

Swedish Utility Experience With ASEA- ATOM-Design Top Guides



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R E P O R T S U M M A R Y

SUBJECTS Nuclear plant corrosion control / Nuclear component reliability

TOPICS BWR Stress corrosion cracking
Reactor components Radiation effects
Cracking (fracturing)

AUDIENCE Plant engineers / R&D scientists

Swedish Utility Experience With ASEA-ATOM-Design Top Guides

Examination of ASEA-ATOM core grids, which are comparable to top guides in General Electric–design BWRs, revealed intergranular stress corrosion cracking of guide bar bolts, possibly accelerated by crevice condition and irradiation. Prompted by these guide bar bolting failures and concern about irradiation-assisted stress corrosion cracking, two Swedish utilities have replaced their core grids. Analysis showed no cracking in the core grid itself.

BACKGROUND Irradiation-assisted stress corrosion cracking (IASCC) has emerged in recent years as a potential problem in nuclear reactors, particularly for BWR components—such as top guides, core shrouds, and support plates—that are not easily replaced. The core grid in ASEA-ATOM BWRs in Sweden is comparable to the General Electric (GE) BWR top guide in the United States except that the Swedish design is more easily replaced. Bolt-ing failures in the core grids of several Swedish BWRs, along with concerns about the possibility of IASCC in the core grid, led to replacement or planned replacement of the entire grid at several plants.

OBJECTIVES To document recent guide bar bolting failures and to trace the change in design philosophy for the ASEA-ATOM BWR core grids.

APPROACH The investigative team reviewed vendor records and data from 11 ASEA-ATOM BWRs related to the design and operating histories of five generations of core grids. The team traced the philosophy behind the evaluation of each of these designs, with particular attention to occurrences of intergranular stress corrosion cracking (IGSCC) and concerns about IASCC. They conducted detailed analyses of several guide bar bolt failures, as well as core grid repair and replacement programs at several plants.

RESULTS Guide bar bolts made from alloy A-286 and Type 316 stainless steel have cracked in nine Swedish BWRs; fast-neutron fluence ranged from 1.8 to 9.0×10^{20} n/cm². Cracking seems independent of location and thus not dependent on fluence level; however, crevice-induced IGSCC, aggravated by accumulated fluence, seems a likely cause. Nine plants have performed

repair procedures on the guide bars and associated bolting. Five of these plants considered these repairs as temporary: Oskarshamn-1 and -2 subsequently replaced the entire core grid assembly, and Ringhals-1 and Barsebeck-1 and -2 plan replacement during the next two years. All components in the replacement core grids are or will be constructed of Type 316L stainless steel, with limited silicon, phosphorous, and sulfur content. Visual inspection of the old Oskarshamn-2 core grid—exposed to a maximum fluence level of 1.3×10^{21} n/cm²—revealed no evidence of cracking or other damage to the grid itself.

EPRI PERSPECTIVE IASCC of major components, such as the top guide in a GE BWR, would prove costly to a utility. Unlike the ASEA-ATOM design, the top guide in a GE BWR is not easily replaced, and replacement could cost more than \$100 million. Bolting failures in the ASEA-ATOM core grid do not directly apply to GE top guides, as the GE design does not contain bolted grid bars. However, the fact that the core grid itself did not crack after fluences as high as 1.3×10^{21} n/cm² is significant, since the GE top guide can experience similar fluence levels and stresses.

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ABSTRACT

The main features of the 16 core grids (top guides) designed by ABB ATOM AB are briefly described and the evolution of the design is discussed. One important characteristic of the first nine grids is the existence of bolts securing guide bars to the core grid plates. These bolts are made of precipitation hardened or solution annealed stainless steel. During operation, bolts in all nine grids have cracked. The failure analyses indicate that intergranular stress corrosion cracking (IGSCC), possibly accelerated by crevice conditions and/or irradiation, was the cause of failure. Fast neutron fluences approaching or exceeding the levels considered as critical for irradiation assisted stress corrosion cracking (IASCC) will be reached in a few cases only. Temporary measures were taken immediately after the discovery of the cracking. For five of the nine reactors affected, it was decided to replace the complete grids. Two of these replacements have been successfully carried out to date. IASCC as a potential future problem is discussed and it is pointed out that, during their life times, the ABB ATOM core grids will be exposed to sufficiently high fast neutron fluences to cause some concern.

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Section 1

INTRODUCTION

There are now eleven ABB ATOM Boiling Water Reactors in operation (Table 1-1). During the approximately 100 years of experience that have been accumulated so far, only a few technical problems have occurred. Especially noteworthy is the fact that incidents involving intergranular stress corrosion cracking (IGSCC) have been rare. One of these incidents, which later was found to represent a generic problem, was the fracture of bolts in the core grid. This was first discovered in Forsmark 2 during 1982 and later in all reactors which were fitted with such bolts. The core grid is analogous to the top guide in the General Electric BWR.

