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Progress and Quality Assurance Regime at the EPR Construction at Olkiluoto

Safety Implications of Problems Encountered

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Executive Summary

This report assesses the safety implications of quality assurance problems in the construction of an EPR reactor in Olkiluoto. The affected components include piping, containment liner and concrete base slab.

The quality assurance problems connected to the primary piping are of high potential safety significance. The safety case for this piping relies on “break preclusion”. Break preclusion is a doubtful concept at best. It presupposes near-perfect control of manufacturing, and regular inspections of very high accuracy and reliability. It is clear that control of manufacturing was considerably less than perfect for the Olkiluoto 3 components so far.

If the problems persist, the probability of loss-of-coolant accidents will be increased, and hence the probability of a core melt.

The containment liner constitutes an important barrier against releases. In case of a severe accident, a defective liner is likely to lead to releases which are higher and occur earlier, than in case of an intact liner.

Technical specifications for the liner were not met, which was accepted by STUK. It is not definitely clear to which extent the overall state of the containment liner, after implementation of all measures, will be inferior to the original, error-less design.

The base slab has to withstand loads during plant construction and operation, as well as in case of internal and external accidents. The strength of the concrete is a parameter important for plant safety. Deviations from safety requirements have been accepted. Details of a counter-measure planned are not known to date.

It should be investigated whether the higher water content of the base slab concrete could aggravate problems in case there are malfunctions of the core catcher during an accident.

Open questions remain until today, regarding the quality assurance problems at the Olkiluoto 3 site. It is clear, however, that safety requirements have been slackened.

Chances for basic improvements at the site are slim, since the plant is constructed under a turnkey contract and the pressure of time is greater than ever, after the delays which already occurred.

It does not seem likely that the “first-of-a-kind” factor play a large role regarding the problems. Future plants will also be built under a tight schedule, with high cost pressure. Since there are many different

concepts for new NPPs, only a few units will be built of each of those types.

The EPR is supposed to belong to a new generation of reactors with an enhanced safety level. The experience at the Olkiluoto 3 site indicates, however, that it is highly questionable whether even present-day safety standards will be kept at this plant.

1. Introduction

The European Pressurised Water Reactor (EPR) is the flagship of the Generation III reactors; the first reactor of this generation to be built in Europe. The EPR has been developed from the French N4 and the German KONVOI reactor lines, and has been designed by the company AREVA NP.

One of the goals of EPR development was to significantly improve the safety level, compared to that of its predecessors. Design features relevant for safety, including those features which actually constitute a reduction of safety margins, have been summarily discussed in the "Nuclear Reactor Hazards" report, prepared for Greenpeace International [HIRSCH 2005]. They will be referred to here only as far as required when discussing the safety implications of quality assurance issues.

It must be borne in mind that the safety of a reactor does not only depend on the design as it is planned, but also the quality assurance (QA) during construction constitutes another very important factor influencing reactor hazards – the hazards of the subsequent operation of the reactor can be significantly increased if systems, structures and components are not built to specification because of QA shortcomings. (A further factor highly relevant for safety is the safety culture during operation, which will not be further discussed here since the EPR is still under construction.)

Since late 2005, it has become known that there are considerable quality assurance problems at the Olkiluoto site where the first EPR is under construction. Some information has been made available – if tardy – from the Finnish nuclear regulatory authority STUK, as well as in industry newsletters.

Problems which have occurred, with priorities as seen by the authors:

1. Primary components and piping – highest priority. Those problems are directly relevant for safety; they can lead to increased hazards of accident initiation by LOCA (loss-of-coolant accident, i. e. loss of water coolant from the primary cooling circuit, which directly cools the reactor) and hence, to increased hazard of severe core damage.
2. Containment liner – 2nd priority. This problem is directly relevant for safety, once an accident occurs. After an accident sequence has been started, weaknesses of the liner can lead to higher releases and hence, aggravate the course of events.

3. Concrete base slab – 3rd priority. This problem shows shortcomings of safety culture and could eventually, if no appropriate counter-measures are implemented, lead to longer-term deterioration of reactor building, safeguard buildings (auxiliary buildings with safety systems) and fuel building base. It also raises questions in the context of severe accident mitigation.

These issues will be discussed here. The focus will lie with their safety significance. The discussion of the first issue is based on information provided by STUK in response to requests from the authors, as well as from industry magazines and newsletters.

The second and third issue are treated at length in the STUK investigation report 1/06 [STUK 2006]. Regarding the concrete base slab, additional material has been made available by STUK. Furthermore, as in the case of the first issue, replies from STUK to questions submitted by the authors were used for this report.

2. Issues of QA and Their Safety Implications

2.1 Primary Circuit Piping

<u>Problems with primary circuit components and piping at Olkiluoto 3:</u>

The primary circuit is the central part of a nuclear power plant with a pressurized water reactor. The quality of this circuit is of highest importance for plant safety since it contains the water coolant which directly cools the reactor.

