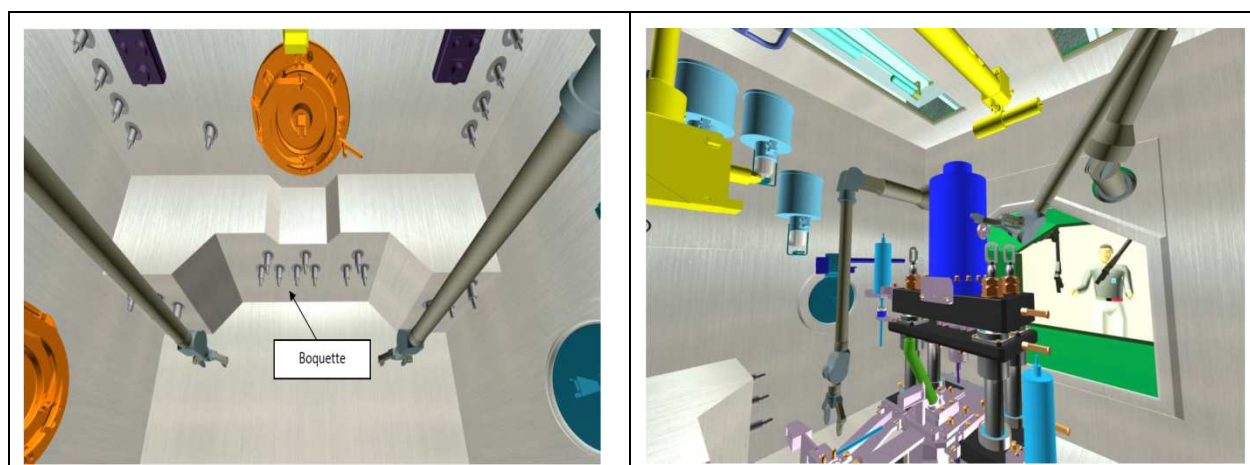


The Von Mises stresses and the displacements were calculated for some units, like the frame, columns and mounting flanges. Results for the stresses gave, respectively, 4, 4 and 8 Dan per mm<sup>2</sup>, and for the displacements, 0.08, 0.05 and 0.02 mm.

## 7. 3D Nuclearization

The 3D simulation was realized within the CEA using the 3DS Max Autocad software [6], [7], [8], with multiple objectives. First, the simulation enabled a recreation of the hot cell environment space with the unit input-output airlock, the overhead traveling crane and the remote handling equipment, as well as the press set up in the cell. It also enabled virtual entry and exit of the units through the airlock and the progressive assembly of the press using the equipment available. Finally, accessibility could be checked and the tools necessary for press assembly, dismantling and maintenance were defined.

The study showed that among 3 possible hot cell solutions, all could house the press provided internal adaptations concerning the areas inaccessible via remote handling took place. **Fig 5** shows some stages of the study with the location of "blocks" to minimize the dead volumes.



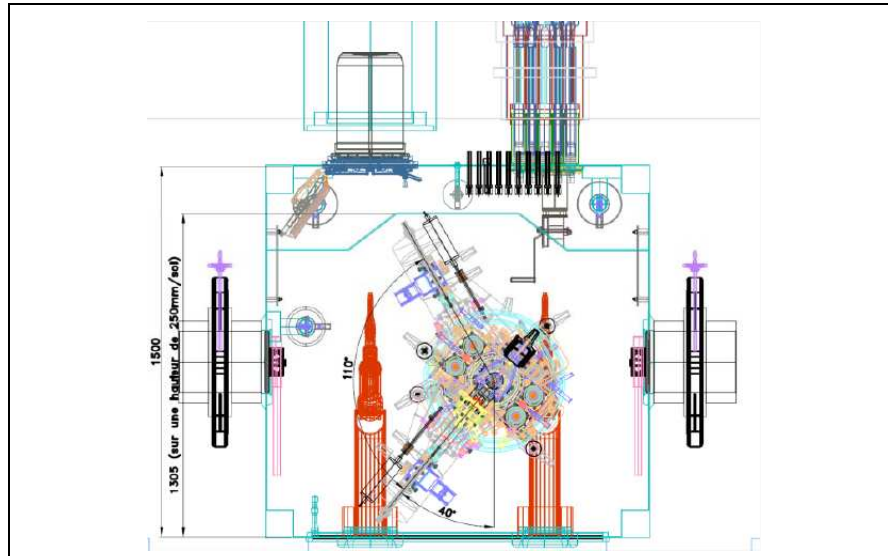
**Fig 5: Views of the “block” for scenario 1(left) and of the press inside the cell**

For the 3 scenarios, **Tab 4** lists the size of the hot cell with its associated remote handling, and the size of the blocks.