Irradiation assisted stress corrosion cracking (IASCC) has emerged in recent years as a potential problem for reactor internals. At one time the belief was that some of the bolt failures were caused by IASCC. Although this is less certain today, interest has been focused on this corrosion phenomenon for other reactor internal components, especially those constructed of austenitic stainless steels such as the core grid. The present report reviews the core grid status for the ABB ATOM BWRs with the background of the IASCC problem.

Table 1-1

ABB ATOM NUCLEAR POWER PLANTS

	Gross Capacity MWe	Scope of supply	In operation
Oskarshamn 1	460	Turnkey	1972
Oskarshamn 2	615	Nuclear Island	1974
Oskarshamn 3	1100	Nuclear Island	1985
Ringhals 1	780	Nuclear Island	1975
Barsebeck 1	615	Nuclear Island	1975
Barsebeck 2	600	Nuclear Island	1977
TVO 1	735	Turnkey	1979
TVO 2	735	Turnkey excl civil works	1980
Forsmark 1	940	Nuclear Island	1980
Forsmark 2	940	Nuclear Island	1981
Forsmark 3	1100	Nuclear Island	1985

Section 2
CORE GRID DESIGN

The main function of the core grid in the ABB ATOM BWR is to laterally support the fuel element top and the tubes carrying core instrumentation and neutron sources. The moderator tank lid and the steam and moisture separators are also supported, as shown in Figure 2-1. This drawing refers to TVO 1 and 2 but could also represent Forsmark 1 and 2, which are similar. Other ABB ATOM reactors differ in details but have the same general lay-out. One important, common feature is the fact that the core grid can be removed relatively easily.

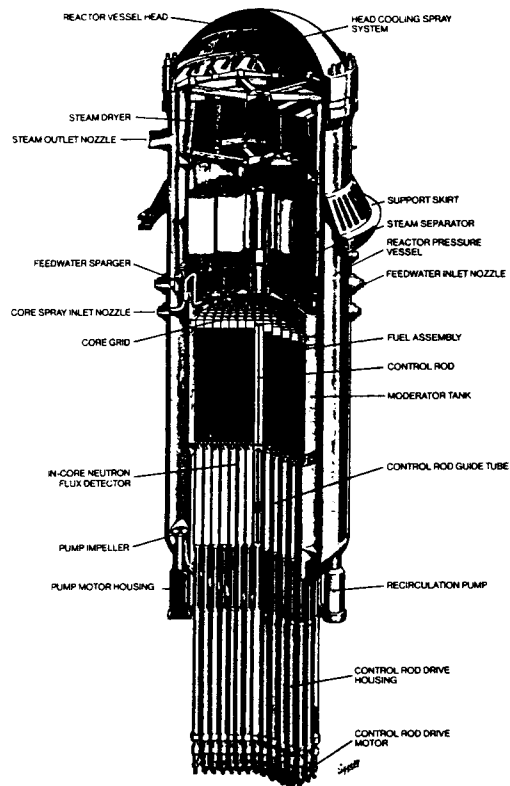


Figure 2-1
General Outline of the TVO Reactors Showing the Position
of the Core Grid and Other Internals

A core grid is composed of upended plates forming a square pattern. Slots in the plates assure that they are correctly positioned. The grid is welded to a support ring. Each square houses a core module consisting of four fuel bundles and one control rod. Except for Oskarshamn 3 and Forsmark 3 guide bars are fixed to the sides of the squares. These bars delineate four subsquares, each one guiding one fuel bundle. Springs on the top of the bundles assure their positioning.

A diagram of the Forsmark 3 core grid is shown in Figure 2-2. The relevant design data for all core grids manufactured until the present are presented in Table 2-1. The Table also contains information on core grids currently being manufactured. The details of the Table are discussed below.