At the time of writing, there were problems with quality management for almost all components of the primary circuit at Olkiluoto 3:

<u>Reactor pressure vessel:</u> As reported in an industry newsletter, five of the six forged pieces for the vessel did not meet French quality standards and had to be redone. Further problems were encountered in the welding processes for attachments to the vessel [NW 2006a, 2006b]. STUK, however, recently stated that all forged pieces fulfilled the requirements from the beginning, and only some internal parts of the pressure vessel had to be remanufactured [STUK 2007c]. This contradiction remains to be clarified. It is noteworthy that the newsletter report from 2006 also refers to a STUK source.

<u>Pressurizer:</u> Four of the five forgings for the pressurizer had to be recast. The pieces had not been properly cooled after casting because a propeller for circulating water in a cooling pond was not operating. TVO, Areva NP and STUK had all surveyed the factory but failed to notice the problem [NEI 2006b].

<u>Steam generators:</u> Deviations also occurred in the manufacture of the steam generators, necessitating corrections which led to delays [NEI 2006a].

The last problems which became known concern the primary coolant pipes. Those pipes have a diameter of about one meter. They provide transport of hot water from the reactor vessel to the steam generators (hot leg piping), and back to the reactor vessel via the main coolant pumps (cold leg piping). Like modern French and German PWRs, the EPR has four coolant circuits and hence, four cold and four hot leg pipes.

Because of the high relevance for plant safety, primary piping must be manufactured from carefully selected materials, with high accuracy and with a high level of quality control. Inspection by non-destructive testing (NDT) is required after the manufacture of the pipes, and again after the pipes have been installed. Furthermore, during the whole operating time of the reactor, periodical in-service inspection has to be performed. The most important tool of this inspection program are ultrasonic detection methods.

Information on problems with the primary piping of Olkiluoto EPR was first published in an industry newsletter in October 2006, concerning the hot legs only [NW 2006c]. Soon afterwards, it became known that the cold legs were also concerned, i. e. the primary piping in its entirety [NW 2009d].

Manufacture and quality control of cold and hot leg piping:

The steel used for the primary circuit piping at Olkiluoto 3 is a well-known austenitic (i. e. stainless) steel [STUK 2007a].

Originally, it was found that three of the four hot legs were not made to specification. However, eventually it became clear that all legs of the primary piping were concerned. The problem is that the grain size of the steel is too big for the type of ultrasonic testing which has been qualified by STUK and is to be applied at Olkiluoto 3. According to STUK, the manufacturer was not able to reach the criteria due to the big size of the forgings and the proposed forging and heat treatment size [STUK 2007a]. This is somewhat surprising since the manufacturer (Creusot Forge) is an experienced company. The obvious assumption would be that the root cause of the problems was the pressure to keep costs low; however, no information clarifying this point is available.

When the shortcomings of the pipes became known, TVO and Areva at first considered finding a new testing method which could be qualified by STUK [NW 42, 2006]. In December, however, Areva announced that they had abandoned that approach and decided to refabricate some of the coolant lines. At that time, it was not clear how many [NW 2006d]. Finally, in March 2007, it became known that Areva had decided to recast all eight pipelines (using the same type of steel) [TVO 2007].

The actual status by the end of March 2007 is as follows [STUK 2007a]:

- Four new hot leg forgings and one new cold leg forging have already been cast. All forgings will be completed during spring.
- Results of destructive and non-destructive testing are expected during spring and early summer.
- Areva will wait for the test results from the first cold leg prior to manufacturing the other three cold legs.
- Manufacturing of the new forgings is based on optimized heat treatment of the most critical areas of the forgings. (This implies that other areas are not optimally treated. Details, however,

were not provided by STUK. Therefore, the significance of this point cannot be assessed here.)

- STUK has reviewed and approved the new manufacturing program.

Because of the high safety relevance of the main coolant pipes, the decision to recast all legs was appropriate in the view of the authors. It also appears appropriate that one cold leg is manufactured at first, with the others following after the test results from this leg are available.

On the other hand, the same procedure has not been followed with the hot legs, since test results are not available yet and nevertheless all four hot legs have already now been produced.

STUK has accepted this because of changes in the manufacturing programme: In the new manufacturing programme, one hot leg is forged from one piece, whereas in the first programme, two hot legs were made of one forging and cut in two afterwards. Thus, the forging size is significantly smaller now which is expected to lead to better results regarding grain size – together with optimised forging and heat treating [STUK 2007b].

Nevertheless, it could be argued that in view of the importance of the primary piping, the cautious approach adopted for the cold legs would have seemed appropriate for the hot legs, too.

There seems to be no guarantee that the optimization of the manufacturing process will yield the desired results. More fundamental changes, up to selecting a different type of steel, might become necessary.

Non-destructive testing of cold and hot leg piping:

As already mentioned above, non-destructive testing (NDT) is a highly important measure. Effective NDT is required to guarantee that all components fulfil the safety requirements during power plant operation.