Hot cell	Width	Height	Depth	Boquette size (mm)	Remote handling type	Capacity (daN)
1	1650	1750	1500	400 to 250x450	2 MA 11-80	7.5
2	1560	2213	1510	400 to 250x250	2 Mod G	5
3	1560	2213	1510	400 to 250x250	2 MT 120-800	12

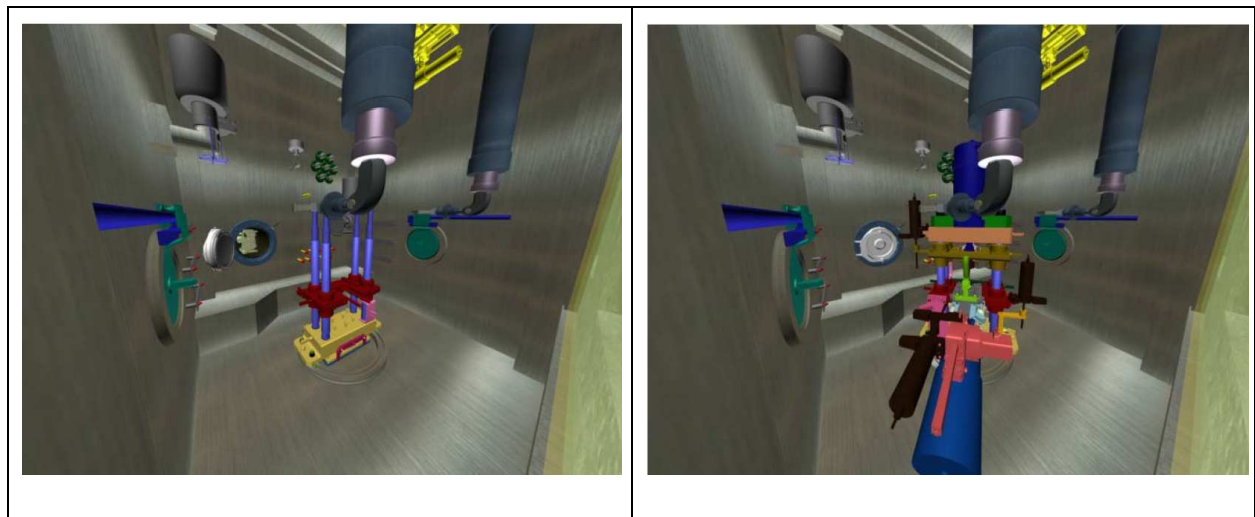
**Tab 4: Block dimensions depending on the cell and type of remote handling**

This study also enabled the optimal positioning of the press within the hot cell, as it was seen that the press has a greater rotation in the hot cell if its centre point is off-centre compared to the hot cell. Furthermore, if the rotation and the gravity axes are aligned, the rotation angle is bigger, see **Fig 6**.



***Fig 6: Optimal positioning of the press within the hot cell***

Finally, as shown in **Fig 7**, the 3D simulation study enabled not only the validation of all module entry operations through the 240 mm diameter entry-exit airlock, but also the step by step module assembly.



***Fig 7: Simulation of the press module entry and assembly operations***

To simplify the build-up operations, the press often needs to be oriented in particular directions. All the modules can pass through the small-diameter airlock, “ringardage” is often necessary and the use of a bracket crane in the hot cell is essential. Through this study, the construction project was proved to be in conformity with the specifications, meaning greater confidence when ordering the final press.

## **8. Virtual Nuclearization**

The objectives of the virtual reality 3D simulation studies [9] were to simulate the assembly, dismantling, maintenance and functioning of the press within the hot cell. Over and above the previous 3D simulation (§7), virtual space was created in the hot cell with force feedback from the remote handling equipment. For higher precision, the unit assemblies were fully simulated unlike 3D simulation where this stage is shunted.