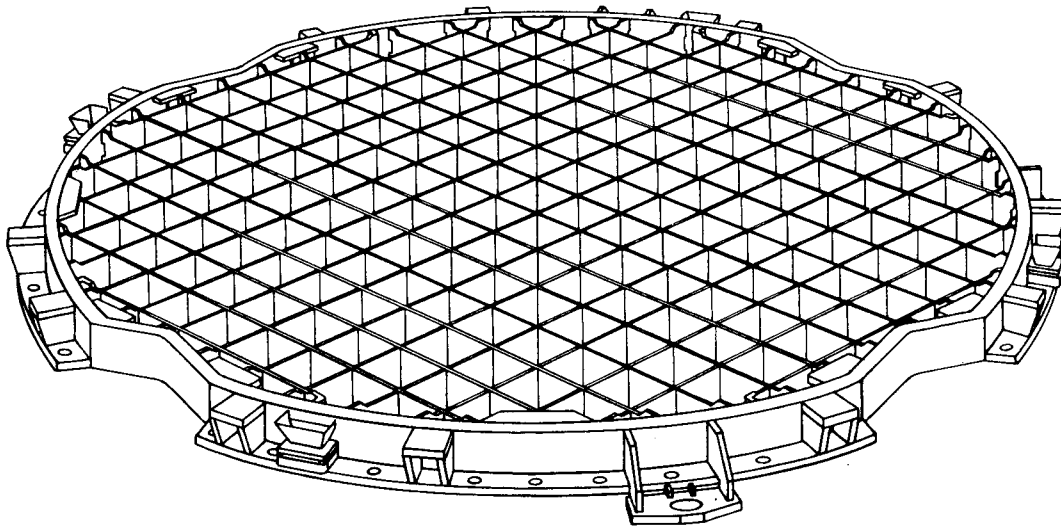


Figure 2-2
Core Grid - Forsmark 3

It can be noted in Figure 2-2 that the outer ring of the Forsmark 3 grid is provided with arrangements, such as holes and brackets, to assure the correct positioning of the grid and other structures. Although the Forsmark 3 and Oskarshamn 3 grids are special in many respects, which will be discussed below, these features are also present in other ABB ATOM reactors.

Table 2-1
CORE GRID DATA

Start of operation	Core grid	Generation	Material		Grid plates			Effective Full Power Hours	Max fast neutron flux rate $n/cm^2 \cdot s \times 10^{-12}$	Max fast neutron fluence $n/cm^2 \times 10^{-20}$
			Grid plate and guide bar	Bolt	Width mm	Thickness mm	Slot depth mm			
1972	Oskarshamn 1/1	1	347	316	235	7	31/206	86000	2.6	8.1
1974	Oskarshamn 2/1	2	304	316	320	7	42.5/280.5	81700	4.4	13
1975	Ringhals 1/1	1	347	316	400	7	298.5/208.5	68500	4.2	10
1975	Barsebeck 1/1	2	304	316	320	7	42.5/280.5	81900	4.5	13
1977	Barsebeck 2/1	2	304	316	320	7	42.5/280.5	75800	4.5	12
1979	TVO 1	3	304	A286/316L	360/278	7	41.5/278.5	63400	4.1	9.4
1980	TVO 2	3	304	A286/316L	360/278	7	41.5/278.5	49500	4.1	7.3
1980	Forsmark 1	3	304	A286/316L	360/278	7	41.5/278.5	48400	4.1	7.1
1981	Forsmark 2	3	304	A286/316L	360/278	7	41.5/278.5	41700	4.1	6.2
1983	Oskarshamn 3	4	304L	-	200	9	-	13600	1.2	0.67
1983	Forsmark 3	4	304L	-	200	9	-	15500	1.2	0.67
1986	Oskarshamn 1/2	5	316L	316L	235	7	118.5/118.5	7200	2.6	0.67
1986	Oskarshamn 2/2	5	316L	316L	320	7	161/161	7300	4.4	1.2
1988	Ringhals 1/2	5	316L	316L	400	7	201/201	-	-	-
1988	Barsebeck 2/2	5	316L	316L	320	7	161/161	-	-	-
1989	Barsebeck 1/2	5	316L	316L	320	7	161/161	-	-	-

As shown in Table 2-1, a total of 16 core grids have been designed by ABB ATOM AB. It is both convenient and relevant to consider this series as a number of development steps, and earlier experience was continuously taken into account. Obviously, operating experience has been of importance only for the more recent grids. Although Oskarshamn 1 had been in operation for a few years when the design of the core grids for TVO 1, TVO 2, Forsmark 1 and Forsmark 2 was finalized, this experience was too limited to really influence the design. From Oskarshamn 3 and Forsmark 3 on, however, operating experience was exploited.

The original core grids of Oskarshamn 1 and Ringhals 1, here designated Oskarshamn 1/1 and Ringhals 1/1, can be considered as representing Generation 1. These grids were manufactured from a niobium stabilized stainless steel in accordance with Swedish Standard SIS 2338, corresponding to Type 347 SS. The same material was used for the guide bars. (In Table 2-1, for brevity, the corresponding American material designations are used.)

Figures 2-3 and 2-4 show how guide bar pairs are fixed to the core grid plate. All grids belonging to Generations 1 through 3 have the same arrangement although the dimensions vary, as indicated in Table 2-1. The bolts were manufactured from molybdenum alloyed stainless steel (Swedish Standard SIS 2343 corresponding to Type 316 SS). The positioning slots of the two perpendicular systems of plates have different depths. The plates are welded to each other.

