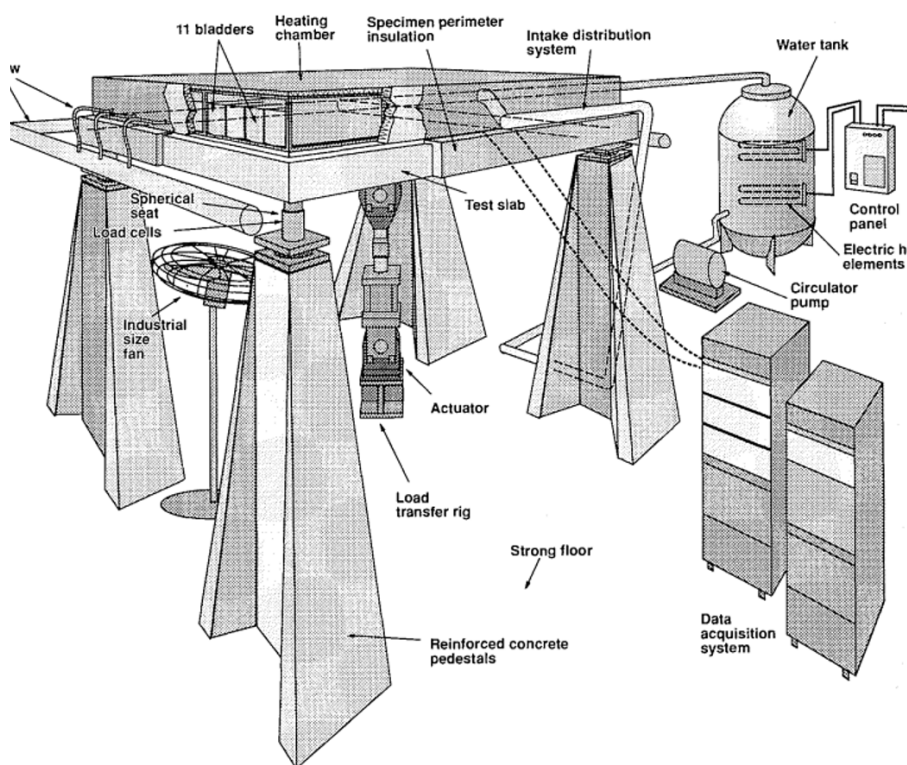
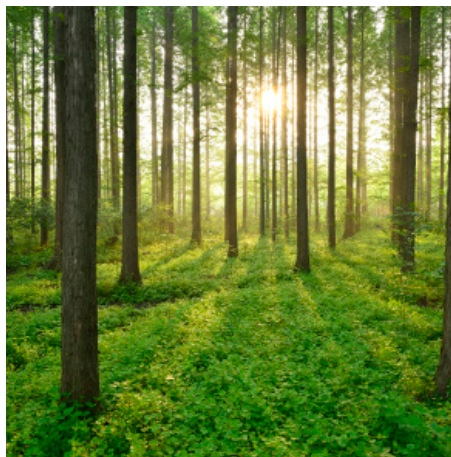


TEMPERATURE INFLUENCE ON THE CONCRETE IN THE SPENT FUEL POOLS

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Foreword

A nuclear power plant consists of a large number of concrete structures that are important both from a safety and operational perspective, e.g. the fuel pools. Used fuel is stored in the fuel pools for cooling before further transport to the intermediate storage.

This report summarizes the state of knowledge regarding large temperature gradients and their effects on the concrete structures in the fuel pools at nuclear power plants and present proposals for possible future research and development projects within the area.

The survey was carried out by Cenk Tort and a team from AFRY, Finland. The study was conducted among the experts working in nuclear power plants and nuclear waste storage facilities in Sweden and Finland.

The Nuclear Power Concrete Technology program is a part of the Energiforsk nuclear portfolio, financed by Vattenfall, Uniper, Fortum, TVO, Skellefteå Kraft and Karlstads Energi. In addition, the program is financed by Swedish Radiation Safety Authority (SSM) and SKB (Svensk Kärnbränslehantering AB).

These are the results and conclusions of a project, which is part of a research programme run by Energiforsk. The author/authors are responsible for the content.

Summary

In nuclear plants, spent fuel rods are kept inside storage pools before they are moved to their intermediate storage location. The pools are reinforced concrete type wall structures. Despite their reduced radioactivity, the spent fuel rods continue to release energy and heat the water in the pools. There often exists a cooling system to prevent uncontrolled increase of the temperature. However, there may be incidents where the water temperature can reach to moderate or even high levels beyond boiling point.

The temperature variation inside the pools results in a temperature gradient over the walls of the pools, which may lead to formation of through cracks and may even cause leakage through these cracks. The increased temperature also affects the strength and stiffness properties of concrete. Therefore, while designing or evaluating the safety of spent fuel pools, cracking of concrete due to thermal loads should be taken into account.

This study aims at identifying research needs for better evaluation of thermal stresses in design of spent fuel pool structures. A survey study was conducted among the experts working in nuclear power plants and nuclear waste storage facilities in Sweden and Finland. In this survey, critical information about the spent fuel pools, effect of thermal gradients, measures or studies to remedy the effect of thermal cracking in concrete was compiled. The details about findings of the survey study and literature review are presented in this report. Key areas of further research were detected as outlined below for spent-fuel pool structures:

- Design temperatures
- Selection of tightness class
- Effects of thermal cracking and thermal creep on structural behavior

Keywords

Thermal cracking, spent fuel pool, steel liner, leakage, temperature effects

Sammanfattning

I kärnkraftverk förvaras använda bränslestavar i bassänger innan de flyttas till mellanlagringen. Poolerna är konstruktioner av armerad betong.

Trots den minskade radioaktiviteten fortsätter de använda bränslestavarna att frigöra energi och värma upp vattnet i bassängerna. Det finns ofta ett kylsystem för att förhindra okontrollerad temperaturhöjning. Det kan dock förekomma händelser där vattentemperaturen kan nå måttliga eller till och med höga nivåer över kokpunkten. Temperaturvariationen inuti bassängerna resulterar i en temperaturgradient över bassängernas väggar, vilket kan leda till bildning av genomgående sprickor och till och med orsaka läckage genom dessa sprickor. Den ökade temperaturen påverkar även betongens hållfasthets- och styvhetssegenskaper. Därför bör sprickbildning i betong på grund av termiska belastningar beaktas vid utformning eller utvärdering av säkerheten hos pooler med använt bränsle.

Denna studie syftar till att identifiera forskningsbehov för bättre utvärdering av termiska spänningar vid design av bassänger för använt bränsle. En enkätstudie genomfördes bland experter som arbetar på kärnkraftverk och kärnavfallslagrar i Sverige och Finland. I denna kartläggning har kritisk information om använt bränslebassänger, effekt av värmegradienter, åtgärder eller studier för att åtgärda effekten av termisk sprickbildning i betong sammanställts. Detaljerna om resultaten av enkätstudien och litteraturöversikten presenteras i denna rapport.

Följande nyckelområden för ytterligare forskning identifierades för bassänger för använt bränsle:

- Designtemperaturer
- Val av täthetsklass
- Effekter av termisk sprickbildning och termisk krypning på strukturellt beteende

List of content

1	INTRODUCTION	7
2	SCOPE	9
2.1	Summary of the investigations	9
2.2	Literature Study	9
2.3	Recommendations	9
3	INTERVIEW MEETINGS	10
3.1	Information about existing pool structures	10
3.2	Information about past investigations and design:	14
3.3	Need for further study and concerns:	15
4	LITERATURE SURVEY	17
4.1	Propagation of concrete cracking under temperature variation	17
4.2	LINER ANALYSIS	23
4.3	CONCRETE STRENGTH AND STIFFNESS AT MODERATE TEMPERATURES	24
4.4	SELECTION OF TIGHTNESS CLASS	28
5	RESEARCH AND DEVELOPMENT IDEAS	30
6	CONCLUSION	31
7	REFERENCES	32
Appendix A:	Questionnaire	34
	Information about existing pool structures:	34
	Information about past investigations and design:	34
	Need for further study and concerns:	34

