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INTERESTS OF CONCRETE FEASIBILITY STUDIES IN CONSTRUCTION PROJECTS OF EPR TYPE NUCLEAR POWER PLANT

Frédéric Coppel[1], François Lecornez[2], Guillaume Zammout[3], Etienne Gallitre[4]

[1] Senior Engineer, Materials for Civil Works Department, EDF-Ceidre/TEGG, Aix en Provence, France
[2] Senior Engineer, Materials for Civil Works Department, EDF-Ceidre/TEGG, Aix en Provence, France
[3] Senior Engineer, Civil Works laboratory, EDF-Ceidre/TEGG, Aix en Provence, France
[4] Senior Engineer, EDF-SEPTEN, Lyon, France

ABSTRACT

The construction of an EPR type nuclear power plant requires approximately 400 000 m3 of concrete. This includes ordinary concrete and more technical concrete like the High Performance Concrete (HPC) used for the inner containment.

Concrete for safety classified structures must meet high standards of performance and durability which are defined in the design and construction codes for these structures (ETC-C: EPR Technical Code for Civil Works). Concrete is made with local materials, following the requirements and practices of each country. It is also important to consider that the civil engineering works, and in particular the construction of the containment of the EPR, are on the critical path of the construction program.

In order to comply with the numerous requirements imposed and to better anticipate any future construction difficulties, EDF has developed an approach that includes performing feasibility studies for the most critical technical concretes, well in advance of the pour of the first concrete of the nuclear island. This approach is presented in this publication. These feasibility studies, carried out by EDF, serve several purposes:

- They demonstrate that local materials used to make concretes meet the numerous specified requirements,
- They enable project management to ensure that national practices are consistent with the requirements of the ETC-C.
- They serve as a reference point for technical exchanges between the National Nuclear Safety Authorities and EDF,
- They facilitate both the writing of contractual documents and technical exchanges with the bidders for civil works contracts.
- Finally, when the construction contractors develop their own concrete mixes, the feasibility study is a tool for dialogue, support and critical analysis of the contractor’s activities. This minimizes the risk of delays in the construction program.

The success of these feasibility studies begins with the identification of the most sensitive concretes and concludes with the analysis of results of laboratory tests. These tests ensure that the many requirements imposed on different concretes are achievable, although this can sometimes lead to having to find a compromise. The results of these studies may lead to tailored solutions either in the design phase or in the construction phase.

In conclusion, the concrete feasibility studies, carried out by EDF, permit critically important concrete to be identified and developed to ensure its in-service performance, casting and availability under the construction program.

INTRODUCTION

The safety requirements for the civil structures on an EPR type nuclear power plant are defined in the design. These requirements reflect two main design evolutions with respect to the previous generation of nuclear reactors: a reduction in the probability of core fusion and a limitation of the radiological consequences in the event of an accident.

The civil structures fulfil two safety functions: protection of the nuclear installation against all possible hazards (in particular for external hazards, the impact of a commercial aircraft) and protection of the environment in the case of an accident (considering in particular the most serious possible accident situations). These evolutions have had consequences for the design and an impact on the required performance of the materials used in the design.

In addition, the current economic environment has lead to an increase in the proposed operating life of the reactors, meaning the meeting of requirements must now be guaranteed for an operating life of at least 60 years. The concrete to be used is therefore affected by both the safety requirements for performance and for durability.

The civil engineering works, and in particular the construction of the inner containment, are on the critical path of the construction program. The construction program's first milestone is usually linked to the pouring of the first concrete for the raft foundation of the nuclear island. There are several sensitive aspects to defining and developing these concretes both in terms of their expected performance and their ability to fit with the prescribed deadlines.

To this is added the fact that the majority of concretes used are materials produced on site, from local resources and according to local practices and the standards of the host country.

In order to comply with the numerous requirements imposed and to better anticipate future construction difficulties, EDF, as a project manager and owner, has developed an approach that includes performing feasibility studies for the most critical technical concretes, well in advance of the pour of the first concrete for the nuclear island.

