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# A New Way for Designing Nuclear Power Plant Vessels

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## Introduction

### Could it be that the combined use of rebars and prestressing is not the best technical solution for constructing Nuclear Power Plant Vessels (NPPV)?

The safety of NPPV is critical for society and is a subject which has aroused much controversy. In very broad terms, there are two main approaches for designing these NPPV:

- A single wall NPPV made from very thick reinforced concrete with a thin metal liner on the inner surface;
- A double wall NPPV. The inner wall is made with a lot of rebars and prestressing in two directions (vertically and horizontally). The external wall is made with traditional reinforced concrete. These two walls are separated by an airspace which is around two meters wide.

### What is a single wall NPPV with a metal liner?

This is the oldest type of design. It is based on a very simple view of the role of the NPPV. The reinforced concrete wall designed resist to all external loadings, whether accidental or otherwise. The role of the metal liner is to ensure that the NPPV is sealed to prevent radioactive gas to escape from the reactor core in the event of an accident. Whilst at first glance this design is suitable apt and effective, it has however been called into question in recent decades, particularly by engineers in France. The main doubts was about the use of the metal liner. Criticisms focus on two main aspects:

- Firstly, the installation of the liner is considered to be time-consuming and costly because the component metal plates must be welded together with the utmost care.
- Secondly, there is a potentially significant risk of corrosion, particularly around the welds (areas which are sensitive to this type of damage). This led to frequent inspections of the NPPV, which are time-consuming and expensive.

Consequently, French engineers decided to develop a new concept: the double wall NPPV.

### What is a double wall NPPV?

The most recent design, the double wall NPPV, is based on several sound ideas. First of all, the “inner” wall must be heavily reinforced and prestressed (in both directions). The purpose of this is to ensure that the NPPV can withstand the internal pressures caused by the accidental rupture of the primary cooling circuit of the reactor core (high level of reinforcement). And to seal the NPPV to prevent accidental leaks of radioactive particles. In this design, the bidirectional prestressing is designed to close up any cracks which may form during the concrete hardening process.

The role of the second or “external” wall is solely to allow the NPPV to resist to external loadings (e.g. earthquakes, storms, explosions, airplane crashes). Lastly, the airspace between the two walls, also known as the annulus, is de-pressurized by a ventilation filtration system. It is designed to contain airborne radioactive particles in the event of an accident and allow them to be removed. However, one problem remains: a certain number of NPPVs designed in this way have shown transverse cracking (across the full thickness of the inner wall). This issue has been highlighted during 10-year tests which involve pressurizing the internal wall with gas. These cracks must then be filled in. An expensive job which also raises questions about the reliability of NPPVs.

Consequently, French engineers decided that, for future “new generation” nuclear plants, a “belt and braces” approach would be used on NPPVs! This means a double concrete walls with, on the internal wall, a metal liner. It goes without saying that such a solution had significant financial consequences, leading to a marked increase in the cost of NPPVs. This is caused in part by their construction (increased construction time), as well as the inspection plan (much more attention must be paid to changes in the welds of the metal liner). However, this "belt and braces" approach did not prove to be safe as had been thought. Indeed, the transverse cracking of the internal wall is still present. And corrosion of the welds may still occur. On top of which, steel behaves fairly poorly when subjected to high temperatures.

### Are there new solutions?

Today, it would not be unreasonable to assume that there must be more innovative designs to rival this expensive solution. Such new solutions chiefly involve a critical analysis of the original French design. Specifically, a wall which is heavily reinforced and prestressed in two directions. In fact, this technical choice, which in some instances led to the presence of transverse cracking, maybe based on an improper approach to the use of prestressing. In historical terms, the technique of prestressing concrete was invented at start of the last century by the French engineer Eugène Freyssinet. In very broad terms, it involves removing tensile stresses within the structure by applying compression (due to the prestressing) in the part of the structure where these tensile stresses are very high (e.g. pillar, slab, segmental lining). These tensile stresses did not do the concrete any good, being the cause of the cracks. This technique allows for the construction of concrete structures with large spans (the span is the distance between two supporting points). In general, prestressing replaces all of the flexural rebars in the case of full prestressing or a large part of these rebars in the case of partial prestressing. What may be incorrect, in the case of French-style containment buildings, is the application of bidirectional prestressing on concrete which is already heavily reinforced in both directions! "If it isn't broke, don't fix it", as the saying goes. Is this the case for NPPVs?