For the primary piping, the NDT methods used are surface inspection methods (visual and penetration testing) as well as volumetric methods like ultrasonic and radiographic testing [STUK 2007a].

Usually, the surface inspection methods are used before the reactor goes into operation, or as additional control in case possible defects have been detected by other methods during the operational life of the plant. Ultrasonic test methods are used at all times (after manufacture of a component, after its installation, and in the course of in-service inspections during operation). The same practice is to be followed at Olkiluoto 3. The inspection intervals, however, have not yet been determined. According to STUK, all welds are inspectable during operation [STUK 2007b].

It is noteworthy that STUK mentions ultrasonic testing (UT) as volumetric method only. Volumetric methods are not optimal for the detection of near-surface cracks, which are most important for safety (since they are most likely to grow under accident conditions). There are special UT methods which can also be used for near - for example, TOFD (Time of Flight Diffraction).

It can be assumed that such methods also are to be used at Olkiluoto 3. At the moment, however, it is not yet determined which inspection technology will be used [STUK 2007b]. The process of determination and qualification of the UT methods will follow the Finnish Regulatory Guide YVL 3.8 [STUK 2003], which relies significantly on the recommendations of ENIQ (European Network for Inspection Qualification) which are generally used in EU countries.

It has to be emphasized that good inspectability is not only required before start-up of the reactor, but also over the plant's whole lifetime (60 years). Volumetric methods alone are unlikely to guarantee sufficient detection accuracy. This holds particularly since at Olkiluoto 3, break preclusion for the primary piping is assumed – i. e. complete break of one of those pipes is excluded and not regarded as a credible accident (see below for further discussion).

For a more detailed assessment of the test methods employed, it would be necessary to have more information about the methods employed and the extent of their use. At the moment, important features like inspection intervals and inspection technology have not been determined [STUK 2007b].

Potential safety significance of the issue:

The safety case for the main coolant lines of the Olkiluoto EPR relies mainly on break preclusion. This issue has very high significance for safety; in the view of the authors as well as in the view of STUK [STUK 2007a].

For every NPP, so-called design basis accidents (DBAs) are defined by the nuclear regulations. Those DBAs are accidents which definitely have to be controlled by the safety systems. According to Finnish regulations [STUK 1996], those systems are usually provided with a "n+2" redundancy – i.e., there is still sufficient capacity if one train happens to be in repair or maintenance at the time of the accident, and another train fails. (There are similar requirements in other countries, e. g. in Germany.)

The design of safety systems is based on accident analyses. Those analyses have to be performed in a conservative manner for DBAs. This means that the results have to be on the safe side, leaving some leeway (safety margin) for inaccuracies or small errors.

The operating Finnish nuclear power plants have been constructed on the basis that an unlimited break of a main coolant pipe (so-called 2A-break since coolant water can escape on both sides of the break through the full area of the cross-section) is a design basis accident, in accordance with the Finnish Regulatory Guide YVL 3.5 [STUK 2005, p. 46].

For Olkiluoto 3, however, requirements have been weakened in this regard, the Guide YVL 3.5 is not fulfilled and the 2A-break is not among the DBAs. The design basis for the emergency core cooling system is the break of the largest pipe connected to the primary circuit, and not a main coolant pipe. The redundancy of the emergency core cooling system is merely "n+1" for a 2A-break of the latter, and not "n+2" as required for a DBA. Furthermore, accident analyses for the unlimited break of a main coolant pipe are carried out with best-estimate methodology only, which does not provide the safety margins conservative analyses would guarantee [STUK 2005, pp. 45, 46, 57, 58].

It is claimed by STUK that in spite of the deviations from the YVL safety codes, *"[t]he design basis for a primary circuit pipe break used for the Olkiluoto 3 Nuclear Power Plant […] still provides at least an equivalent level of safety"* [STUK 2005, p. 46].

This statement relies mainly on the break preclusion concept as mentioned at the beginning of this section. The emergency core cooling system has reduced redundance in case of a 2A-break, and the calculations performed for this accident do not provide safety margins like conservative calculations would. These limitations are to be compensated by extensive strength analyses of the pipes, as well as by stringent quality requirements and an extensive in-service inspection program [STUK 2005, p. 44].

Considering the quality control problems encountered so far with components of the primary circuit, and with the primary piping in particular, STUK's statement from 2005 appears rather doubtful. As problems keep recurring, there is no guarantee that all shortcomings and deviations from specifications are in fact discovered.

The problems with the main coolant piping primarily concerned reduced inspectability of pipes. This increases the probability of overlooking significant flaws in the materials, and hence indirectly also increases the probability of pipe failure. Furthermore, quality problems of steels such as higher grain size can directly influence the strength of the material, and hence the probability of an accident.

If the probabilities of initiating events like pipe breaks are increased, there is also an increase of the core melt probability – as compared to studies in which it is assumed that all design requirements are kept. In the case of a 2A-break, the limited capabilities to control this accident further aggravate the picture.