After a reminder of the principal design characteristics of concretes for an EPR type nuclear power plant, this publication will cover:

- The purpose of the feasibility studies,
- Guidelines for carrying out feasibility studies, and
- An example of their use for the UK EPR construction project.

A REMINDER OF THE DESIGN CARACTERISTICS AND SPECIFICATIONS FOR THE CONCRETES USED FOR AN EPR

A reminder of the design

Some of the characteristics of the different French PWR reactors are listed below to illustrate the evolutions in design:

Table 1: Reminder of the characteristics of the different French PWR reactors

		900 MWe CP0	900 MWe CP1/CP2	1300 MWe P4	1300 MWe P'4	1400 MWe N4	1600 MWe EPR
Start of Commercial operation		1978-80	1980-87	1985-87	1987-94	2000-02	-
Inner containment	Thickness (m)	0.85	0.90	0.90	1.20	1.20	1.30
	Free volume of containment (m^3)	47356	51350	81440	70437	72700	~80000
	$fc28_{cyl}$ (MPa)	40	40	40	40	40	60
External containment	Thickness (m)	-	-	0.55	0.55	0.55	1.80/1.30*
	$fc28_{cyl}$ (MPa)	-	-	40	40	40	45
Raft	Diameter (m)	38.70	38.80	51.9	50.9	50.9	55.6
	Thickness (m)	1.00	4.50	~3	~3	~3	4,00
	$fc28_{cyl}$ (MPa)	40	<40	40	40	40	40
Proposed operating life (years)		40	40	40	40	40	60

(*) 1.80 m for the planar portions and 1.30 m for the curved portions

The design evolutions (increase in power output, reassessment of possible accidents and external hazards) have lead to an increase in the thicknesses of containment walls and an increase in the mechanical strength of the concretes used. The density of reinforcement has also greatly increased, which has significantly influenced the methods used to lay the concrete and has necessitated the adjustment of the concrete workability (increase in fluidity, reduction in the maximum aggregate size).

Current construction methods favour single pours of concrete in order to avoid construction joints (note: the common raft o the Taïshan EPR was achieved in a single pour of 10 000m3.). This can lead to problems with the exothermic characteristics and concrete formulae must be adapted and optimised for this use, in order to avoid premature thermal cracking and the problem of delayed ettringite formation (DEF).

In the past, the highest performance concretes had a compressive strength (cylinder) of 36 MPa at 28 days; these were relatively high performing in the 1980s. For the EPR, High Performance Concrete with C60/75 compressive strength is used. The principal reason for the increased concrete strength for the EPR is to improve the shear strength of the structure, particularly with a view to protection against beyond design basis events and thermal overload (severe accident conditions). It has little impact on the compression capacity as the stability of the structure is provided by a network of walls in both directions

The PWR power stations, before the EPR, were designed for an operational lifetime of 40 years, today this lifetime as been significantly increased (60 years of operation).

At the time of construction of the 900MWe power stations, certain concrete disorders were not understood or understood badly. The growth of understanding in this area has indicated the necessity for testing, sometimes long term tests, and these must be anticipated in order that they can remain compatible with the program.

The superposition of numerous and sometimes contradictory requirements (for example: high strength and low heat of hydration) requires the development of formulas that will provide the best compromise.

Concrete specification

The construction of an EPR type Nuclear Power Plant requires around 400 000 m3 of concrete. This volume includes both conventional concretes and more developed concretes, like High Performance Concretes (HPC), used for the inner containment and the turbo-alternator platform.

Concretes with a strength class greater than 35 MPa (C35/45) and especially HPC (C60/75) also have restrictive specifications for their constituents (for example: restrictions on the use of Silica Fumes for inner containment concrete) and on the expected results.

The specifications for the concretes (see table 2) are:

- Mechanical performance
    - Compressive strength
    - Tensile strength
    - Static modulus of elasticity
- Durability of performance related to:
    - Delayed deformations (shrinkage and creep)
    - Transfer properties of concrete (porosity, permeability limiting external chemical attack
    - The absence of phenomena leading to swelling (alkali aggregate reactions and internal sulphate attack)
- Control of heat release in mass concrete in order to avoid cracking during cooling
- Necessary workability in order to allow easy concreting over long periods sufficient for concreting large volumes (2 layers of 5000 m3 for the raft foundation of the EPR at Flamanville).