1 INTRODUCTION

The dependency on fossil fuels has been questioned in the recent years by the law makers due to unreliable sources and environmental concerns. Despite its high initial cost and operation expenses, nuclear energy has been proven to be stable and efficient source of energy, where it constitutes about 10 % of the world's electricity from about 440 power reactors [11]. The share of nuclear energy for Sweden and Finland is about 50 % and 33 %, respectively [11]. Development of safe waste management systems, the diversity of fuel resources, high capacity factor of the plants is among the key advantages that led several governments to develop policies for promoting construction of new nuclear plants and upgrade the existing ones. The big global thrust in nuclear energy is to be supported by new technologies to ensure the safety of the nuclear plants. The safety nuclear plants consist of three main functions as outlined below [13]:

- To control reactivity.
- To cool the fuel.
- To contain radioactive substances

In this respect, the structural integrity and tightness of the spent fuel pools is critical for nuclear plants to contain radioactive substances. The spent fuel pools are reinforced concrete structures where used radioactive rods are placed and stored until they decay further so that they can be transported to the next level of waste storage. In nuclear power plants, there often exist several spent fuel pools. The location of the pools varies according to the type of reactors. In the case of boiling water reactors (BWR), the spent fuel pools are placed right above the containment and outside of it. However, structurally they are part of the containment. On the other hand, for pressurized water reactors (PWR), the spent fuel pools are also outside of the containment, but they are located in a separate building. However, there are pools inside the containment of PWR type reactors as well for short term storage or for other miscellaneous purposes (e.g., IRWST). It is also possible that plants with BWR type reactors also have separate spent fuel buildings with additional pools for later stages of storage. The main challenges in the design of the spent fuel pools are to ensure radiation shielding and the tightness. The radiation shielding is provided through filling the pools with water and constructing thick wall structures. On the other hand, for tightness, the inner surface of the pools is covered by stainless steel liner and in some cases pre-stressed steel tendons existing inside the walls contribute to the tightness as well. A leak detection system embedded inside the walls is also common. Despite all these measures, there still exists a risk of leakage through the walls of the pools due to thermal cracking in concrete.

Nuclear energy is created through fission reaction taking place under water. The generated heat is used to generate steam where electricity is produced when the

steam is transferred to the turbine. Once nuclear fuel decays and is consumed, it is transported to the spent fuel pools available in the power plants. In these pools, the spent fuel is stored until it cools down and ready for long term storage. Under normal conditions the temperature inside the pools stays quite moderate up to 50 °C maximum. However, during new fuel transport or maintenance shutdown of the reactor, it is possible the temperature of coolant water may reach to extreme levels up to 93 °C. In the case of accidents when cooling is lost, the water in the pools may start boiling. In PWR type reactors, for the short-term storage pools located inside the containment, significant overpressure can develop and boiling point may reach up to 132 °C.

The temperature fluctuations of the coolant over the lifetime of the pools generates a heat gradient between the outside and inside surfaces of the pools. The heat gradient investigated in this work does not happen instantaneously due to large thickness of the concrete walls. It takes days to reach a steady state. The effect of this heat gradient and also increased temperatures on the pool structures will be investigated in this study. Main emphasis would be the temperatures and heat gradients attained under extreme and accidental cases. The current state of the art on the topic will be reviewed and the areas that need further research will be identified.

2 SCOPE

The scope of this study consists of the following items:

2.1 SUMMARY OF THE INVESTIGATIONS

Effect of thermal heat gradient and temperatures on the spent fuel structures are discussed through interviews with representatives from Swedish and Finnish Power Plants as well as from SKB. The principles employed in the original designs, recent works on the topic and future trends are discussed and recorded. The objective is to understand how the existing pools in the plants perform against thermal effects, to detect any problems or any required investigation related to the topic.

2.2 LITERATURE STUDY

The results from the interview meetings are compiled into the report. The results are also evaluated for the issues that needs further study and development. A literature survey is conducted on the selected topics. The summary of principles and findings of the relevant international publications are summarized.

2.3 RECOMMENDATIONS

The findings of the literature survey are presented and areas that still require more investigation are noted.

3 INTERVIEW MEETINGS

Thermal gradient in spent fuel pools is an issue that is observed in all power plants of Sweden and Finland. Despite there exist similarities between the design of the plants, different approaches are available on how to design for thermal gradient. The construction times of the plants are different. Therefore, both analysis technologies and adopted design specifications show quite a variation. It was decided to perform individual interview meetings with the representatives from the power plants and nuclear waste storage facilities to discuss about thermal cracking and about its implications for both design and operation. Before conducting the interview meetings, a survey was sent out to all participants and it was requested to be filled out. The survey questions can be found in Appendix A. The participants joined the meeting and completed the questionnaire are from the institutions that are listed below:

- Forsmark – Vattenfall - Sweden
- Oskarshamn – OKG Aktiebolag - Sweden
- Ringhals – Vattenfall – Sweden
- CLAB - SKB - Sweden
- Olkiluoto – TVO - Finland
- Loviisa – Fortum - Finland

The questionnaire consists of different parts with respect to the type of information that is requested. The results from each section of the questionnaire are summarized.

3.1 INFORMATION ABOUT EXISTING POOL STRUCTURES

This section of the questionnaire is developed to document the quantity and geometric properties of the pool structures. This includes the number and location of the pools and well as wall thicknesses, depths and plan dimensions. Information about leak detection system, insulation details and reinforcement type of the pools are also requested.

The inner surfaces of the pools often have a higher temperature compared to outer surfaces. This results in high thermal loads on the concrete walls. The type of reactors available in Sweden and Finland are summarized in Table 1.

Table 1 Reactor type of power plants in Sweden and Finland

Plant	Location	Type / Reactor(s)
Forsmark	Sweden	BWR / F1, F2, F3
Oskarshamn	Sweden	BWR / O3
Ringhals	Sweden	PWR / R3, R4
Olkiluoto	Finland	BWR / OL1, OL2, PWR / OL3
Loviisa	Finland	PWR / LO1, LO2

Spent fuel pool structures contain set of wall elements and usually there exist multiple units surrounded by internal and external walls. Each unit is separated from each other by gates and in these units fuel rods are stored at the bottom. It is common that the external walls and pool bottom are thicker compared to internal walls. The design for the thickness of the walls is not only governed by design loads but also by radiation shielding. Therefore, any structural optimization for wall thicknesses is not critical. In Table 2, the common wall thicknesses are reported for the spent fuel pools. It can be seen that the thicknesses range from 1 m to 2 m. In Table 3, the depths of the spent fuel pools are documented. The common depth of the pools where fuel rods are stored for long duration is 11-12 m. For transfer pools and channels, the depth is usually around 7 m.

Table 2 Wall thicknesses of spent fuel pools

Power plant	Wall Thicknesses ¹ (mm)
OLKILUOTO ²	1000 - 1600
LOVIISA ³	(300) ⁴ 1000 - 1500
SKB-CLAB	1500 - 1700
FORSMARK ⁵	1000 - 1600
RINGHALS ⁶	1800 - 2000
OSKARHAMN ⁷	1300 - 1600

¹ Wall thicknesses are provided for ranges defined by minimum and maximum values covering both side walls and pools bottom

² The thicknesses are from the units OL1, OL2, OL3, and KPA

³ The thicknesses are from KPA1, KPA2 building, LO1, and LO2

⁴ The thickness is for the wall between the pools in LO1, and LO2

⁵ The thicknesses are from the units F1, F2, and F3

⁶ The thicknesses are from fuel buildings of units R3 and R4

⁷ The thicknesses are from the unit O3

Table 3 Depth of spent fuel pools

Power plant	Depth of Pools ¹ (m)
OLKILUOTO ²	7,0 – 13,5
LOVIISA ³	12,0 – 14,5
SKB-CLAB	13,0
FORSMARK ⁴	9,5 – 14,0
RINGHALS ⁵	12,5
OSKARHAMN ⁶	7,0 – 12,0

¹ The pool depths are provided for ranges defined by minimum and maximum values

² The pool depths are from the units OL1, OL2, OL3, and KPA

³ The pool depths are from KPA building

⁴ The pool depths are from the units F1, F2, and F3

⁵ The pool depths are from fuel buildings of units R3 and R4

⁶ The pool depths are from the unit O3

The plan dimensions of the pools show a significant variation usually governed by the capacity of the plant and also number of pools.