2.2 Containment Steel Liner

Situation at Olkiluoto according to STUK investigation report 1/06 [STUK 2006]:

The EPR is equipped with a double containment. The outer containment is a reinforced concrete cylinder which is to provide protection against external influences. The inner containment is a pre-stressed concrete cylinder with an elliptical top gable. It is equipped with a structural steel liner at the inside.

The liner has a thickness of about 6 mm. Its purpose is to provide a high degree of leak-tightness for the containment, in order to prevent or minimise releases of radioactive substances in case of an accident. It consists of several plates which are joined together by welding.

The steel liner was designed and supplied by the German firm Babcock Noell Nuclear GmbH, and manufactured by a sub-contractor, a Polish engineering firm (Energomontaz-Polnoc Gdynia).

The traditional fields of activity of this company, according to their website, are industrial construction, repairs and modernisation, as well as shipbuilding, ports and shiprepairing and offshore activities. They seem do have no experience at all in the nuclear sector [EPG 2007].

Because of control problems in the builder-supplier-manufacturer chain, outdated working practices and equipment of the manufacturer, lack of emphasis of the safety significance of the manufacturer’s work, deficient quality control by supplier and manufacturer which would have required extra activities by TVO and STUK, and other factors (for the whole list, see [STUK 2006, p. 35], a number of errors occurred in the production of the liner, which required repairs and extra tests.

Among these errors were:

- The root gaps of the weld between plates repeatedly exceeded the maximum specified gap of 5 mm.
- Use of non-approved welding methods for repairs – a method less advanced than the approved one was employed.
- Holes for pipe penetrations were cut in wrong locations.
- The bottom part of the liner was wavy, leading to the possibility of air pocket formation between the liner and the concrete.

The acceptability of the welds with excessive root gap was verified by STUK by additional qualification tests. (At the time of the writing of the STUK Investigation Report 1/06, STUK had only seen preliminary results of those tests; the final report had not yet been submitted to STUK. For further information, see below.)

The welds produced with a non-approved method were removed by grinding and re-done with a qualified method (i. e. a method which was checked and accepted by the authority). The holes at the wrong locations had to be patched up; the repair was verified by X-raying.

Regarding the bottom part of the liner, the report expresses the expectation that it will be straightened by the concrete which is to be placed on top of it. In addition, concrete will be injected between the steel liner and the base plate at a later time to eliminate the possibility of air pockets.

Additional information provided by STUK [STUK 2007a]:

The issue of root gap acceptability has been further investigated in the meantime. STUK has completed the evaluation of the test results. Based on those results, and on inspections, STUK has concluded that the wider root gaps do not compromise the safety and quality of the liner. (The test results have not been made public to date.) Nevertheless, the authority decided that the gap as originally approved shall be applied in welds in principle and deviations could only be applied in exceptional cases.

Thus, STUK accepted a violation of technical specifications. This is highly problematic even if the additional tests performed indeed demonstrated that the deviating welds are still adequate for fulfilling the containment requirements, as STUK claims. Crossing a line by accepting a deviation from specifications at one occasion makes it very difficult to avoid further exceptions in the future.

There were altogether 49 penetrations which were cut in wrong locations, with a diameter of 72 mm. Repairs had been performed with qualified welding procedures. The weld seams were radiographically examined and leak-tested by 100 %, to the satisfaction of STUK.

The proposed method for injecting concrete below the steel liner has been tested in a mock-up. After the test, the procedure was modified. New tests led to the assessment of STUK that the modification was successful. In addition, STUK has commissioned an expert statement to evaluate the significance of small air pockets under the liner. The conclusion of this statement is that small pockets are not significant, since the liner is coated with paint to protect the base material, and there is no corrosive environment under the steel liner.

Potential Safety Significance of the Issue:

In case of severe accident (core melt), the containment constitutes the last barrier against radioactive releases. It is of foremost importance that the containment remains undamaged and leak-tight for as long as possible. The later the releases occur, the more time is available for emergency measures to protect the population; and, even more important, the smaller the release will tend to be, since condensation and deposition processes will go on inside the containment as time goes by, reducing the amounts available for release.

The original EPR design apparently did not include a steel liner for the inner containment. Based on a preliminary safety analysis, STUK required a liner because it was assumed that the tightness of an unlined concrete building would be poor [STUK 2005, 5.2]. (A containment steel liner is also part of the design of the Flamanville 3 EPR [EDF 2006, 6.2.1.1].)

Thus, the importance of the containment steel liner was well recognised by the authority – long before the various shortcomings and errors were discovered in the first half of 2006. Even in this case, the case of a recognised and very important safety-relevant component, the authority could not keep the quality assurance and communications problems along the chain of component supply under control. This is an alarming sign of the difficulties involved in supervising the EPR project in its whole complexity.

The containment steel liner constitutes the third and last barrier against releases of radioactive materials into the environment (the first and second being, respectively, the fuel rod hulls and the pressure-bearing boundary of the primary cooling circuit).