These specifications should be respected by both the nominal and derived formulas (the derived formula is the nominal formula with proportions of the different constituents modified to simulate weighing differences at the concrete batching plant)

Table 2: Summary of structural concretes for an EPR

Structure	Concrete Class	Constraints	Volume in m^3
Inner containment	C60/75	Strong prestressing Small deformations over the life time Significant reinforcement in particular zones (equipment hatch, bracket)	13400
Turbo alternator platform	C60/75	Mechanical stresses and vibrations Requires increased strength and module of elasticity Concreting in a single pour	2500
External containment	C45/55	Air tightness Strength	19000
Aircraft Protection Shell	C45/55	Significant reinforcement in particular zones: opportunity for a micro concrete or a self compacting concrete? Aircraft impact stresses	29000
Common raft	C40/50	Limit the number of construction joints	28150

Internal structure of the reactor building, Electrical building, Fuel building, Safeguard building	C40/50	Anchoring of safety classified material	16700 35700 16050 13460
Pumping station and outfall structures	C40/50	Actions of sea water on the structures Aircraft impact stresses Certain particular structures in C60/75	68000
Diesels infrastructure Effluent treatment building Underground outfall gallery	C35/45	Water permeability	6800 11000 16000

Figure 1. View of the EPR building site at Flamanville 3 (December 2009)

THE PURPOSE OF THE FEASIBILITY STUDIES

The concrete feasibility studies carried out for the EPR projects, undertaken at the initiative of EDF, owner and project manager, should allow the identification and secure the development of concretes which are sensitive either in terms of their required performance, or the methods of their implementation, and ensure their availability with respect to the construction schedule.

Nevertheless, the quality of the concretes on site remains the responsibility of the contractor charged with their production. The Contractor remains free to make their own industrial choices in order to meet the requirements defined by EDF.

These feasibility studies should be started relatively early in the program in order that they can be used to benefit the different stages of the project.

The diagram below shows the optimal position for the concrete feasibility studies in the program for an EPR

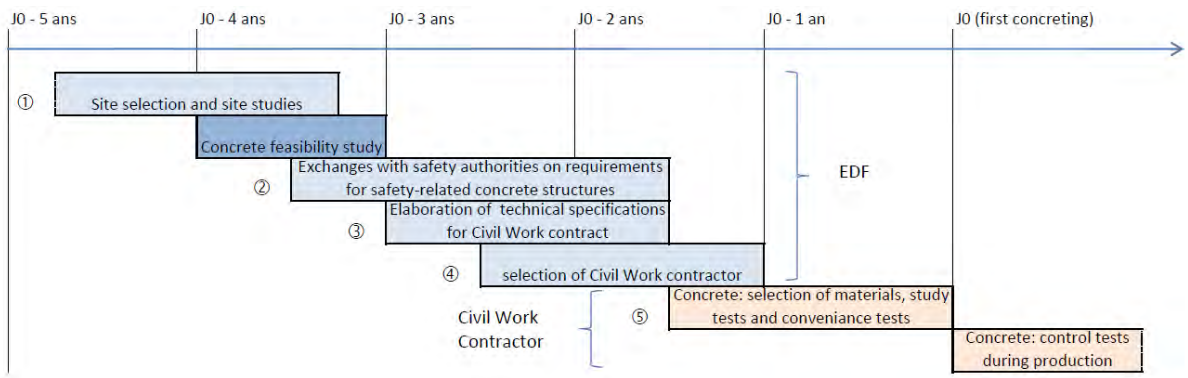

Figure 2. Optimal position for the concrete feasibility studies in the program for an EPR

① During the site selection phase, the concrete feasibility studies provide, early on, information on the materials potentially available near the site (principally aggregates). As concretes are produced with site specific constituents, it is therefore necessary to verify that the performance necessary for the design is attainable with the materials available: these therefore need to be tested well in advance, and be available in sufficient quantities

② The national nuclear safety authorities may have particular requirements that may impact the formulation and production of concretes. These requirements are generally reproduced from national documents but it should be ensured that these are compatible with the civil engineering code specific to the nuclear reactor concerned (ETC-C for the EPR). There may be therefore, an investigation phase to compare the different national requirements and the contents of the nuclear code for Civil Work in order to establish a required performance.