In all of the aforementioned power plants, the interior surfaces of the pools are covered by a stainless-steel liner usually 3-4 mm in thickness. The plates are installed in rectangular pieces and welded together into embedded steel profiles inside the pool wall. The welds between the steel plate and embedded profiles are either groove welds or fillet welds. A typical connection detail can be seen in Figure 1. The embedded profile is often an angle profile or a channel profile with an anchoring device welded into it. The typical material grades of the steel liner are given below:

- AISI 304 L
- SIS2343
- SS2333
- SS2348
- EN 1.4307

The steel liner is designed as the primary barrier. Therefore, the possible leakage from the pools is only possible through the welded connection between the plates and the embedded profile. For detection of any leakage and collection of the leaked water, a leak detection system is placed inside the walls. This system is existent in all the power plants and in interim storage facilities. It is constructed by installing a

channel on both sides of the embedded profile. The performance of the leak detection system is often satisfactory. However, for the pools having boric acid admixture inside the water, in some of the facilities, clogging of the boric acid was observed inside the leak detection system.

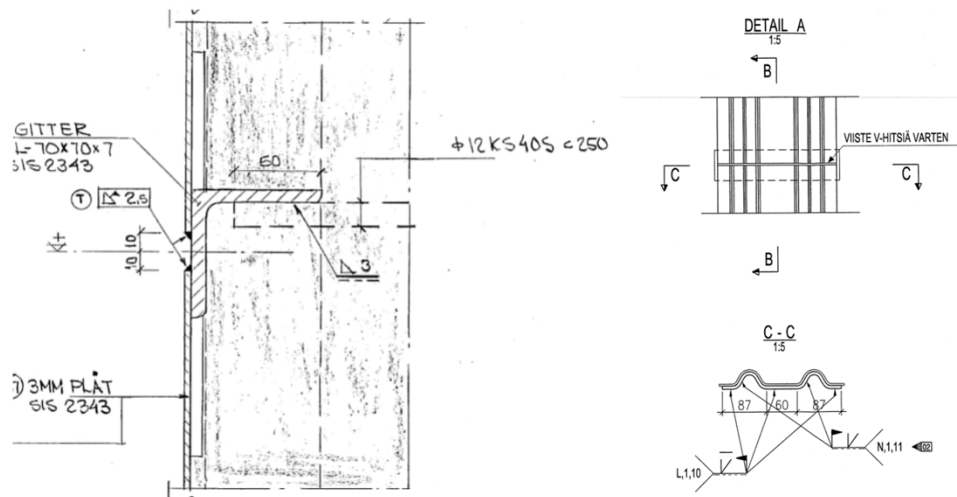


Figure 1 Connection detail between steel linear and concrete wall

Introducing horizontal pre-tensioning to the pool walls is commonly utilized in BWR type reactors and this also contributes to the tightness. For these reactors, the pre-stressing from the containment also extend to the pool walls in the vertical direction. Typical prestressing strands in the pool walls can be seen in Figure 2.

The main reinforcement of the pools structure is always ribbed. Nonconventional rebar sizes are not used and maximum rebar diameter is found to be 32 mm.

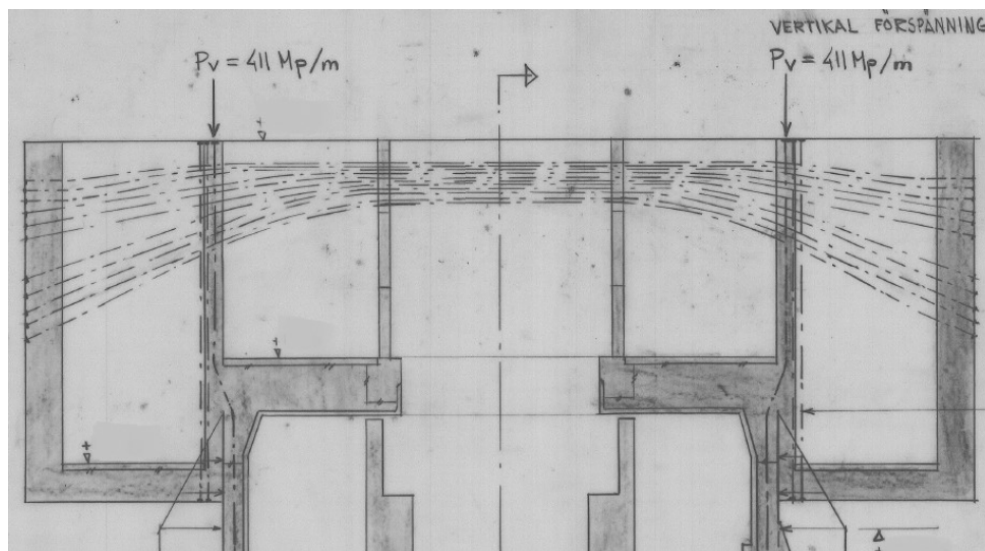


Figure 2 Prestressing strands of spent fuel pools

3.2 INFORMATION ABOUT PAST INVESTIGATIONS AND DESIGN:

Principles of original design for thermal cracking is requested from the project participants. This information is critical to assess what methods were utilized in the past and how these methods can be compared to the current practice. It will also shed light to the performance of the pools with respect to thermal cracking and provide insights for future work and studies. In this part of the questionnaire, it is also asked to provide information related to critical design parameters in the original design such as crack width limitations and design temperatures.

The design temperatures are asked for 3 different stages including normal, exceptional and accidental conditions. The summary of the temperatures can be seen from Table 4. There exists quite a variation for design values for exceptional and accidental cases. The majority of the plants considered an accidental case when water in the pools starts boiling. The accidental case is often studied after the Fukushima incident. 3D finite element models of the pools were developed using solid elements. In these models, cracking in the concrete was observed but structural integrity of the pool was maintained. Therefore, safety of the pools was verified. In the majority of the power plants, both original design and later studies took into account the reduction in concrete material properties due to temperature increase. The most common approach that is reported is reducing the stiffness of the concrete section. For some of the plants, 50 % of stiffness reduction is noted. In the design of the pools, the steel liner is the primary barrier for leakage. The stresses in the steel reinforcement were also found to be limited and steel linear was expected to prevent any leakage even in accidental cases. However, for some of the power plants, crack width limitations ranging from 0,1 mm to 0,4 mm were provided. The crack width limitations can be intended to prevent leakage, but in some cases the limitations were given just to prevent corrosion. The design for spent fuel pools wall thicknesses was governed by radiation shielding as well as design loads. High utilization ratio of the walls under accidental load cases were also observed. There is not much room for structural optimization to design for thinner walls.

Table 4 Temperature loads for Swedish and Finnish power plants

Power Plant	Unit	Normal (°C)	Exceptional (°C)	Accidental (°C)
OLKILUOTO	OL1,OL2	30	40	60
	OL3 (IRWST)	42	-	130
	OL3 (Fuel Building)	45	70	100
	KPA	50	-	100
LOVIISA	LO KPA	50	65	132
SKB	CLAB	35	60	100
FORSMARK	F1, F2, F3	40	60	100-120
RINGHALS	Fuel Buildings of R3 and R4	50	93	100
OSKARHAMN	O3	40	60	100

3.3 NEED FOR FURTHER STUDY AND CONCERNS

The majority of the power plants in Sweden and Finland have been in operation for decades. A vast amount of information and experience has been gained with respect to the performance of the spent fuel pools. In this part of the questionnaire, the intent is to determine what type of improvements are needed to address thermal cracking in concrete. It is also questioned for any desired functional requirements of the pools related to thermal gradient.

For liquid retaining structures, degree of leakage protection is a major design decision to be considered. The allowable cracking is dependent on the degree of leakage that is targeted. Liquid retaining structures are covered by EN 1992-3, the following leakage classes are available as given in Table 5.

Table 5 Classification of tightness (EN 1992-3)

Tightness Class	Requirement for leakage
0	Some degree of leakage acceptable, or leakage of liquids irrelevant
1	Leakage to be limited to a small amount. Some surface staining or damp patches acceptable
2	Leakage to be minimal. Appearance not to be impaired by staining
3	No leakage permitted

Tightness Class 0 structures, EN1992-1-1 Cl 7.3.1 may be followed using recommendations for buildings. Class 0 structures would refer to structures storing dry materials such as silos, thus this class would not apply to a water retaining structure. In Tightness Class 1 structures some leakage may occur, the allowable crack width ranges between 0,05 mm to 0,2 mm depending on height of water.

During the interview meetings, it is asked for the assumed tightness class of the spent fuel pool structures. The preferred tightness class is either 1 or 2. For spent fuel pools at their outer face, damp patches are not desired. For some of the representatives, the selection of tightness class is raised as a further research topic.