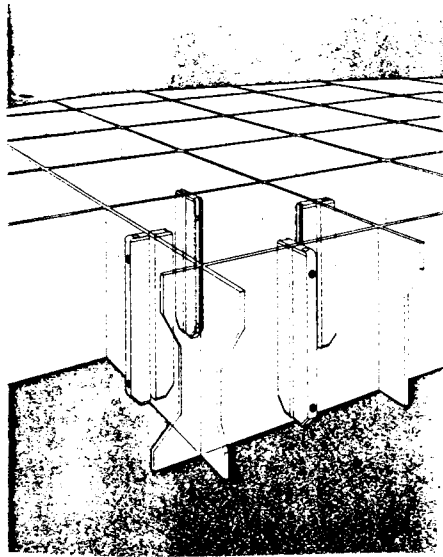


Figure 2-3
Attachment of Guide Bar Pairs to Core Grid Plates

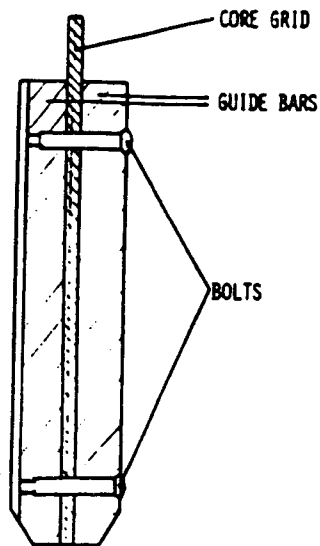


Figure 2-4
Guide Bar Assembly

Stabilized austenitic stainless steels have traditionally been widely used in Europe, and especially so in Germany. It was therefore natural to select such a material when the first reactors were designed in Sweden. Later, however, a regular standard Swedish 18/8 chromium nickel austenitic stainless steel with a carbon content of maximum 0.05 % was believed to be satisfactory for the core grid application. A change to this material also led to lower costs. This was the background for the introduction of SIS 2333 (Type 304 SS) material in the Generation 2 core grid, which is represented by Oskarshamn 2/1, Barsebeck 1/1 and 2/1. Material to SIS 2333, corresponding to Type 304 SS, is used for grid plates and guide bars. Bolts are made from SIS 2343 as for Oskarshamn 1/1 and Ringhals 1/1. The positioning arrangement with different slot depths in the two systems of grid plates is similar to Generation 1.

The TVO and Forsmark grids, representing Generation 3, are similar and have grid plates and guide bars made of the same material (SIS 2333/Type 304 SS) as Generation 2. The bolts, however, were made from the precipitation hardening stainless steel SIS 2570 corresponding to A286. These were later exchanged, and the new bolts were made from SIS 2353 (Type 316L SS). The two systems of grid plates have different widths. The slots in the wide plates are closed in both ends allowing the narrow plates to be inserted, positioned and welded.

When the TVO and Forsmark reactors were designed, certain postulated events resulted in large lateral forces in the core grid region, which required the guide bar bolts to be made of high strength material. After the cracking of these bolts (see below) new calculations were made and it was shown, that Type 316 L SS material indeed was sufficient.

Oskarshamn 3 and Forsmark 3 (Generation 4) are unique in that they are manufactured from forged plates. This means that the "guide bars" are integral with the grid and so the need for welding was avoided. This design was selected because certain earth quake criteria had to be applied. The material is SIS 2352 (Type 304L SS).

Due to the high cost this fabrication method was abandoned for Generation 5, represented by Oskarshamn 1/2 and 2/2, installed in 1986, and Ringhals 1/2, Barsebeck 2/2 and 1/2 now being manufactured. SIS 2353 (Type 316L SS) is used for all these five grids, as well as for guide bars and bolts. Due to IASCC considerations the silicon, sulphur and phosphorus contents were reduced for the last three grids. The two plate systems have slots of the same depth. The guide bar assembly has a new, proprietary design which is believed to be completely safe from the stress corrosion point of view.

Section 3

OPERATING HISTORY

As of the summer of 1987 (refueling outage) the core grid operating times vary from 7200 (Oskarshamn 1/2) to 86000 hours (Oskarshamn 1/1), see Table 2-1. Due to slight differences in design, the maximum fast neutron fluxes on the lower side of the core grids vary between different reactors. The two Barsebeck grids have the highest flux rate ($4.5 \cdot 10^{12}$ n/cm² ·s) whereas the corresponding value for the grids of Oskarshamn 3 and Forsmark 3 is only $1.2 \cdot 10^{12}$. The highest fast neutron fluence experienced so far is $1.3 \cdot 10^{21}$ n/cm² and refers to Oskarshamn 2/1 and Barsebeck 1/1. Due to replacement during 1986, this value represents the final fluence for Oskarshamn 2/1. It should be noted at this point that this replacement was prompted by fractures of the guide bar bolts (see Section 4) and not by cracks in the core grid or guide bars themselves.

Section 4

GUIDE BAR BOLT FAILURES

The guide bars are fixed to the core grid plates with two bolts, as shown in Figures 2-3 and 2-4. All grids belonging to Generations 1 through 3 have the same guide bar arrangement. Dimensions and design details vary slightly however. Different materials have been used for the bolts, as discussed earlier.

During the refueling outage of Forsmark 2 in 1982 it was shown by ultrasonic inspection that a large number of bolts had cracked (more than 200 indications). At least two bolts had fractured completely. Later that same year the status of the bolts was investigated for Forsmark 1, TVO 1 and TVO 2. Fractured or cracked bolts were found in all three reactors. For all Generation 3 core grids the original bolts were manufactured from precipitation hardened A286 material.