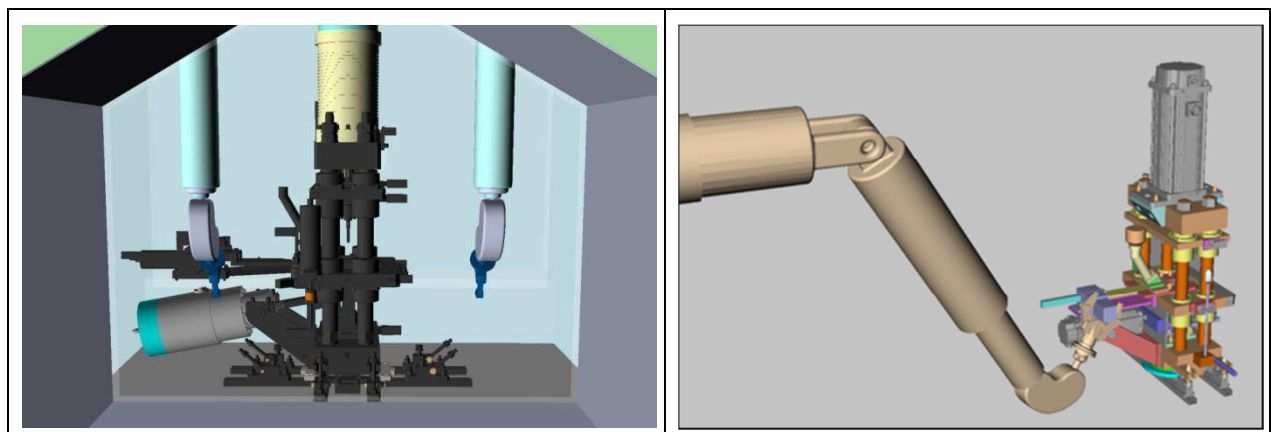
The CEA Marcoule site has an immersive room called PRESAGE, which enables validation of assembly operation feasibility right from design steps by assessing, in particular, the accessibility of different areas within the hot cell, as well as ergonomic aspects of the work station, the tasks and the operation scenarios. This tool groups all technologies enabling a user to benefit from virtual immersion and interaction with the press in the hot cell.

The room is equipped with an Infitec passive stereoscopic display system and a 3.7 m x 2.3 m screen wall where the user has a relief view of the virtual environment. It also has a tracking system where four cameras capture user movement. Glasses equipped with reflecting targets give interactivity by adapting screen display to the view point of the user.

The flystick equipped with targets provides the advantages of a classic joystick and enables the displacements within the scene. The room is fitted with a force feedback haptic arm (the Virtuouse 6D35-45). Via this interface, it is possible to manipulate different objects in a 3D scene and to feel the collisions and the frictions of our object compared to the other objects in the scene. The room is fitted with a stereo sound system which enables additional information feedback to the user, for example when two objects collide.

By using the simulator pre-set to work with these virtual reality tools, it was possible to validate the design of remote handling equipment and to verify its suitability for the environment, taking into account the size of the system and the detection of any collisions between the machine and the various apparatus in the environment. It was also possible to vary the kinematics parameters of the remote handling machine, in particular the movement angles and the runs of the various degrees of freedom.

The studies are continuing, but are not still totally completed to enable a full assessment of the real interest of such a technology for the project needs. The addition of the second haptic arm seemed to us essential to ensure the best working conditions. Very high precision is necessary for the assembly operations, and special developments must be carried out to improve calculation capacities because of the large size of the digital models to be processed. **Fig 8** shows some screen snapshots of the current work.



**Fig 8: 3D simulation in virtual reality**

## 9. Physical trials

To complete press developments based on the 3D and virtual simulations, physical trials are planned in a mock-up at the CEA Marcoule technological platform, see **Fig 9**. This cell mock-up is fitted with mobile panels, which adapt the hot cell size depending on the technology to be tested, and equipped with Lacalhène MT 120 remote manipulator arms. The operator will pilot the arms looking through a porthole identical to that of a real cell, so that the visibility is really representative.