For spent fuel pools, it is common that some equipment is installed for operational purposes including service bridges, gates or railings. It is noted that during accidental case none of the attached equipment are required to be used. However, they are expected to be operation in exceptional cases. In exceptional loading cases, the displacements often do not reach to the levels that will harm the attached equipment of spent fuel pools.

The spent fuel pools are expected to have larger clear cover to protect the reinforcement from corrosion and to accommodate the support profiles for liner and grooves for leak detection system. From the available drawings of spent fuel pools, the largest clear cover is reported to be 90 mm, but 50 mm and 70 mm clear covers are also common. Usually, the inner surface of the pools has larger clear cover. No nonconventional rebar sizes are used.

One of the critical questions responded by the power plant representatives is the areas that need further research and development for better evaluation of thermal cracking. The following issues were identified.

- Propagation of concrete cracking under temperature variation
- Evaluation of liner strain
- Deciding on tightness class
- Reduction in concrete stiffness

4 LITERATURE SURVEY

A detailed literature survey was conducted based on the research development topics identified during the interview meetings. The key publications were studied, and key principles are summarized as outlined below:

4.1 PROPAGATION OF CONCRETE CRACKING UNDER TEMPERATURE VARIATION

Cracking of concrete results in reduction of stiffness of the pool structures. This will also reduce the level of forces and causes force redistribution. While analyzing or designing pool structures, the cracking effect to be accounted for as outlined in the following studies either by reduction factors or by rules in constitutive relations.

A series of both computational and experimental work to evaluate the effect of thermal cracking in reinforced concrete structure are presented in Vecchio [15], Vecchio and Sato [16] and Vecchio et al. [17]. Vecchio [15] developed a nonlinear analysis method to simulate the behavior frame structures under thermal and mechanical loads. The proposed method involves an iterative procedure that monitors nonlinearity at the stress-strain level. The reinforced concrete sections are subdivided into individual steel and concrete layers. Based on the computed section deformations the strain level at each layer is computed. Through constitutive relations, the stiffness and stress are obtained that leads to member forces and stiffnesses through integration over the layers. Then, an iterative process starts where the integrated member forces achieve an equilibrium condition with the applied loads. The analysis continues to the next load step with updated section stiffness values. The basic advantage of this method is that it allows incorporation of material nonlinear phenomena that are thermal creep, concrete cracking, tension stiffening and reinforcement yielding. The analysis method was also applied to experimental specimens and good correlation was achieved. However, it is only applicable for frame structures and requires advanced constitutive relations. Vecchio and Sato [16] conducted an experimental study to investigate the behavior of frame structures under thermal loads. A total number of 3 large scale portal frame specimens made up of 2 columns connected 1 beam member were tested. The test setup can be seen in Figure 3.

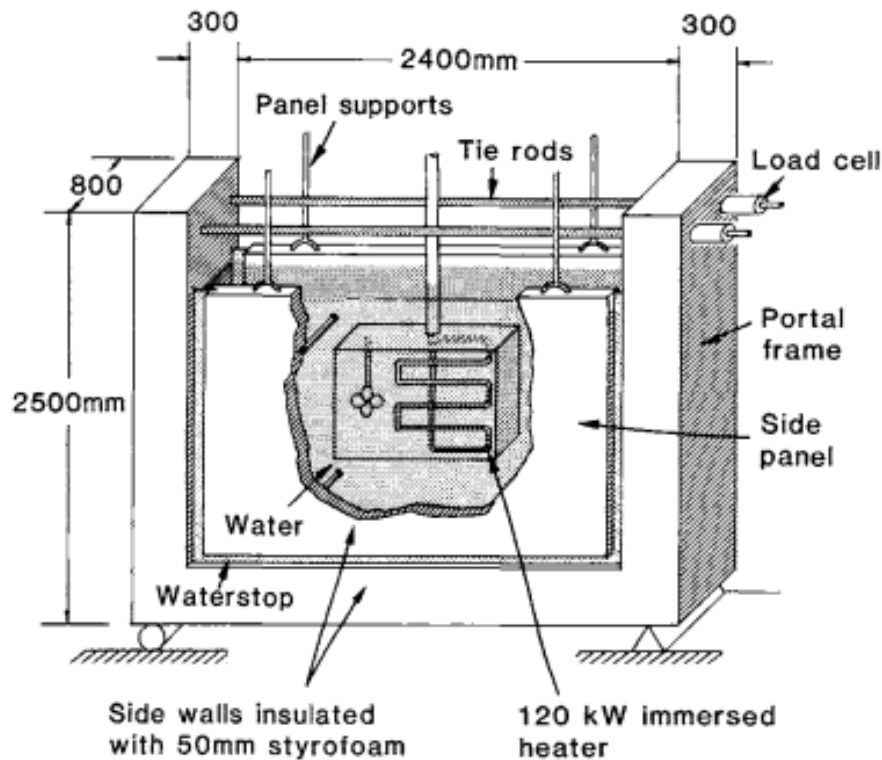


Figure 3 Test setup of Vecchio and Sato [16]

The main design parameter between the specimens was the amount of reinforcement. The thermal load was applied by enclosing a heated body of water between the portal frame members. Both mechanical and thermal loads were applied through various loading combinations. The maximum thermal gradient that is introduced was 80 °C and the maximum attained temperature was 95 °C. 3 main loading protocol was applied in terms of thermal loads including Series I: unrestrained condition, Series II: restrained condition with mechanical loads and Series III: unrestrained condition with mechanical loads. The mechanical loads were applied as either by pretension through a cable attached between the columns ends or through lateral force applied to the column members. The attached cables also simulated the restrained condition for Series II loading protocol. The thermal loads were applied 1 to 7 days of duration. The test result showed that the effect of thermal gradients is most evident shortly after application the loads, where peak of deformations, crack widths and restraint forces were observed. Under thermal loads, there exist gradual transition from cracked to uncracked stage indicating the importance of tension stiffening. Therefore, analysis methods based on cracked section properties may underestimate the restrained forces. Simultaneous application of mechanical and thermal loads may result in localized damage. Within short time periods, significant relaxation in restraint forces was observed. For some of the members, noticeable reduction in restraint forces was noted within 24 hours. No significant change in concrete material properties was observed for temperatures less than 100 °C. The proposed method for analysis of reinforced concrete structures by Vecchio [15] was quite accurate to

calculate the restraint forces over increasing temperature gradient. On the other hand, methods based on fully cracked or uncracked stiffness yielded unsatisfactory prediction of experimental behavior. The comparison of experimental and computational results can be seen in Figure 4 for Series I specimens as an example.

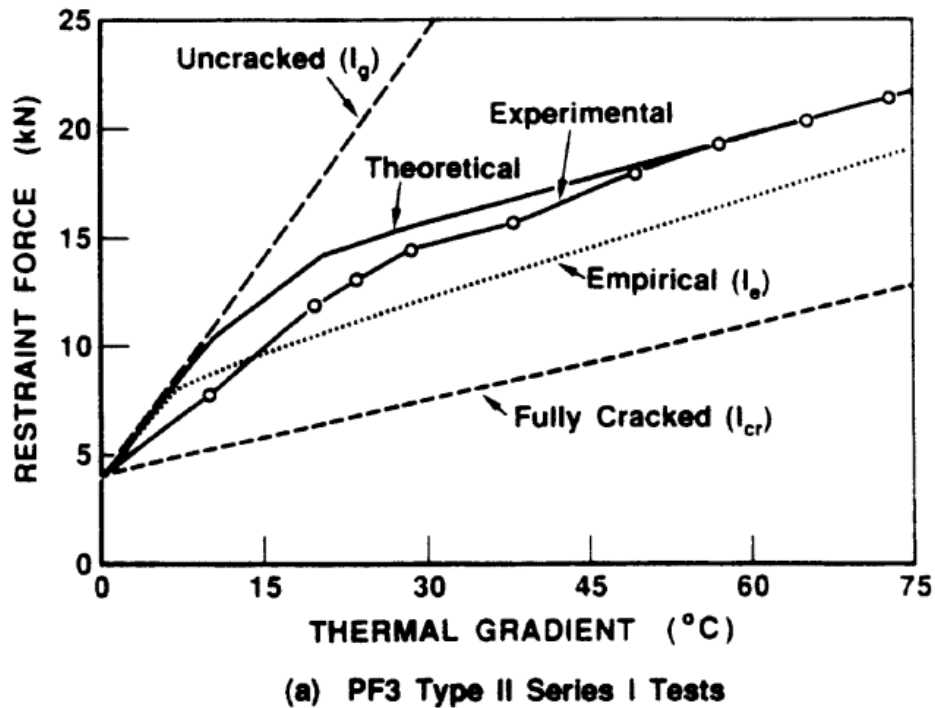


Figure 4 Comparison of experimental and computational results in Vecchio and Sato [16]

Vecchio et al. [17] tested the performance of shell type structures under thermal gradient. Experimental tests were conducted on a square slab of 150 mm thickness. The slab was placed on supports located at the corners and mechanical loads were applied at the center. The thermal gradient was generated through a heat chamber at the top part of the slab. The test setup can be seen in Figure 5.