In 1984, during refueling of Oskarshamn 1, a fuel bundle was dropped on the core grid. One pair of guide bars was broken loose and another deformed. It was subsequently found that one of the Type 316 SS bolts in the first pair had fractured before the incident. In 1985 the status of the Type 316 SS guide bar bolts in Ringhals 1, Oskarshamn 2 and Barsebeck 1 was checked ultrasonically. More but less severely cracked bolts were found in all three reactors. From the fall of 1984 Barsebeck 2 was operating in an 18 month cycle. The status of the guide bar assemblies could therefore not be checked until the 1986 refueling outage. Ultrasonic testing revealed, that bolts had also cracked in the Barsebeck 2 core grid.

In all, cracked bolts have thus been found in nine core grids, i.e. in all grids belonging to Generations 1 through 3. Bolts from five of these have undergone structural investigations. The observations will be briefly summarized below. Table 4-1 gives a few numerical data related to the investigated bolts. The geometries of bolts in different grids vary slightly, as shown in Figure 4-1.

Table 4-1
BOLT INVESTIGATIONS

Core grid	Generation	Material	Number of bolts investigated	Maximum crack depth, mm ¹⁾	Fast neutron fluence $n/cm^2 \times 10^{-21}$ ²⁾	Hardness Vickers ²⁾
Forsmark 2	3	A286	2	unknown	unknown	285/-
Oskarshamn 1/1	1	316 SS	4	2	0.23/0.90	235/235
Oskarshamn 2/1	2	"	4	0.9	0.14/0.18	280/-
Barsebeck 1/1	2	"	4	0.8	0.18/0.7	300/-
Ringhals 1/1	1	"	4	0.5	-/0.35	240/240

Notes

- 1) Not including complete fractures (Forsmark 2, Oskarshamn 1/1 and Ringhals 1/1)
- 2) First values refer to upper bolt

The A286 material for the Forsmark 2 bolts was precipitation hardened to a yield strength of approximately 665 N/mm^2 (hardness 300 Brinell). The two bolts investigated belonged to the same guide bar assembly. They had both cracked in the area of smallest diameter, the lower bolt in the plane of the area reduction and the upper 3 mm further down, i.e., both bolts had cracked in the region subjected to the highest stress (see arrow in Figure 4-1). The fracture surfaces were covered with a dark oxide layer.

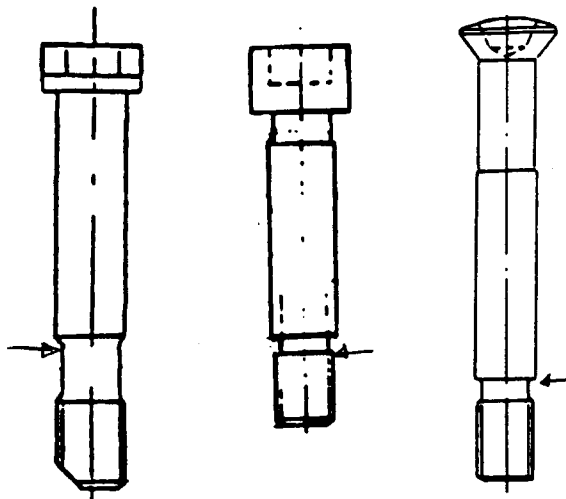


Figure 4-1
Core Grid Bolts for Forsmark 1, Forsmark 2, TVO 1 and TVO 2 (left), Oskarshamn 1 (center) and Ringhals 1, Oskarshamn 2, Barsebeck 1 and Barsebeck 2 (right). (Ringhals 1 is slightly different.)

Both fractures were almost completely intergranular. Small areas (less than 2-3 mm) with different appearance were interpreted as residual fractures. This indicates that IGSCC has propagated through the whole cross section. Hardness of the upper bolt was measured and found to be approximately the same as for new material. When the cracks were discovered in 1982, Forsmark 2 had been in operation for only one year and the neutron fluence received by the bolts should have been relatively low.

The cracking of the A286 bolts was considered as a clear case of IGSCC, possibly accelerated by the crevice geometry. The bolts may have been stressed to approximately 80 % of the yield strength. It has been known for some time that precipitation hardening alloys, if highly stressed, are quite sensitive to IGSCC in normal BWR water chemistry (1). This is especially true for the A286 alloy, and it is therefore not surprising, that the bolts did crack.

The bolts from the two damaged guide bar assemblies in Oskarshamn 1/1 were investigated in 1984. The upper bolt in the deformed guide bar assembly was found to be completely broken at the first thread (see arrow in Figure 4-1). The fracture surfaces were oxidized. The bolts in the guide bar assembly that had been broken loose by the falling fuel bundle had fresh fractures. Microstructural investigations showed that all four bolts had numerous shallow intergranular cracks. In threads and recessed areas, a slightly cold worked structure was present close to the surface. This was not related to the cracks. No grain boundary carbides were found. The hardness has increased from 170 to 235 Vickers approximately, which could be expected due to the irradiation hardening. No difference between upper and lower bolts was observed.