This harmonising phase can lead to the rewriting of the civil engineering code for each host country.

In this phase the concrete feasibility studies help to ensure that the national standards are compatible with the design and proposed construction methods for the nuclear power plant.

These studies also enable the contractor and owner to get a clear view of the local industrial reality and anticipate potential problems with the national safety authorities and with the contract specifications.

③ The results and lessons learned during the concrete feasibility studies facilitate and assist with the writing of the technical requirements in the civil work contracts.

The Civil Work contractor is required to develop a concrete formula that takes into account:

- The local constituent available near the sites (the investigation of local quarries needs to be carried out very early on)
- The National and International standards, specific to each contract
- The exposure classes that the concretes will be subjected to as a result of the site locations (especially for concretes in contact with soil or water)

- The reinforcement densities
- The specific requirements which are not current industrial practice
- The requirements of the local nuclear safety authority

In addition, durability justifications can be carried out and can lead to the necessity for long term performance tests (1 year or more once the concrete formula is established). These tests are necessary, in certain cases, in order to inform decisions on:

- The absence of risk of internal swelling
- The creep characteristics of the prestressed concrete, taken into account during the design phase.

④ In the contractor selection phase, information obtained through the feasibility study helps the project manager to better understand the technical proposals submitted by the bidders. The results of the studies allow for a critical appraisal of the offers.

In addition, the feasibility studies enable the sensitisation of the bidders to specific problems posed by the concretes for the EPR (large volumes of concrete cast in a single pour, exothermic characteristics, durability...). They also provide an indication of the high level of quality expected and EDF’s involvement.

The studies also give the bidders, if necessary, an insight into the formulation of technical concretes in a regional context.

⑤ Finally, in the contract implementation phase and particularly at the start when the contractor is developing their own concrete formulas, the feasibility study is a tool for dialogue and helps to minimise the risk of delays to the construction schedule. In reality, the contractor does not have a lot of time to develop their own formulas and EDF is able to guide and accompany them in this step.

GUIDELINES FOR FEASIBILITY STUDIES

Identification of sensitive concretes

The different concretes used for construction of most of the structures and buildings of an EPR are presented in table 2 (taken from the EPR at Flamanville 3, France). An inventory of all the concretes must be carried out first in order to ensure that the scope of the feasibility study takes into account the most sensitive concretes.

In order to define the sensitivity of concretes the following elements should be taken into account:

- The technical requirements (performance, concreting method, volume of pour)
- The scheduling of the first concreting (to secure the timing of the different steps)
- The local practices in the field of high performance concretes (for example where no local companies produce HPCs)
- The aggressive character of the environment to which the concrete will be exposed (for example: the existence of large concentrations of sulphates in the soils).

Inventory of locally available concrete constituents

Investigations should be undertaken to establish the list of available materials for producing concrete. These investigations should highlight the local specificities. These investigations should help to ensure the quality (in respect to the requirements of the Civil engineering code) and the quantity (volumes of concrete required) of materials available for use. They concern therefore:

- The aggregates (distance from the nuclear site, size of the quarry, characteristics of the aggregates, homogeneity of the deposit, quality of the facility)
- The cements (nature, physicochemical characteristics, regularity of production...)
- The additions (availability of siliceous fly ash, blast furnace slag, silica fume...)
- The admixtures (properties, performance).

Testing program and laboratory production of concretes

In order to understand and become familiar with the local formulation and implementation practices, it is preferable to carry out the feasibility studies in the country concerned. In order to understand the differences, inter-comparison tests can be performed to compare the operating practices for local testing and those cited in the original civil engineering code.

The results of these studies can lead to the adaption of either the design solutions or the implementation solutions.