In case of a severe accident, a defective liner is likely to lead to releases which are higher, and occur earlier, than in case of an intact liner – and hence to a higher number of casualties and a larger area of contaminated land.

After the problem was recognised, STUK has acted and according to the information provided, the measures taken seem appropriate to mitigate the problem. It is not clear, however, to which extent the overall state of the containment liner, after implementation of all measures, will be inferior to the state which would have corresponded to the original, error-less design. STUK's assessment is that the quality of the liner is not compromised [STUK 2007b]. However, very little additional information has been provided which has not already been included in the investigation report 1/06. Hence, it is also not clear at the moment whether an increase of plant hazards resulted from this issue.

2.3 Concrete Base Slab

Situation at Olkiluoto according to STUK investigation report 1/06 [STUK 2006]:

The reactor building, the safeguard buildings (auxiliary buildings with safety systems) and the fuel building of Olkiluoto 3 share a common base slab. Apart from loads occurring during construction, this base slab must also withstand loads during plant operation, loads caused by internal accidents (for example, in case of over-pressure of the containment), loads of external collisions against the plants and loads due to earthquakes.

The base slab is made of concrete; it is 103.1 m long and 100.8 m wide. The thickness of the slab under the reactor building is 3.15 m, under the safeguard buildings 1.5 m. It is supported by rock, over its entire area.

The base slab was designed by Finnprima, the concrete supplied by Forssan Betoni Oy and the concreting work performed by Hartela Oy.

Because the call for tenders for the base slab did not specifically emphasize the special requirements on quality management applying to the construction of a nuclear power plant, and because of deficiencies in the quality control of Forssan Betoni, there were problems regarding the characteristics of the base slab concrete.

At the core of the problems was the water-cement ratio of the concrete which was higher than designed. The water-cement ratio determines the compressive strength of concrete, as well as its durability.

Regarding compressive strength, it was found that in "almost all" cases, the reference strength determined from samples fulfilled the requirement for 91-day reference strength of K40 strenght class concrete. The durability requirements for exposure classes XC2 (carbonation) and WS1 (chlorides) are met, whereas the requirement for exposure class XA1 (chemically aggressive substances) is not met. Hence, the concrete did not meet strength requirements, as well as requirements regarding the resistance to certain chemical substances (sulphates).

It is pointed out in the STUK report that compressive strength continues to increase after 91 days, and that the concrete area not fulfilling the requirement was only slightly below the required value. Hence, the requirement for compressive strength was considered to be fulfilled.

With respect to the durability requirement for chemically aggressive substances, STUK pointed out that there is a high amount of slag in the concrete which implies good chemical resistance. This argument is further elaborated in a report from Kymenlaakso University of Applied

Sciences [KYMENLAAKSO 2006]. This report points out that regarding chemical resistance, the Finnish concrete code does not differentiate between different cement types although it is known that slag concrete gives better sulphate resistance than, e.g., Portland cement concrete.

Nevertheless, STUK reports that TVO has announced that they will require an additional protection of the base slab against external moisture, to ensure base slab chemical resistance.

Additional information provided by STUK [STUK 2007a]:

The measure envisaged by TVO has not yet been implemented; it has not yet been submitted to STUK for approval. At present, TVO is investigating the issue with AREVA.

Due to this early stage of planning, it is not known so far whether, if the measure is implemented, it will be possible to test or inspect the surfaces concerned at a later date in order to ascertain that adequate protection is indeed provided.

Potential Safety Significance of the Issue:

The EPR Olkiluoto 3 is planned to operate for 60 years. Should weakening of the concrete base slab occur during this time because of the influence of chemically aggressive substances in groundwater, this could impair the base slab's ability to withstand the design loads. Accidents which occurred could therefore be aggravated.

Given the presentation of the problem in the STUK investigation report 1/06, its direct safety significance appears low.

The evaluation of concrete quality control performed by Kymenlaakso University did not cover test results from the day with the highest water/cement ratio, which was mentioned in an early report [KYMENLAAKSO 2006a], but omitted in a later, summarising report [KYMENLAAKSO 2006b]. However, STUK informed the authors on inquiry that in the STUK assessment results from the day with the highest water content were taken into account. They were based on specimen from routine sampling according to regulations, as well as on additional specimen cut from the base slab. STUK arrived at the conclusion to approve the test results based on all those data [STUK 2007b]. Hence, there clearly were problems associated with Kymenlaakso's investigations which, however, seem to have been clarified by STUK.

Quite apart from this point, the concrete issue provides another example for the complexity of the construction project which frequently leads to problems. It is noteworthy that a requirement of the Finnish concrete code is not kept - and then, in retrospect, this violation is declared as practically irrelevant. Surely it was known well beforehand that slag cement concrete has a particularly good sulphate resistance; the argument would be more convincing if it had been made clear from the beginning that the code requirement was not appropriate for the concrete in question. Finally, the question arises why counter-measures are planned by TVO if the chemical resistance of the concrete is good enough anyway.