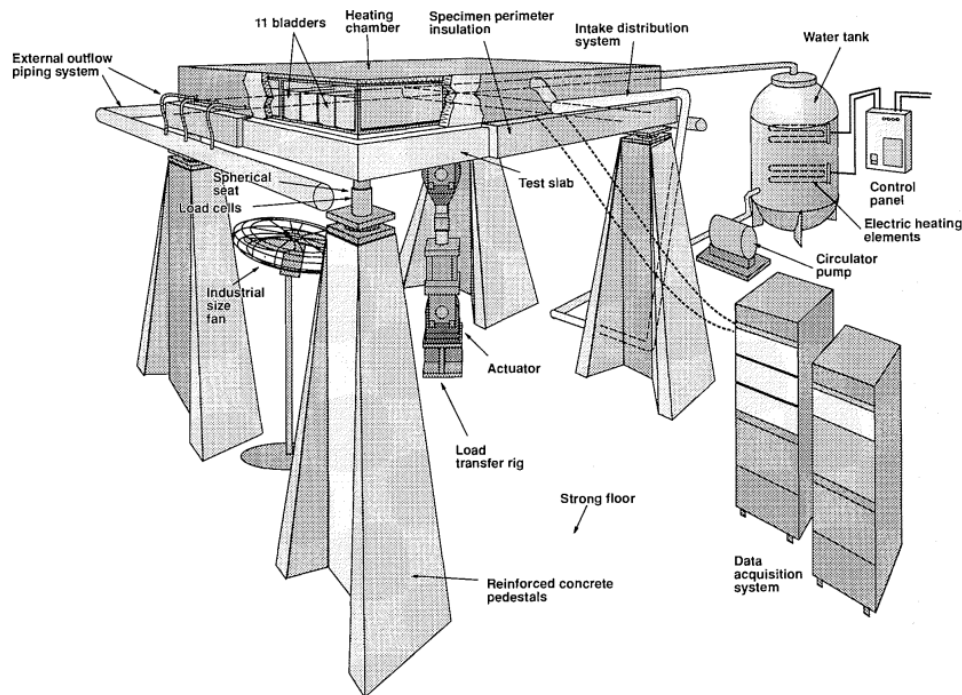


Figure 5 Test setup of Vecchio et al. [17]

A total number of 8 specimens were tested under different loading combinations for thermal and mechanical loads. The primary parameter among the specimens was the amount and arrangement of reinforcement. The experiments were conducted in 3 phases where Phase I: thermal loads were applied to unrestrained specimens. In Phase II: thermal loads were applied to restrained specimens, and Phase III: the mechanical and thermal loads were applied concurrently until ultimate limit state. The maximum thermal gradient achieved in the tests was 38 °C. Under Phase 1 loading, the specimens did not exhibit any cracking and insignificant upward deflection was observed. In Phase 2 loading, the restraint was ensured by an actuator preventing upward movement of the slab. Soon after reaching thermal gradient of 26 °C - 28 °C, significant restraint forces started to occur following formation of concrete cracking. It was followed by an abrupt reduction of restraint forces. The reduction of restraint forces continued as thermal gradient was increased up to 35 °C. In Phase 3 loading, the specimen was subjected to downward increasing load under constant thermal gradient of 36 °C. A nonlinear softening response was obtained. The achieved ultimate loads exhibited a variation based on provided reinforcement quantity and layout. A finite element model was developed to simulate the experimental study. The slab was modelled employing shell elements. A constitutive relation taking into account tension stiffening of concrete was utilized. In Phase II tests, the finite element study exhibited that the restraint forces significantly overestimated since thermal creep was not accounted for in the constitutive relation. At the ultimate limit state, in Phase III, finite element model estimated the experimental value with good accuracy. The summary of results can be seen in Table 6.

Table 6 Finite element results of Vecchio et al. [17]

Specimen	Peak restraint forces (Phase II tests)			Ultimate load capacity (Phase III tests)		
	$P_{r(exp)}$ (kN)	$P_{r(theor)}$ (kN)	$\frac{\text{Experimental}}{\text{Theoretical}}$	$P_{u(exp)}$ (kN)	$P_{u(theor)}$ (kN)	$\frac{\text{Experimental}}{\text{Theoretical}}$
TS2	27.9	74.5	0.374	328	270	1.213*
TS3	15.4	68.3	0.225	306	310	0.987
TS4	13.8	57.4	0.240	325	330	0.985
TS5	25.3	70.6	0.358	371	375	0.989
TS6	17.1	74.0	0.231	440	470	0.936
TS7	12.7	71.9	0.177	385	390	0.987
TS8	23.2	63.9	0.363	210	210	1.000
TS9	24.7	67.1	0.368	207	210	0.986
Mean			0.292			0.981
COV (%)			27.8			2.1

*Excluded from statistical averages due to premature failure.

In the USA, design of reinforced concrete structures subjected to thermal effects in nuclear power plant are covered in document ACI 349 [2]. This code provides guidance on evaluation of thermal effects and propose simplifications in analysis and design. The thermal effects create stresses that are self-relieving. Therefore, once concrete cracks and reinforcement yields, the thermal force and moments are greatly reduced. The thermal effects often do not reduce the capacity of the structures under mechanical loads. In ACI 349 [2], thermal effect is considered in design for serviceability and mainly intended for control of cracking. It is stated that thermal gradient less than 56 °C and uniform temperature change of 25 °C need not be accounted for since very small strain values are expected for concrete and steel in these cases. Both hand calculations and computer-based analysis methods are recommended for assessment of thermal effects. For hand calculations simplified approaches are introduced for analysis of simple structures and also for verification of computer-based methods. When using elastic finite element method, 50 % reduction of concrete stiffness is noted as past practice to account for cracking, creep and yielding.

Adediran and Ghosal [4] performed a computational study to assess cracked properties that accounts for thermal effect on reinforced concrete structures. In ACI 349 [2], cracked moment of inertia is noted as 50 % of the gross moment of inertia and it is translated into as $0.5E_cI_g$ in all thermal analysis, where E_c is modulus of elasticity of concrete, I_g is gross moment of inertia. It is stated that this 50 % factor is provided as a conservative approach and no guidance is provided for its use and applicability. A parametric study was conducted based on a portal frame structure also provided as a benchmark problem in ACI 349 [2]. The main parameters that are focused were axial load level in the columns and amount of thermal gradient. The analysis method is based on section analysis. This analysis is done at 3 points along the member length. Following the calculation of strains over the sections, the internal forces of moments and axial forces are back calculated through stresses. Then, moment of inertia is calculated by transforming the tensile reinforcement and ignoring tension in concrete and compression reinforcement.

For the selected points, the cracked moment of inertia is obtained by averaging the inertia values for the mechanical load case and final load case including thermal effects. Then, the cracked inertias for the selected points are utilized in a modified Branson (ACI 349 [2]) equation to obtain an effective cracked moment of inertia for the element. In this research study, it was mentioned that ACI 349 [2] committee was considering to replace the 50 % cracked moment of inertia factor with the recommendations in ASCE 43 [5]. Although, it was found to be an improvement, recommendations were also given based on the results of this study as given in Table 7.