The preliminary conclusion was that the cracking had been caused by IASCC. The general sensitivity of the bolt material for intergranular corrosion was checked using a modified Strauss test and the Huey test according to ASTM A 262-82, Practice C. None of these tests revealed sensitivity.

An attempt was also made to analyze the grain boundaries of the steel by using a Scanning Transmission Electron Microscope (STEM) with analyzing capabilities. No proofs of enrichment or depletion in the grain boundaries were obtained. The elements analyzed were chromium, nickel, molybdenum and silicon. Although not conclusive, this finding made the IASCC hypothesis less probable.

Another theory was that the failure cause could have been IGSCC initiated by molybdenum disulfide. Proofs that this lubricant had been used could not however be found although this could not be ruled out. That molybdenum disulfide is detrimental is a well known fact and its use has for a long time been prohibited in ABB ATOM BWRs. Surface deposits were

analyzed by X-ray fluorescence and surface oxides by SEM. No traces of molybdenum disulfide were found.

In 1985 bolts from Oskarshamn 2/1, Barsebeck 1/1 and Ringhals 1/1 were successively investigated. The general picture was similar to Oskarshamn 1/1. Numerous rather shallow intergranular cracks were found in all investigated bolts. However, with few exceptions, the cracks were concentrated to the cylindrical part with the largest (8,5 mm) diameter. An example of crack distribution is shown in Figure 4-2.

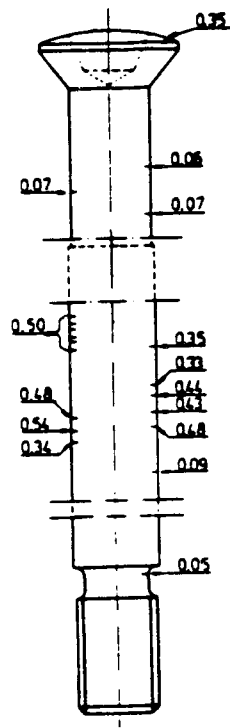


Figure 4-2
Crack Pattern in one Ringhals Bolt
Numbers indicate depth in mm

Two of the Ringhals 1/1 bolts belonging to the same guide bar assembly were removed because of ultrasonic indications. These two bolts were completely broken. The fractures were located in the recess area, where the diameter changes from 8,5 to 8,0 mm.

Microstructures were in all cases normal for solution annealed material. No signs of sensitization were found. As in Oskarshamn 1/1 slightly cold worked areas were observed, especially in threads and recesses. However, no cold work was found in the area where most cracks were observed, i.e. the largest diameter region. Crevice and/or wear marks were observed locally in this region. In some cases cracks had been initiated there.

Intergranular cracking has thus been found in a large number of guide bar bolts. Although no systematic study has been made, it seems likely that the general cracking behavior is relatively independent of the location of the bolts and thus of the fast neutron fluence. It is probable, that the upper bolts from Ringhals 1/1 have received a fluence of less than 10^{20}n/cm^2 , still one of these bolts was completely broken. This fluence is a factor of at least five lower than what is generally believed to be a critical range (see below). An IASCC mechanism therefore seems to be less probable, although it cannot be ruled out.

It is known that non-sensitized stainless steels and nickel base alloys may undergo IGSCC in crevices under BWR conditions if the surrounding water conductivity is high (above 0,2-0,3 $\mu\text{S/cm}$), (2). In the ABB ATOM BWRs the conductivity is generally well below 0,2 $\mu\text{S/cm}$ even when operating with normal water chemistry.

A complete understanding of the guide bar bolt failures has thus not been established. It can only be stated that the cracks are intergranular and that the existence of an aggressive crevice chemistry probably has played an important role. In most cases the fast neutron fluences are below the level normally considered critical with respect to IASCC ($5 \cdot 10^{20} \text{n/cm}^2 > 1 \text{ MeV}$), (3). It is, however, possible that the conditions for IASCC were aggravated by crevices in which cracking initiated. Crevice induced IGSCC aggravated by the accumulated irradiation fluence thus cannot be ruled out.

Section 5

CORE GRID REPAIR PROCEDURES AND REPLACEMENT PROGRAMS

The first indication that bolts had cracked or broken in Forsmark 2 were found during the regular refueling outage early in May 1982. During the following weeks, similar observations were successively made in TVO 1, TVO 2 and Forsmark 1. It was quickly decided to replace all bolts and guide bars in the four reactors.

For TVO 1 a temporary solution was applied in 1982 involving the modification of 37 fuel element top plates to assure that damaged guide bar assemblies were kept in place. This work prolonged the outage one week.

For the other three reactors, beginning with Forsmark 2, procedures had to be worked out, material purchased, replacement components manufactured etc. in the shortest possible time. This, of course, led to a considerable prolongation of the scheduled outages. For Forsmark 2 the reactor was shut down 16 weeks instead of five, i.e. eleven weeks more than planned. For Forsmark 1 and TVO 2 the prolongation was only seven and two weeks, respectively. The experience gained from the work at Forsmark 2 could thus be successfully exploited. One reason for the very short prolongation experienced in TVO 2 (and TVO 1 the year after) is the fact that these reactors have fewer guide bar assemblies (the number of bolts is 730 for Forsmark 1 and 2 as compared to 536 for the TVO reactors).