The situation is similar regarding the compressive strength requirement. It is a general fact that concrete strength increases past the 91 day-tests and it is not clear why this could serve as justification for not fulfilling the requirement in this particular case. Since the strength values in question were only slightly below the requirements, and the overall number of samples was over 400 [KYMENLAAKSO 2006], this point, by itself, seems to be of lesser importance. Still, it is one more example of crossing a line by accepting deviations.

It is noteworthy that concrete for the nuclear island at Olkiluoto 3 will no longer be supplied by Forssan Betoni, as was announced April 25, 2007 [NNF 2007]. On the one hand, this seems to be an adequate response to the problems encountered with the base slab. On the other hand, change of an important sub-contractor during construction renders the project still more complicated and could give rise to new problems in the future.

In the context of the base slab concrete, furthermore, an entirely different question arises, which – to the knowledge of the authors – has not been dealt with in published information so far: It should be clarified whether the higher water content of the base slab concrete could in any way interact with the functioning of the so-called core catcher (an installation for containing and cooling the molten core in case of a severe accident) of the EPR.

There is a spreading area of 170 m^2 for the molten core; the floor of this area is covered by iron elements with a thickness of 20 cm, on which a concrete layer of about 10 cm will be poured [STUK 2005, 5.5]. The base slab is not in direct contact with the core catcher, since there is a special concrete slab between the core catcher and the steel liner (with a thickness of 50 cm), as well as a further concrete slab (thickness – 15 cm) below the liner. According to STUK, the design concept is such that molten core material will not reach the first concrete slab below the core catcher [STUK 2007b].

When concrete is heated by the molten core, spalling can occur – cracking off of pieces because of very rapid evaporation of water in the concrete, which leads to increasing pressure. Spalling can propagate through the concrete. It makes the core-concrete interaction inpredictable and can significantly accelerate concrete erosion. Spalling occurs more easily in concrete of higher water content [SEVÓN 2005].

The base slab's higher water content is unlikely to lead to problems as long as the core catcher functions according to its design concept, if an accident occurs.

However, considerable uncertainties are attached to the operation of the core catcher because it is very difficult to model or test by experiment. Hence, it appears possible that the core catcher will not function as expected during an accident sequence. If, in this case, the two dedicated concrete slabs directly below the core catcher are melted through, direct interaction of the molten core with the base slab concrete will occur, and the higher water content of this concrete could be highly disadvantageous.

Taking the thickness of the special slabs below the core catcher into account, their melt-through cannot simply be postulated to be excluded. Investigations concerning possible malfunctioning of the core catcher and the consequences for the concrete slabs are urgently required.

3. Summary and Conclusions

3.1 Summary Concerning the Problems Discussed

Primary piping:

This issue is of high safety significance. The safety case for the primary piping relies on break preclusion. An unlimited break of the piping is considered, by vendor, licensee and STUK, to be practically excluded at Olkiluoto 3. It is not an accident which has to be definitely controlled by the safety systems (design basis accident, DBA). (It is a design basis accident for the operating Finnish NPPs.)

For design basis accidents, Finnish nuclear safety standards require a sufficient cooling capacity even in case of failure in one train of the system, and simultaneous unavailability of another because of repair or maintenance ("n+2" principle). For a complete break of the primary piping, the emergency core cooling system merely has "n+1" capacity.

Furthermore, accident analyses have to be performed in a conservative manner for design basis accidents, leaving safety margins for inaccuracies and errors. The analyses for complete break of primary piping, however, are only carried out with so-called "best estimate" methodology, further reducing overall safety.

Break preclusion is a doubtful concept at best. It presupposes near-perfect control of manufacturing, and regular inspections of very high accuracy and reliability. It is clear that control of manufacturing was considerably less than perfect for the Olkiluoto 3 components so far. The primary piping, in its entirety, did not conform to the safety criteria. Even an experienced manufacturer had problems with the big size of the forgings. Thus, the pipes could not be inspected by the ultrasonic methods selected for Olkiluoto 3.

A new manufacturing program is now under way. Most pipes have already been cast, although test results from the first forgings are not yet available. Very little information on the inspection methods and the extent of their use has been made available so far.

Problems have also occurred in the manufacture of the other main components of the primary circuit – the reactor pressure vessel, the pressurizer and the steam generators.

If the problems persist, the probability of loss-of-coolant accidents will be increased, and hence the probability of a core melt.

Containment liner:

The containment steel liner constitutes the third and last barrier against radioactive releases to the environment. In case of a severe accident, a defective liner is likely to lead to releases which are higher and occur earlier, than in case of an intact liner.

The original EPR design did not include a steel liner. STUK insisted on a liner to improve the tightness of the containment. Thus, the safety significance of the liner is obviously rated very high by the authority. Nevertheless, errors occurred during the manufacture, concerning welds, pipe penetrations etc.

The measures which were taken after the issue was recognised seem appropriate to mitigate the problem. However, standards have been lowered by accepting root gaps in welds wider than specified. Furthermore, it is not definitely clear to which extent the overall state of the containment liner, after implementation of all measures, will be inferior to the original, error-less design. Hence, it is also not clear whether a significant increase of plant hazard resulted from this issue.