Table 7 Effective stiffness values by Adediran and Ghosal [4]

Component	Flexural Rigidity	Flexural Rigidity	Paper Recommendation	Comment
	ASCE 43 [5]	ACI 349 [2]		
Beams - $P < 0,1f'_cA_g$	$0,5E_cI_g$	$0,5E_cI_g$	$0,3E_cI_g$	Applicable when peak member moments from mechanical load case are greater than M_{cr} and thermal gradient greater than $\Delta T = 10^\circ\text{C}$
Beams - $0,1f'_cA_g \leq P \leq \phi P_b$	$0,5E_cI_g$	$0,5E_cI_g$	$0,5E_cI_g$	
Columns - $P < \phi P_b$	$0,7E_cI_g$	$0,5E_cI_g$	$0,5E_cI_g$	
Columns - $P > \phi P_b$	$0,7E_cI_g$	$0,5E_cI_g$	$0,8E_cI_g$	
f'_c – compressive strength of concrete			P_b – axial force at balance point	
E_c – modulus of elasticity of concrete			M_{cr} – cracked moment	
P – axial force			ϕ - resistance factor	
I – gross moment of inertia				

4.2 LINER ANALYSIS

Pirkkanen (2018) carried out a research study on structural behavior of steel liners attached to the walls of the spent fuel pools. The buckling behavior, fatigue characteristics and strain levels in the liners were investigated. Liner plates were assumed to experience hydrostatic pressure and temperature as design loads. The temperature levels of 15°C , 30°C , 45°C , 68°C and 100°C were considered. However, the temperature of 68°C is the highest possible water temperature which occurs in case of maintenance shutdown. A detailed finite element of model the linear was developed using solid elements. The plate, embedded steel profiles, and the welds connecting plate and embedded steel profile were modelled. The finite element analysis was conducted for 2 positions of the liner plate. In the first case, the liner was assumed to be located at the top of the pool side wall experiencing the lowest hydrostatic pressure. In the second case, the liner position was at the bottom of the pool with highest hydrostatic pressure. A buckling analysis of the liner plate was conducted by assuming various initial imperfections. For both positions of the liner plate, buckling was observed under design loads, but the structural integrity of the liner was maintained. Due to large hydrostatic pressure, the linear at the bottom of the pool experienced buckling at higher temperature levels compared to the liner at the top of the pool side wall. The largest liner strain at 45°C was found to be around 0,5 % and it took place at the weld between the plate and embedded profile. The low cycle fatigue performance of the liner was also studied. Under normal conditions, the temperature of the coolant in the pools was assumed to be 30°C . However, during annual maintenance condition the temperature increases to 42°C . This was assumed to happen 80 times over the lifetime of the plant. If there exist a major shut down, the temperature may reach up to 68°C . Utilizing Miner's rule, the fatigue damage of the liner was calculated

for a range of annual maintenance temperatures and a single temperature peak of 68 °C. It was recommended to keep the annual maintenance temperature to be less than 52.3 °C.

4.3 CONCRETE STRENGTH AND STIFFNESS AT MODERATE TEMPERATURES

Jonson and Tornberg [9] conducted a research study on the behavior of concrete under temperature levels up to 20 °C to 120 °C. It was aimed to investigate how Swedish nuclear power plants are affected under moderate temperatures occurring in the reactor containment. A detailed literature study was performed, and laboratory tests were done to study the concrete parameters of compressive strength, tensile strength, modulus of elasticity and weight change.

The literature study was grouped into different parts depending on the phenomena being investigated when concrete is subjected to temperature loads. The first group of research work being investigated was the material factors. The available past research was reported and summarized. Some these material factors were ballast, cement type, moisture, durability class, curing age, porosity, and additive material. The second group of research work in the literature review covers the environmental factors affecting concrete behavior under temperature loads. The environmental factors being examined included temperature, load during heating, exposure time, loading in cold or hot condition, heating and cooling rate. The last set of literature study was conducted for affected parameters of concrete when concrete was subjected to temperature loads. These factors were strength, stiffness, weight loss and microcracks.

As a result of the literature study it was determined that when concrete was exposed to temperature loads, the dominant material factor affecting the mechanical properties was found to be aggregate type. The type aggregate used in Swedish power plants has good resistance under temperature loads. With respect to environmental loads, it was stated that concrete should be avoided to have temperature loads at the early stages of curing. A detailed summary of literature study was provided in a table showing how each material and environmental factors affect the concrete properties and how is their status in Swedish nuclear plants.

New casting of cubical and cylindrical samples was done using the same mix design used in Swedish nuclear plants. These specimens were subjected to temperature levels of 20 °C, 66 °C, 93 °C and 120 °C. In addition to the new casting, drilled specimens from existing plants were also tested. Cubical specimens were used for compressive strength testing while cylindrical samples were used for tensile strength and modulus of elasticity tests. The temperature loads were applied by a heat chamber. Thin slip analysis was also conducted for the specimens to study microcracking, degree of hydration and water cement ratio.

Under increasing temperature, the compressive strength exhibited a reduction up to 6 % until 66 °C. Beyond this temperature, improvement in compressive strength was evident up to 50 % at 120 °C. The tensile strength was found to be affected more from the temperature loading due to microcracking. The common trend was the tensile strength is decreasing at temperatures below 120 °C and then slight

increase takes place. The maximum reduction was observed as 18 %. On the contrary, the concrete specimens cored from an existing plant exhibited a tensile strength increase during temperature loading. This may be attributed to fact that old specimens have enough time to dry out completely. The modulus of elasticity showed a steady decrease as the temperature load proceeds. The reduction was on the order of 12 %. The weight of the specimens decreased as the temperature increased. The decrease was about 4 % and it is mainly attributed to moisture loss and more evident in newly cast specimens. Thin slip analysis indicated that beyond temperatures of 93 °C, the effect of moisture content reduces and therefore an increase in strength in both compressive and tensile strengths is evident at 120 °C.

FIB Model Code [7] provides formulations to determine the effect of temperature on the properties of concrete including compressive strength (f'_c), tensile strength (f'_{ct}) and modulus of elasticity (E_c). The given formulations are provided for the temperature range between 0 °C and 80 °C and they are provided in Figure 6 and Figure 8. It can be noted that the effect of temperature on the tensile strength of concrete is more evident compared compressive strength. A linear reduction is evident for increasing temperature and the reduction of strength can reach to 50 % at 80 °C. The compressive strength and modulus of elasticity follows the same trend and they both decrease with increasing temperature and the reduction can reach to 20 % at 80 °C.

The effect of temperature on the strength of concrete is also covered in the document SP 27.13330.2017 [14]. Reduction factors for compressive strength and tensile strength are given for various temperature levels and the reduction factors corresponding to 50 °C, 70 °C, 100 °C and up 150 °C are provided in Figure 6 and Figure 7. The reduction factors are given for concrete under long term load under both moist (sealed) or dry (unsealed) conditions. The reduction factors for sealed condition represents the state that exist for spent-fuel pool walls better even though they are more like in a semi-seal condition between dry and wet, where wall inner surface is covered with liner but outer surface is bare concrete. It can be seen that the thermal creep is more evident for the moist condition. In SP 27.13330.2017 [14], additional information can be found regarding thermal creep.

FIB Bulletin 1 [8] addresses the effect of moisture content on concrete behavior under elevated temperatures. Increasing temperature levels from 20 °C to 100 °C, mass concrete structures with little moisture exchange exhibit a reduction in compressive strength for about 25 %. On the other hand, if concrete is allowed to dry during this temperature increase, the compressive strength remains almost unchanged. Under this drying state, the compressive strength may even increase for temperature levels beyond 100 °C. This is attributed to the loss of moisture content of the cement paste. When concrete is prevented from drying during its exposure to elevated temperatures, hydrothermal reactions occur inside the cement paste which leads to changes in mechanical properties of concrete. Such exposure conditions would exist in thick concrete sections protected by steel liners. The hydrothermal reactions cause widening of the pore structures, and this results in reduction of compressive strength. If concrete paste contains adequate siliceous

compounds, the reduction is compensated by reactions between these compounds and calcium hydroxide. However, for concrete with limestone aggregates, the strength loss under sealed conditions is more prominent. This phenomena can be seen in the experimental tests conducted by Kottas et al. [10] as shown in Figure 9, where concrete strength reduction is presented for unsealed and sealed conditions. It can be seen that for concrete with limestone aggregate, the reduction in compressive strength is significant under increasing thermal loads.