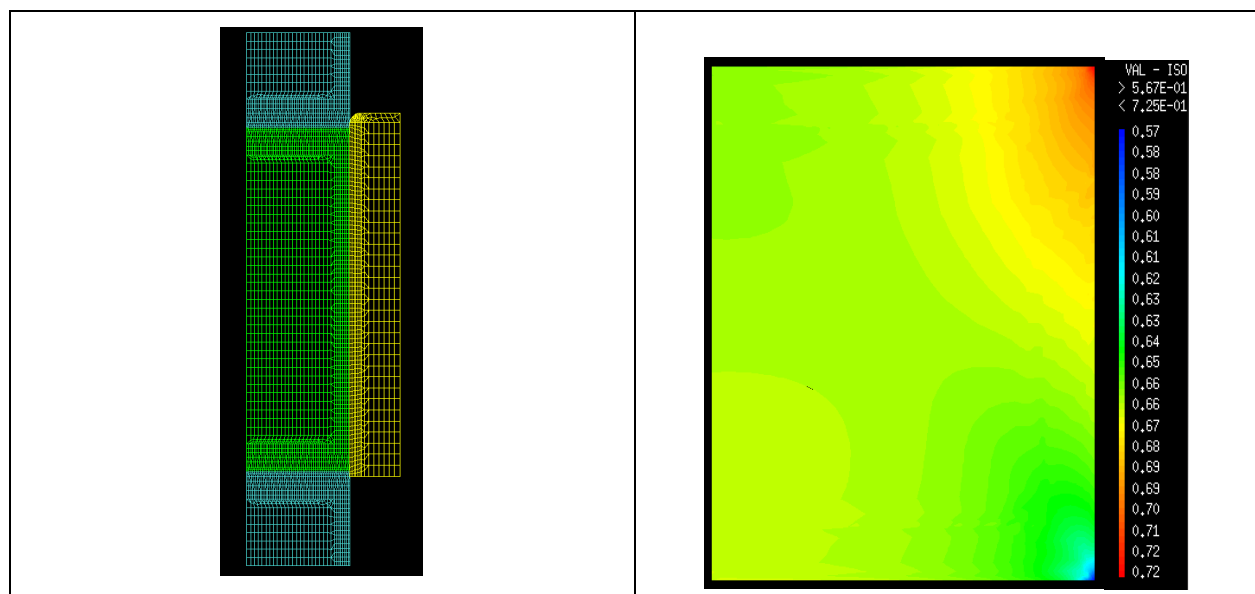
The press will be placed into the box via its ceiling by a lifting unit available in the platform. At present, the press is undergoing tests at Champalle, and it will be shipped to Marcoule very soon. A large number of trials will be carried out to optimize the pressing cycles, validate the maintenance operations, and confirm the accessibilities by going through dismantling and reassembly of the press with all the transfer stages.



**Fig 9 :** *Photo of the mock-up cell during preparation in the technological platform*

## 10. Simulation of the compaction cycle process for optimization

Digital simulation of pellet forming [10], [11] was used to optimize the die pressing cycle. Semi-empirical mechanical models were used in an FEM code, CAST3M [12], see **Fig 10**.



**Fig 10:** *FEM compaction simulation with Cast3M code and Cam-clay model: on the left, mesh of the pellet, punches and die, and on the right, density gradients in the pellet by single compaction cycle.*

Specific powder characterizations also had to be carried out to obtain the mechanical parameters of the compaction model. The methodology of the five main coefficient identifications (index flow, elastic and plastic parameters) using three different powders was applied. Modelling and

simulation had to be successful for the commissioning of the nuclearized press, planned for the last quarter of 2014.

## **11. Conclusion et perspectives**

This paper has described a project to study and create new technology adapted to the constraints of a hostile, cramped hot cell environment. To reach the objectives, an organization was set up to implement some of the most modern design and simulation tools. A combination of 3D and virtual simulations, FEM and dose rate calculation codes was used as a basis for the nuclearization of a MABB manufacturing press. Faced with such an issue to date, no other technology had used electric motors in order to exclude any hydrogenated liquid. The concept proposed gives innovative solutions and has been patented. In a more general context, the apparatus is a small-size instrumentalized press enabling the automatic production of pellets with different shapes. The shaping process is controlled in order to guarantee the best possible geometrical tolerance for the pellet after sintering. Current pressing cycle optimization trials are also using digital simulation. After the press has proved satisfactory in non-nuclear conditions, it will be tested in a radioactive environment to qualify the technology with uranium-bearing materials. To promote sales of the press, Champalle will present its technology during the World Nuclear Exhibition (WNE) at Le Bourget near Paris, 14th-16th October 2014.

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