Concrete base slab:

The base slab has to withstand loads during plant construction and operation, as well as in case of internal and external accidents (for example, earthquakes). The strength of the concrete is a parameter important for plant safety.

Due to a water content higher than specified, compressive strength as well as chemical resistance of the base slab concrete are below requirements. (Reduced chemical resistance implies that concrete strength could suffer in the longer term.)

Regarding compressive strength, according to the STUK investigation report 1/06 the deviations from requirements are small, and their safety significance appears low.

The shortcomings regarding chemical resistance have led to counter-measures being planned by TVO: An additional protection of the base slab against external moisture is envisaged. This measure is still under investigation by STUK. No details are known. In particular, it is not known to which extent inspection of the surfaces concerned will be possible later, in order to ascertain that protection is indeed adequate.

An issue which has not been discussed publicly at all in this context is the possible impairment of the function of the core-catcher due to the problems with the base slab concrete. When concrete is heated by the molten core, in the course of an accident, spalling can occur – cracking off of pieces because of very rapid evaporation of the water in the concrete. Spalling can significantly accelerate concrete erosion; it occurs more easily in concrete of higher water content.

If, in case of an accident, the core catcher does not quite function as planned, and the concrete of the base slab comes into contact with the melt, the resulting problems will therefore be exacerbated.

There are two special concrete layers with an overall thickness of 65 cm between the core catcher and the base slab. Nevertheless, this issue should be pursued further; it is by no means clear that it is irrelevant.

3.2 General Conclusions

Open questions remaining:

About ten months after the publication of the STUK investigation report of July 2006, and about one and a half years after the first published hints about quality control problems at the Olkiluoto 3 project, there are still open questions remaining – in spite of some additional information provided to the authors by STUK upon inquiry.

The open questions concern many issues – they include, for example, the extent of the problems during manufacture of the reactor pressure vessel, the methods employed for in-service inspection of the primary piping, the procedure for remanufacturing the primary piping, the overall state of the containment liner after the repairs performed, the effectiveness of the counter-measures planned because of the reduced chemical resistance of the base slab concrete and the potential significance of the higher water content of the base slab concrete for the functioning of the core catcher.

Slackening of safety requirements:

During the planning and construction phase of the Olkiluoto 3 EPR, safety requirements have been relaxed on several levels.

This is first eveident at the level of basic requirements as they are codified in the STUK safety guides (YVL Regulatory Guides). YVL Guide 1.0 [STUK 1996] requires the emergency core cooling system to carry out its function even if one train fails and another train is inoperable due to repair or maintenance. This requirement implies that two more trains than needed are provided for the safety function ("n+2" principle). It applies to all design basis accidents.

In a description of Olkiluoto 3 published by AREVA, it is claimed that this principle is upheld at the EPR for all safety systems [AREVA 2005a].

However, the unlimited break of a main coolant pipe is not regarded as a design basis accident for Olkiluto 3 (as opposed to the operating Finnish NPPs). As a consequence, there is only one more train than needed ("n+1" instead of "n+2"); and accident analyses are not carried out in a conservative manner (which would provide for safety margins).

On a technical level, specifications for the root gaps of welds between plates of the containment liner were not adhered to, but accepted by STUK nevertheless. In a similar manner, deviations from specifications for the base slab concrete were accepted.

In the latter case, STUK pointed out that the Finnish concrete code does not differentiate between different cement types although it is known that some types have particularly good chemical resistance, even with water contents above specifications. This is an alarming sign of deficient safety philosophy. If a code is not sufficiently differentiated, then this issue should be raised as soon as it is discovered. It is highly inappropriate for "code-bashing" to occur **after** a deviation has been observed.

In any case, accepting the violation of a code requirement is highly problematical. After the disaster of the Challenger space shuttle, which was caused by several slackenings of the definition of what constitutes an acceptable deviation, a NASA representative made the following statement [VAUGHAN 1996]:

"Once you've accepted an anomaly or something less than perfect, you know, you've given up your virginity. You can't go back. You're at the point that it's very hard to draw the line. You know, next time they say it's the same problem, it's just eroded 5 mils more. Once you've accepted it, where do you draw the line?"

<u>Influence of the "first-of-a-kind" factor:</u>

Olkiluoto 3 is the first EPR ever built. It is conceivable that some of the quality control problems encountered in the construction phase are due to the "first-of-a-kind" factor. However, it does not seem likely that the role this factor plays is very large.

Olkiluoto 3 is constructed under a tight schedule, with considerable cost pressure. The same is likely to hold for future nuclear power plant projects. Furthermore, it can be assumed that the number of such future projects will remain rather small, because of lack of public acceptance, the high costs as well as uncertainties regarding the future economic and regulatory environment.