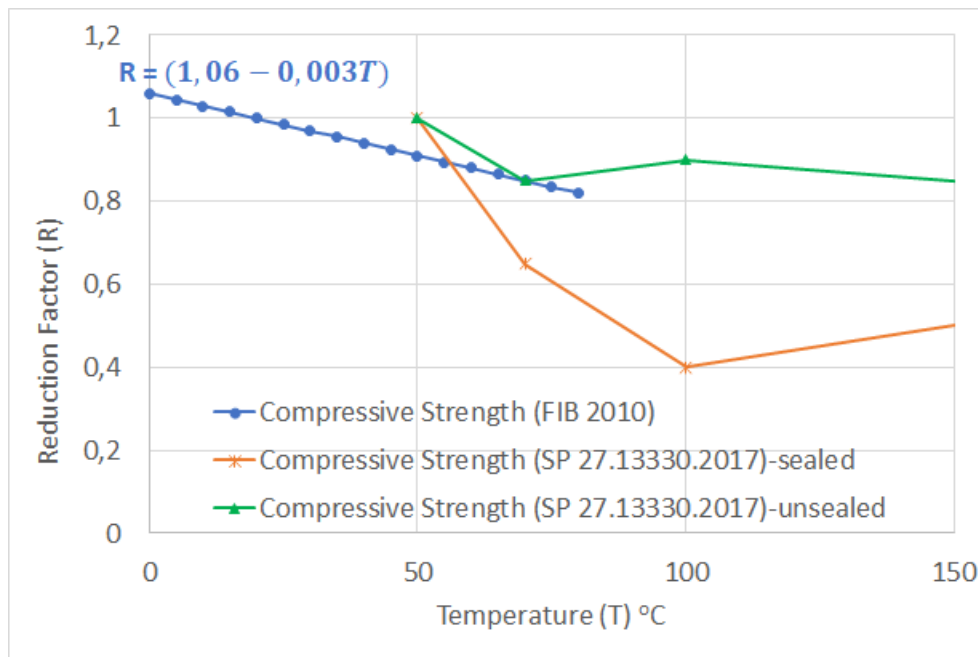


Figure 6 Reduction factor on concrete compressive strength as a function of temperature

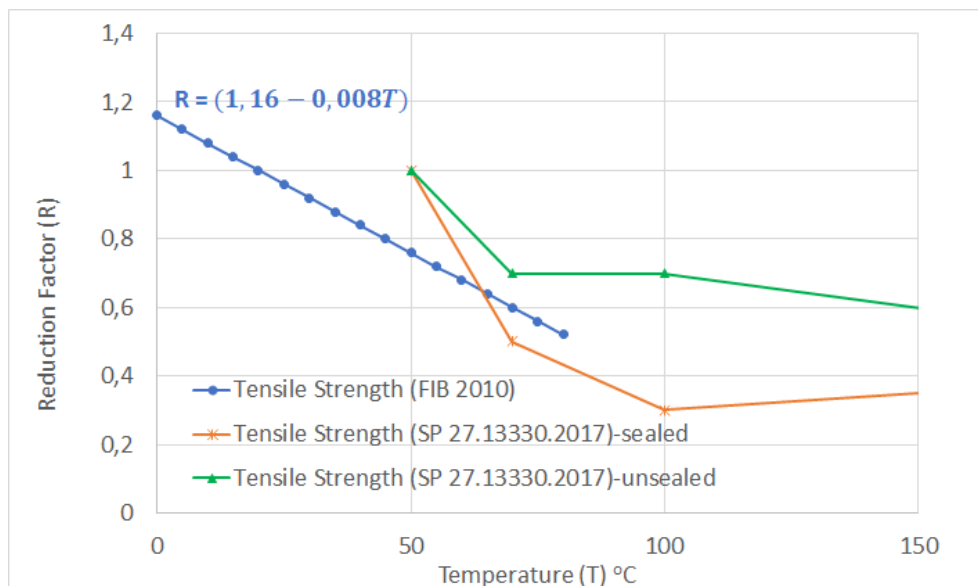


Figure 7 Reduction factor on concrete tensile strength as a function of temperature

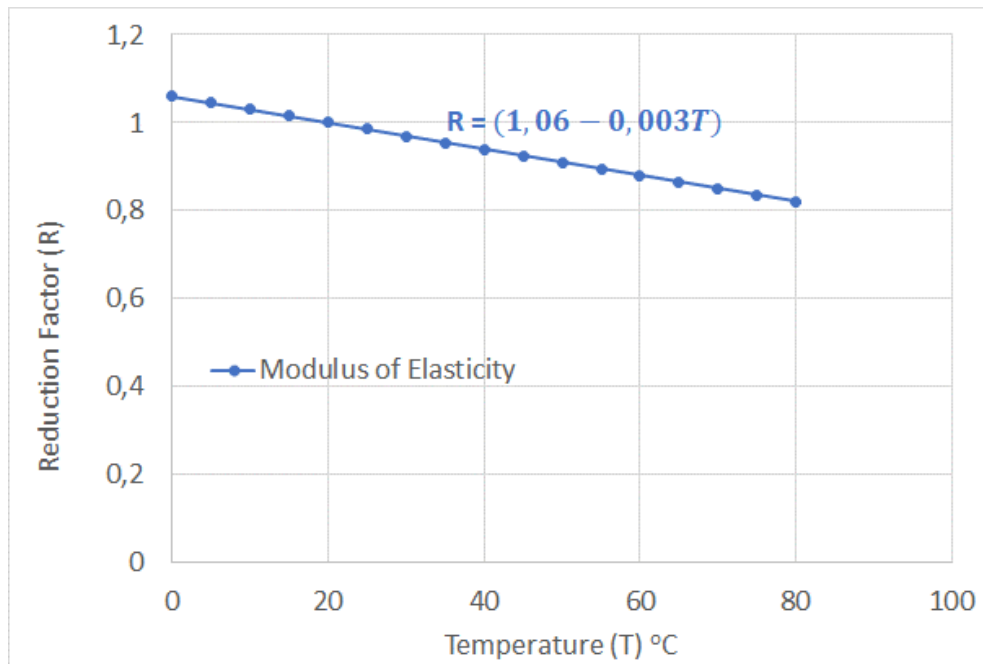


Figure 8 Reduction factor on concrete modulus of elasticity as a function of temperature

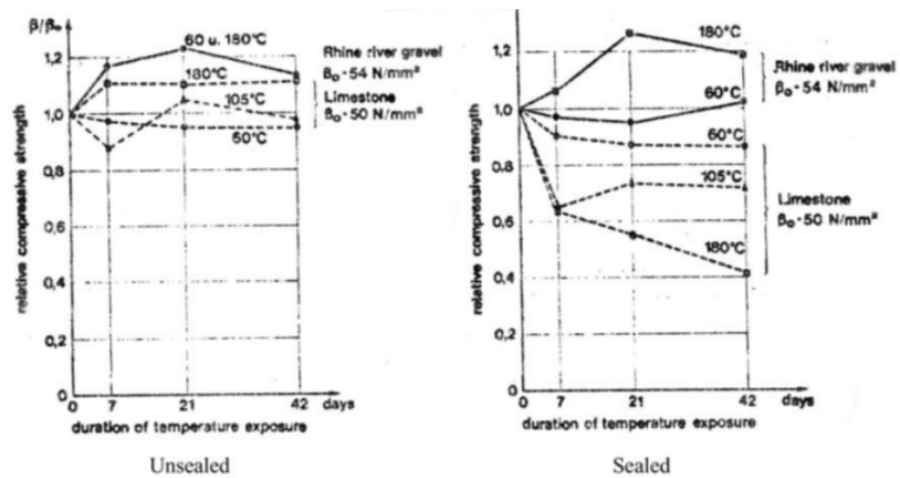


Figure 9 Reduction on concrete compressive strength per Kottas et al. [10]

4.4 SELECTION OF TIGHTNESS CLASS

The design of liquid retention structures is covered by EN 1992-3 [6]. In this document, tightness classes are introduced that defines the level of leakage as design objective. The tightness class definitions are already provided in Table 5. Each tightness class is attained through satisfying prescribed crack width (w_{k1}) limitations as given below:

Tightness class 0 refers to structures containing dry materials and no additional crack limitation is available other than limits to be followed for preventing corrosion.

Tightness class 1 structures are allowed to have some degree of leakage. It is assumed that there may be through cracks over concrete sections. The specified maximum crack width depends on the ratio of the hydrostatic pressure (h_d) to wall thickness (h) as given below:

$$\begin{aligned} h_d/h \leq 5 & \quad w_{k1} = 0,2 \text{ mm} \\ h_d/h \geq 35 & \quad w_{k1} = 0,05 \text{ mm} \end{aligned}$$

For intermediate values, interpolation is possible. If the crack width is less than the prescribed limits, self-healing of the cracks is possible.