The requirements of the code and the contract concerning concretes judged to be sensitive should be checked by a laboratory, to ensure:

- Sufficient mechanical strength
- Rheology and working time are compatible with long concreting times, high densities of reinforcements and pumping over long distances.
- Satisfactory durability (transfer properties, durability of reinforcements and absence of internal swelling reaction)
- Suitable exothermic characteristics at setting in order to limit cracking and disorders linked to internal sulphate reactions

The tests help to ensure that the numerous requirements for the different concretes are attainable but they can also sometimes lead to a need for compromise. This is the most difficult phase of the feasibility studies.

The sensitivity of the formulas can also be tested by simulating dosage uncertainty during future on site fabrication.

The concretes should also be formulated with the view to making them pump-able

Creep tests can be carried out to verify the acceptability of the deformation behaviour of the HPC used for the inner containment.

Finally, the studies can provide an opportunity to develop innovative concretes (for example self compacting concretes) and new performantial approaches, these can be expected to develop significantly in the coming years and bidders will certainly be led to propose them, if the countries standards permit it.

Advanced planning of test accommodates cases where there is a need to carry out long term testing (longer than 1 year): absence of internal swelling reactions (Alkali aggregate reaction or internal sulphate reaction), creep.

AN EXAMPLE OF THE APPLICATION OF CONCRETE FEASIBILITY STUDIES

For the EPR project at Hinkley Point in the UK, EDF carried out the principle concrete feasibility studies very early on.

The studies were carried out in the UK by British laboratories. They identified, amongst other things, the following points

- With respect to the concrete constituents :

Constituent	Observations
Aggregates	- Some quarries able to supply the site were identified, taking into account the volumes of concretes to be produced - Intrinsic characteristics were relatively similar for aggregates from different quarries (local geology) - Characteristics of production varied (cleanliness, regularity of aggregates) - Aggregates susceptible to alkali-carbonate reaction (thaumasite) - Use of marine aggregates (fine aggregates)
Cements	- Few composite cements, mainly CEM I - The CEM Is all had relatively similar physiochemical characteristics - Percentage contents of C_3A and Na_2O_{eq} were relatively high
Additions	- Heavy use of fly ash (and the existence of a category S “superfine”) - Delivery of silica fume in a slurry and not in powder form

- With respect to the concrete: there are no freeze/thaw tests on the concrete and the practices for minimising the risks of Alkali-aggregate reaction and internal sulphate reactions are considerably different from the French practices. The formulation methods are different.

The concretes formulated during the feasibility studies were those for the inner containment, the airplane resistant shell and the common raft. These concretes were selected on account of their technical complexity, their large volumes and their proposed construction dates.

The programme of tests carried out in the UK was supplemented by tests subsequently carried out in France. This second series of tests were intended to:

- Verify the results of the tests carried out by the British laboratories (comparison and inspection for quality assurance)
- Optimise certain formulas, especially aspects pertaining to rheology and exothermic characteristics.
- Complete tests according to French operating practices (i.e. carry out tests which do not exist in the UK).

The results of these studies where used in different stages of the project

- During discussions with the British Safety Authorities
  - The exothermic characteristics of the concrete (prevention of internal sulphate interaction)
  - The approach to alkali-aggregate reaction
- During the writing of technical part of the contract. This took into account, for example :
  - The statistical monitoring of aggregate production
  - The chemistry of the cements

- During discussions with bidders:
  - Critical opinions of certain proposed quarries and of the post treatment of marine aggregates (washing)
  - Opinions on certain concrete formulas proposed by the bidders at the stage of the tender.

CONCLUSION

Concrete feasibility studies are carried out for big construction projects for which EDF is both owner and project manager.

Concretes with a strength class higher than 35 MPa (C35/45) and in particular HPC (C60/75) have restrictive specifications on both their constituents and their expected test results.

The feasibility studies are a process initiated by the owner and project manager which enables them to detect problems and direct the choice of the solutions to these problems

The studies provide interesting, if not indispensible information to the project manager for:

- Identifying the sensitive technical points
- Discussions with the safety authorities, the bidders and contractors
- Judging the quality of bids

In conclusion, the concrete feasibility studies for the EPR projects support the success of the project from a technical, a programming and a financial point of view.