Also, there are many different concepts for new NPPs bearing the label of “Generation III”, besides the EPR. The most important examples for designs roughly in the EPR size category are [HIRSCH 2005]:

Pressurized water reactors: APWR (Mitsubishi/Westinghouse), APWR+ (Mitsubishi), AP-1000 (Westinghouse), KSNP+ and APR-1400 (Korean Industry) and CNP-1000 (China National Nuclear Corporation).

Boiling water reactors: ABWR and ABWR-II (Hitachi, Toshiba, General Electric), BWR 90+ (Westinghouse Atom of Sweden), SWR-1000 (Framatome ANP) and ESBWR (General Electric).

Hence, there will be fierce competition for every new reactor project and it is well possible that only a few units will be built of each of those types. In this case, it will not be possible to gain experience on a large scale, for one particular concept. Every reactor built will be among the “first-few-of-a-kind”, if not “first-of-a-kind”.

It can be expected that every new reactor project will involve a large number of sub-contractors from different countries, as in the case of the Olkiluoto EPR (see below), because cost pressure will induce the main contractor to seek the cheapest bidders for the various tasks. For some kind of work, local sub-contractors will have to be used – possibly with little or no experience with nuclear projects. This complex project structure will further obstruct any learning processes.

Finally, it seems that the value of prior experience with the same reactor type or similar reactor types should not be overrated, anyway. Otherwise, according to an AREVA brochure, the problems at Olkiluoto 3 could never have occurred. AREVA emphasized – well before the quality control problems at the Olkiluoto site became known [AREVA 2005b]:

“The EPR is the direct descendant of the well proven N4 and KONVOI reactors, guaranteeing a fully mastered technology. As a result, risks linked to design, licensing, construction and operation of the EPR are minimized, providing a unique certainty to EPR customers.”

Regarding the “unique certainty” and the absence of risks in the construction phase, the customer TVO meanwhile would probably beg to disagree.

<u>Chances for improvement at the Olkiluoto 3 site:</u>

The prospects for fundamental improvements in the further course of the Olkiluoto 3 construction period look equally bleak. Among the claims which AREVA put forward for selling the EPR, a short construction time featured prominently [AREVA 2005b]:

“The evolutionary approach adopted for the EPR allows its construction schedule to benefit from vast construction experience feedback […].

Provisions have been made in the design, construction, erection and commissioning methods to further shorten the EPR construction schedule as far as possible."

AREVA, as the vendor of Olkiluto 3, is under greater pressure of time than ever before, now that the schedule has already slipped. AREVA will be keen to avoid further disgraces, which would not only lead to trouble with TVO, but also reduce their chances to sell further NPPs on the world market. Hence, the incentive to cut corners is high, and will become higher with each further delay – possibly starting a vicious circle.

Management of the project is particularly difficult because of its complicated structure. By August 2006, about 1100 subcontracts have been concluded, about half of them with Finnish companies. Altogether, there are sub-contractors from 26 countries [NEI 2006]. It is likely that most of the subcontracts were awarded well before the quality assurance problems at the site became apparent, and improvements were attempted. Hence, it is doubtful if substantial improvements in the subcontractors' work will be possible.

The situation is further aggravated because Olkiluoto 3 is constructed under a turnkey contract. A contract of this type implies a fixed price; price increases because of unforeseen problems and delays have to be shouldered by the vendor.

A turnkey contract appears particularly unsuitable for a "first-of-a-kind" project since a more flexible contractual arrangement would create less pressure, and hence leave more leeway for learning processes. This chance, however, has been lost for Olkiluoto 3.

(To be sure, it is more than doubtful whether TVO would have ordered an NPP on a basis other than turnkey. This, however, does not constitute an argument for turnkey contracts, but rather, it casts serious doubt on the economic viability of new nuclear projects.)

Finally, the control of the project by the licensing authority STUK has been rendered very difficult because the detailed design of the plant was not finished at the time the construction license was granted – it was not even finished at the time of the investigation of the quality assurance problems 2006. The time and amount for work required for elaborating the design had been under-estimated [STUK 2006, p. 44/45].

Thus, an attempt to accelerate the project by starting the construction work before finishing the design – with the support of the licensing authority – actually aggravated the problems at the site. As already pointed out, the pressure of time for AREVA is now greater than ever. As a precondition for improving the situation, it would be essential for the licensing authority to strictly repudiate any future attempts at “fast-tracking” which might result from this pressure.

Closing remark:

The EPR is supposed to belong to a new generation of reactors with an enhanced safety level. The experience at the Olkiluoto 3 site indicates, however, that it is highly questionable whether even present-day safety standards will be kept at this plant.

Naturally, any attempt to predict whether problems will keep occurring in the future at the Olkiluoto site is beset with large uncertainty. One thing, however, is not uncertain at all:

In case problems should occur again, the chances that they will become known and will be subject of public debate are greater if there is a well-informed public, supported by effective and alert NGOs and media, following up any hints that things might have gone amiss and keeping up a dialogue with the licensing authority. Thus, as long as the EPR project at Olkiluoto is continued, it needs to be closely and vigilantly observed.

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