Tightness class 2 and 3 structures are not allowed to have through cracks over the reinforced concrete section. This is ensured by limiting the depth of the compression value, x_{min} , to the minimum of 50 mm or $0,2h$. This condition to be considered under quasi-permanent combination of actions. To achieve class 3 tightness, special measures to be applied such as liner and cracking. For class 2 and 3, part of the structure should be under compression.

In the United States, the cracking limits for water retaining structures are regulated in the standards of ACI 224 [1] and ACI 350 [3]. In ACI 350 [3], the distribution of flexural reinforcement is limited through a parameter as a function of stress in the rebar, which corresponds to a crack width of 0,254 mm (0,01 in) for liquids with pH level greater than 5. In ACI 224 [1], the recommended cracking width is provided as 0,1 mm (0,004 in) for water containing structures. However, this value is not provided as a strict limitation.

The comparison of Eurocode and American standards for cracking width limitation in liquid retaining structures can be seen in Figure 10. Up to h_d/h values of 5, EN 1992-3 [6] is slightly more conservative compared to ACI 350 [3]. However, for higher values of h_d/h , the deviation between the given codes appears to be more prominent and EN 1992-3 [6] becomes even more strict compared to ACI 350 [3].

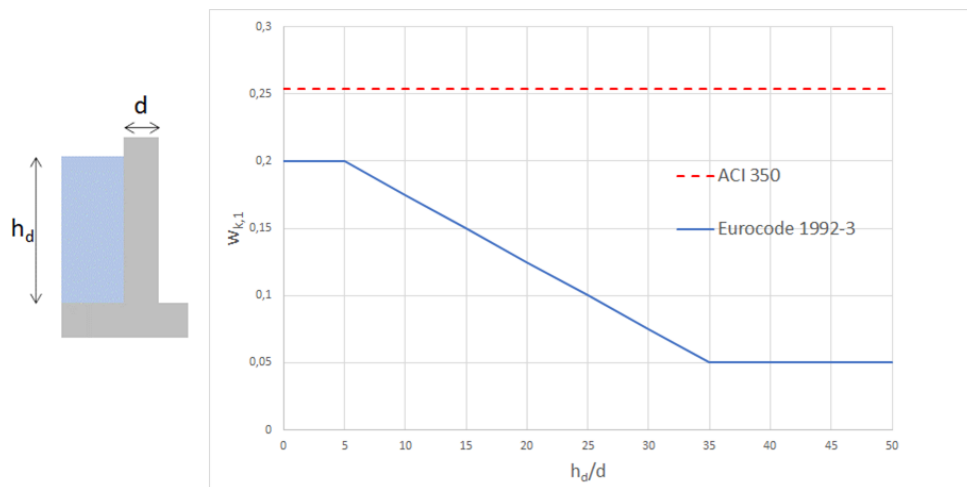


Figure 10 Comparison of crack width limitations for European and American standards

5 RESEARCH AND DEVELOPMENT IDEAS

Based on the interview meetings and literature survey on thermal cracking of concrete in spent-fuel pools, the following research and development ideas are proposed.

- There exists significant variation among design temperature values adopted in the plants for normal, extreme and also accidental cases. These variations indicate a need for research to identify the design temperatures. It will provide common design rules and similar reliability for future plants for temperature effects.
- All spent fuel pools are covered by steel liners on their interior surfaces. Therefore, the pools are satisfying Tightness Class 3 per EN 1992-3 [6]. However, different approaches with respect to tightness classification of the reinforced concrete alone. It is often not intended to satisfy any tightness class in the original designs. This issue is recommended to be investigated to attain a uniformity in design of spent-fuel structures in terms of tightness class selection. It will also prevent imposing stringent or relaxed cracking limits than it is really needed.
- There exist several research work and specification for reduction of concrete material properties due to thermal creep at moderate temperatures. However, the reduction coefficients in these documents exhibit significant variation. There are also some research works indicating no reduction of concrete properties is needed at moderate temperatures. Type of aggregate is the key factor governing thermal creep of concrete and structures with limestone aggregate are found to be the most vulnerable. To address the correct properties of concrete is critical in studies for evaluating the safety of spent fuel pools. So that more realistic element force and displacement values can be obtained from analysis studies.
- When evaluating thermal cracking for frame structures, advanced analysis methods are utilized where the critical phenomena such as cracking, tension stiffening, yielding and thermal creep can be accounted for. This is achieved relatively easily since it requires calibration and verification of uniaxial constitutive models. On the other hand, the simulation of these phenomena is difficult in 2D and 3D finite element models since development of nonlinear multiaxial comprehensive constitutive relations is challenging. Further research is recommended on this topic since 3D finite element models are often employed in structural evaluation of spent fuels pools under thermal loads.

6 CONCLUSION

In this work, the phenomena of thermal cracking in spent fuel structures is investigated through discussions with representatives from Swedish and Finnish Nuclear Power Plants and from nuclear waste storage facilities. The findings from the meetings were noted and a literature survey was conducted to identify issues that requires more research and development study. The recommended research and development work is listed on the Section 5 and additionally the following conclusions are obtained:

- Thermal cracking phenomena has been well examined and the risk of leakage is greatly reduced through design measures such as liners, leak detection system, pre-tensioning or base isolation.
- 3D finite element studies evaluating the safety of spent fuel pools against thermal cracking is quite common. The 3D finite element models inherently are complicated and involve several assumptions.
- In ACI 349 [2], 50 % reduction for cracked concrete moment of inertia is a simplified approach and often noted as conservative. It is considered to be updated in future revisions of ACI 349 [2] to be in line with ASCE 43 [5].
- There may be different scenarios such as malfunctioning of cooling system or accumulation of over-pressure inside the containment. The resulting pressure gradients and its effect on the boiling temperature of water is critical for thermal cracking in spent fuel pools.
- The effect of thermal stresses on reinforced concrete structures emerges mainly in the form of cracking and thermal creep. Both phenomena result in reduction of forces in the structural members. The reduction in concrete stiffness due to cracking is often taken into account. However, the research on design and analysis considering thermal creep is quite limited.

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Appendix A: Questionnaire

Information about existing pool structures:

- [1] How many such water pools exist, that are affected from elevated temperatures during normal operations, exceptional circumstances or accidents?
 - a. Where are the pools located in the plant?
 - b. What are main dimensions and volume of the pools?
 - c. What are typical thicknesses of pool walls?
 - d. Do the spent fuel pools have leak detection system?
- [2] Is there liner plate installed inside the pools to provide sealing? If there is any, what material is used for the liner and how it is connected to the walls?
- [3] What method of reinforcement is used to prevent thermal cracking in pools, normal reinforcing steel or prestressing?

Information about past investigations and design:

- [4] What is the design temperature of the water in the pools in different stages such as:
 - a. Normal operation conditions,
 - b. Exceptional situations,
 - c. Accident
- [5] How did the original design considered the effects of thermal gradient in concrete?
 - a. Is there any subsequent study on thermal effects after the design of the pools was completed?
- [6] Is the effect of high temperature to material properties of concrete and liner taken into account in the original design or subsequent studies of the pools?
- [7] What crack width limitation is imposed on spent fuel pools?
- [8] What are the reasons behind selected thickness of the walls and could they be thinner?

Need for further study and concerns:

- [9] What type of functional requirements for cracking to be ensured in design of the pools?
 - a. Some degree of leakage acceptable, or leakage of liquids irrelevant.

- b. Leakage to be limited to a small amount. Some surface staining or damp patches acceptable.
 - c. Leakage to be minimal. Appearance not to be impaired by staining.
 - d. No leakage permitted
- [10] What type of improvements in the design methods are expected for better evaluation of temperature effect in the spent fuel pools?
- [11] Are there any equipment fixed to the pools that are sensitive for displacements caused by temperature, such as Reactor Service Bridge or gates and are needed during or immediately after accident or exceptional situation?
- [12] Is there any pool structures with design choices beyond available limitations of current design codes?
 - a. Excessive concrete cover
 - b. Rebars with larger sizes than typically accepted in the codes

TEMPERATURE INFLUENCE ON THE CONCRETE IN THE SPENT FUEL POOLS

A nuclear power plant consists of a large number of concrete structures that are important both from a safety and operational perspective, e.g. the fuel pools. Used fuel is stored in the fuel pools for cooling before further transport to the intermediate storage. This report summarizes the state of knowledge regarding large temperature gradients and their effects on the concrete structures in the fuel pools at nuclear power plants and present proposals for possible future research and development projects within the area.

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