The replacement work was carried out in the reactor pool where the core grid was placed under water. It was beautifully demonstrated that the core grids are easily unmounted, moved and put back again.

The replacement in TVO 1 the year after could of course be very carefully prepared, and the total outage time was on the order of six weeks.

When cracked bolts were found in Oskarshamn 1 in 1984 the decision was made to seek a solution that would allow guide bars with cracked bolts to be left in place for a limited time, awaiting a permanent fix. Clamps in the form of "hair pins" were mounted over each pair of guide bars. The principle is shown in Figure 5-1. The clamps were made from Type 304 SS, 10 mm diameter bar. They were solution annealed after manufacture.

Due to the irregular contour of the core grid periphery, several clamp designs had to be manufactured. In the case of Oskarshamn 1 the total number of clamps was 246 of six different designs.

A summary of the measures taken from 1982 on is given in Table 5-1. For all five Generation 1 and 2 reactors two pairs of guide bars were unmounted (or broken loose in the case of Oskarshamn 1). As described in Section 4, bolts from these assemblies were studied in laboratory. In three cases (including TVO 1) the guide bars were not, for various reasons, immediately replaced. Instead, the top plates of the fuel bundles involved were modified in such a way that they were securely fixed.

Removal and replacement of guide bar assemblies were carried out with the core grid in position. The fuel had been removed. The operations involved a number of steps and required the development of a series of special tools.

The mounting of clamps was also made with the core grid in place. For Oskarshamn 1, the first clamp design was unsatisfactory and had to be changed after one year. In the other reactors the clamps have functioned well. However, during refueling and other work, some damage has occurred in a few cases and clamps were replaced.

The fractured guide bar bolts led the utilities to order new grids for Oskarshamn 1 and 2, Ringhals 1 and Barsebeck 1 and 2 shortly after the discovery of the cracking. The five new grids have a Generation 5 design and are similar except for some dimensions. Oskarshamn 1/2 and 2/2 were installed in 1986. Ringhals 1/2 and Barsebeck 2/2 will be installed in 1988 and Barsebeck 1/2 the year after. At the moment no plans for further replacements are known.

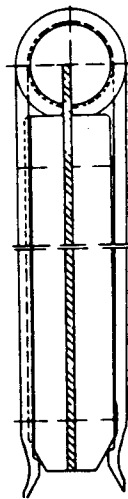


Figure 5-1
Example of Clamping Arrangement

Table 5-1

CORE GRID REPAIR AND REPLACEMENT HISTORY

Reactor	Bolt fracture discovered	Modification of top plates	Replacement of guide bars	Clamps mounted	Clamps replaced	New core grid
Oskarshamn 1	84	84	-	84, 85	-	86
Oskarshamn 2	85	-	85	-	-	86
Ringhals 1	85	-	85	85	86, 87	88
Barsebeck 1	85	85	-	86	87	89
Barsebeck 2	86	-	86	86	-	88
TVO 1	82	82	83	-	-	-
TVO 2	82	-	82	-	-	-
Forsmark 1	82	-	82	-	-	-
Forsmark 2	82	-	82	-	-	-

Numbers indicate year

Section 6

CONCLUDING REMARKS

Figure 6-1 is a summary of the ABB ATOM core grid 1987 status. Shaded bars show the maximum fast neutron fluences received in the different grids so far. For Oskarshamn 1/1 and 2/1 these bars represent the final fluences as the grids were replaced in 1986. White bars show estimated fluences for the expected remaining life of the other grids. For the grids from Forsmark 1 on, it is assumed that the reactors will be decommissioned in the year 2010 which is required by Swedish law. For TVO 1 and 2 a life of 40 years has been assumed. Ringhals 1/1, Barsebeck 1/1 and 2/1 grids will be replaced in the near future, and therefore only small additional fluences will be received.