A structure which is heavily reinforced in both directions is a composite structure with a high degree of mechanical heterogeneity. The Young's modulus of steels is five times higher than that of concrete. When concrete hardens (along with physical and chemical mechanisms), this mechanical heterogeneity causes the appearance of micro cracks close to the steel rebars. Applying bidirectional prestressing to this heterogeneous structure with micro cracks does not close up micro cracks but instead it propagates them: leading to longer and wider cracks. This leads to localized stresses, particularly since in practice the prestressing tendons cannot be perfectly aligned. Finally, it is worth pointing out that it is always difficult to correctly cast a structure in which passive reinforcement (rebars) and active reinforcement (prestressing) are intertwined. Even with self-compacting concrete, this issue can lead to weaknesses that the application of prestressing may turn into cracks. Furthermore, the pressurizing of the NPPV (a pressure of just over three bar may be applied to the enclosure, slightly higher than the pressure in a car tire), which may be cracked, can lead to transverse macro-cracks (by propagating existing cracks).

### What if prestressing was replaced with steel fibers?

Innovative designs, or designs which can be innovative, are based on doing away with prestressing in the internal wall of the NPPV. They draw on an acceptance of the potential existence of cracks which will be controlled so that they are never transverse. The only way to achieve this objective is to use fiber reinforced concrete and, more specifically, steel fiber reinforced concrete (SFRC). Used in combination with traditional reinforcements (rebars).

SFRC has been around for around 50 years. Today, it is very well-known and understood both technically and scientifically. In very broad terms, the fibers play the same role as traditional reinforcement rebars in reinforced concrete with regards to cracking but there are two main differences which distinguish them:

- The fibers are applied to the structure in the same way the other constituents of the concrete. They are part of the mix design of the material;
- The steel fibers are effective in preventing finer cracks than those which are controlled by the rebars. This means that steel fibers are more suitable than rebars for cracks relating to the in-service behavior of the structure.

Combining rebars and fibers therefore leads to a structure designed with multi-level reinforcement (in this case, with fibers and rebars) which is very effective in controlling cracking: from the smallest cracks to much wider ones. International literature shows that the mechanical behavior of fiber reinforced concrete with rebars is greater than that of ordinary reinforced concrete. On the other hand, the use of fibers (with a high percentage, as required in NPPVs) leads to a network of fine cracks which very often are not connected. This effect encourages the phenomenon of self-healing, over time, of the cracks which only happens for very fine cracks.

### Innovation incorporating the use of UHPFRC

The design and sizing of the internal wall of the fiber reinforced concrete (with rebars) NPPV instead of the prestressed reinforced concrete may represent the first stage of the innovation. The second innovation stage (building on the first stage) would be the use of structural ultra-high- performance fiber reinforced concrete (UHPFRC) "formwork". These cementitious composites are in vogue and over the last 20 years they have been used increasingly across the globe. These are fiber reinforced concretes which have much higher mechanical properties and increased durability compared with traditional fiber concretes. This is due to the very high compactness of the cement matrix and the use of a very high percentage of fibers.


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The use of structural formwork in UHPFRC provides three benefits:

- A notable reduction in construction times, as the formwork for the NPPV remains in place;
- A significant mechanical benefit, thanks to a structural formwork with increased mechanical properties;
- A significant increase in the durability of the wall, as the formwork acts as a "skin" which is very well sealed against the transfer of radioactive substances. To an extent, it also replaces the internal metal liner.

Of course, the suitability of these two potential innovation stages is still to be assessed. They represent an opportunity for implementing knowledge acquired in the technological research and development sector. It would be a shame not to assess their benefit for NPPV in social, economic and safety terms.




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