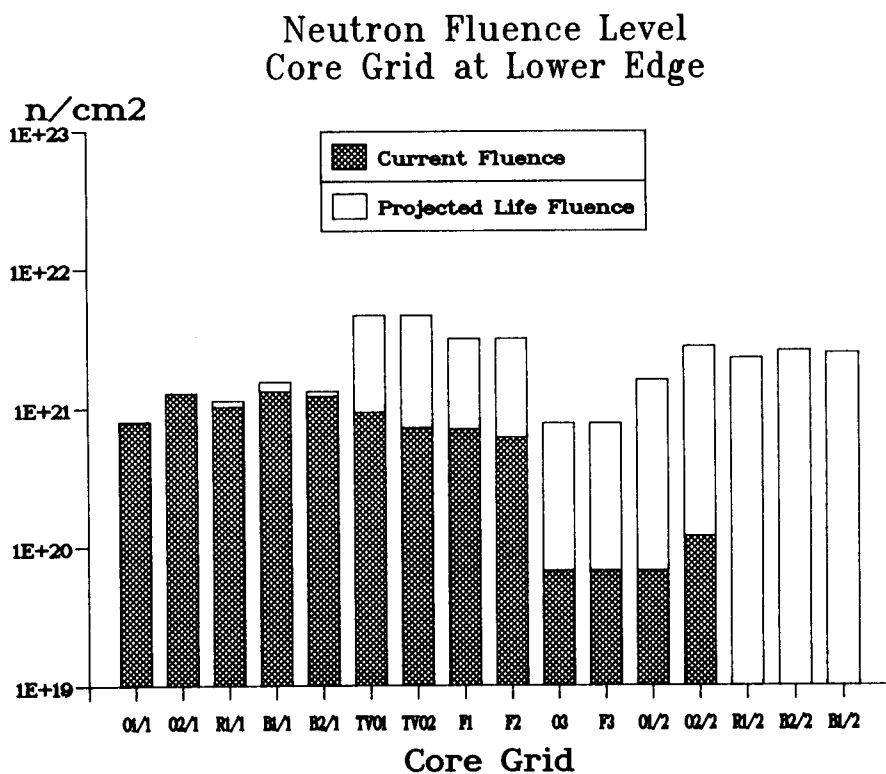


Figure 6-1
1987 Status of ABB ATOM Core Grids
(O, R, B and F stand for Oskarshamn, Ringhals, Barsebeck and Forsmark respectively, R1/2 means the second core grid in Ringhals 1 etc).

That IASCC may be a problem in austenitic stainless steels when the fast neutron fluence reaches values above approximately $5 \cdot 10^{20}$ n/cm² is now generally accepted (3). It is also accepted that certain impurities such as silicon and phosphorus play an important role for this form of stress corrosion. A summary of laboratory results is presented in Figure 6-2 (4). These results are not necessarily relevant for in-reactor condition. According to these data 50 % of the cracked area is intergranular when testing after irradiation to a fluence of approximately $2 \cdot 10^{21}$ n/cm².

The old core grid of Oskarshamn 2 (O2/1) has recently been investigated visually in the reactor pool. No cracks or other damage were found. The maximum fast neutron fluence was $1.3 \cdot 10^{21}$ n/cm² (see Table 2-1). As evident from Figure 6-1, all grids are expected to receive fluences higher than $5 \cdot 10^{20}$ n/cm² during their life time. Replacements may therefore be justified. The fact that Ringhals 1/2, Barsebeck 1/2 and 2/2 are manufactured from steels with low impurity concentrations makes it probable that they can be safely used for the rest of the operating time. Research under way in Sweden (5) and in other countries will certainly create a more solid basis for later judgements.

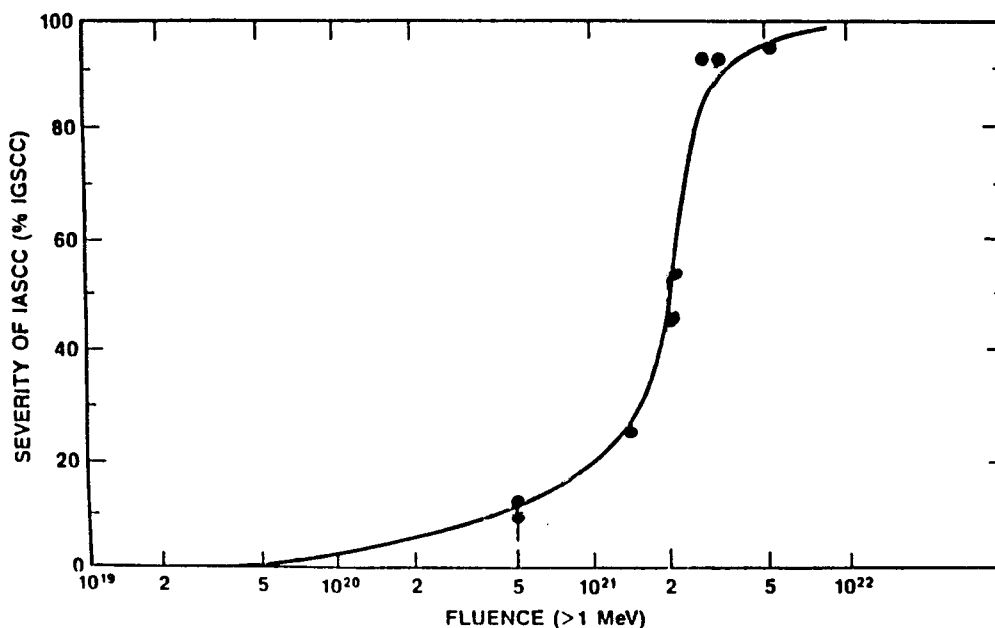


Figure 6-2
IASCC CERT Results on Irradiated Annealed
Type 304 SS (288°C, pure H₂O with 32 ppm O₂)

Section 7

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