HOW TO KEEP YOUR STEAM GENERATOR WORKING WITH LOW COSTS FOR A LONG AND RELIABLE OPERATING TIME

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ABSTRACT

Strategic planning of steam generator (SG) maintenance and repair is a key issue for plant availability and reliability. In Germany, maintenance and eventual repair considerations are an integrated part of a multistep concept for reliable SG performance. This concept is addressed as early as in the design phase of a nuclear power plant.

In contrast to the tube degradation problems that have been encountered worldwide, SGs of the Siemens/KWU design have proven by operating experience that they are very efficient in minimizing tube corrosion or any other SG related problems.

A multilevel concept has been developed, applied and wherever necessary improved in order to ensure reliable operation. The main elements of this concept are thorough design engineering incl. proper material selection and stringent requirements and quality control for fabrication accompanied by tight control requirements of water chemistry environments. In order to counteract tube deficiencies a complete arsenal of maintenance, inspection- and repair-techniques have been developed and successfully applied.

Performance of SG is continuously evaluated and fixed in lifetime databases. The main indicator for SG integrity still is the eddy-current testing of SG tubes. SG tubes which have shown indications at the eddy current tests are rated with lifetime threshold values and SGs affected by tube damages are inspected, and eventually, repaired, based on individual assessment criteria.

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1. INTRODUCTION

Operating pressurized water reactors (PWRs) with U-tube steam generators (SGs) have encountered difficulties associated with either one or a combination of inadequate material selection, poor design and manufacturing and an insufficient water chemistry control which resulted in excessive tube degradation. Tube degradation is related to corrosion phenomena, such as wastage, pitting, intergranular attack (IGA), primary water stress corrosion cracking (PWSCC), intergranular stress corrosion cracking (IGSCC) and other phenomena, such as denting, flow induced vibration fretting and wear.
In contrast to the above mentioned tube degradation problems that have been encountered worldwide, SGs of the Siemens/KWU design have proven by operating experience that they are very efficient in minimizing tube corrosion or any other SG related problems.

A multilevel concept has been developed, applied and wherever necessary improved in order to ensure reliable operation. The main elements of this concept are thorough design engineering incl. proper material selection and stringent requirements and quality control for fabrication accompanied by tight control requirements of water chemistry environments. In order to counteract tube deficiencies a complete arsenal of maintenance, inspection- and repair-techniques has been developed and successfully applied.

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2. DESIGN ENGINEERING

The first level comprises thorough design engineering, proper material selection, deliberate specification and control of water chemistry guidelines and stringent requirements and quality controls for manufacturing.

2.1 Design Engineering/Material Selection

The Siemens/KWU design encompasses a broad spectrum of steam generator parts and components. In all cases it has been and will be Siemens/KWU's objective to consider the following main design criteria:

- Avoid concentration of impurities by avoiding heated crevices and flow stagnation zones.
- Avoid high stresses in the tubes.
- Minimize tube vibrations.
- Provide adequate access for inspection and maintenance.
- Use experimentally optimized moisture separators and dryers.

Already the very early steam generator designed by Siemens/KWU contained features, which were incorporated only after thorough experimental and/or analytical investigations had confirmed that they are adequate for the specific application in a nuclear steam generator (see Fig. 1).

3. WATER CHEMISTRY CHARACTERISTICS

Besides detailed design engineering, proper material selection and careful manufacturing, chemistry guidelines within rather close limits have to be specified and monitored. Nevertheless, considering the exceptional features of the Siemens/KWU steam generators, the possibility for relaxation of chemistry guidelines was considered in the actual specification, thus enabling the Utilities to operate the plant more flexible.

3.1 Primary Side

The chemistry restrictions for the steam generators are much less demanding than those corresponding to the rest of the primary circuit. In all cases the limiting factors are found in other components (reactor, fuel elements) or in other objectives pursued (dose rate buildup minimization). Therefore, no steam generator related chemistry guidelines for Siemens/KWU replacement steam generator.

3.2 Secondary Side

Important factors affecting the corrosion behavior of steam generator tubes are corrosion products, impurities (salts and organic substances), oxygen and other oxidants. The corrosion products have the greatest influence. They are deposited particularly in regions of high heat flux and stagnant flow (SG tubes, tubesheet, crevices between tube and tube supports).

Towards the end of the seventies, more and more wastage occurred in SG tubes. In addition to short term remedies (e. g. lancing of the tubesheet), strategies were established for improvement of the overall integrity of the secondary side. Most utilities replaced their condenser tubes with new ones made out of stainless steel or titanium, thereby creating suitable conditions for increasing the pH level and considerably reducing the entrainment of corrosion products into the steam generator. Depending on the plant-specific circumstances, the hardware modifications took varying periods of time, so it took ten years before full change to this new chemistry was completed.

4. PROVISIONS FOR REMEDIAL ACTIONS

4.1 Maintenance, Inspection- and Repair-Techniques

For inspection, maintenance and repairs, sufficient access to both chambers of the primary head is provided by manways. The accessibility of the manways and the design of the manway covers, studs and nuts allow use of stud tensioners. This shortens the opening and closing process and contributes to the ALARA man rem dose concept. The upper portion of the steam generators is equipped with a largely sized manway. The large size in combination with the utilization of a stud tensioner helps to reduce the exposure time for personnel during inspection, maintenance and repairs.

Four handholes are located above the tubesheet. These handholes allows inspections of the lower area of the tube bundle and the secondary surface of the tubesheet. The strategic location as well as the large size of the handholes facilitates sludge lancing and simplifies the necessary activities above the tubesheet and reduces the time needed for any inspection and maintenance activities in this area.

To have access for inspection to the most sensitive internals inside the SGs, many locations such as steam dryers, separators, feedwater ringline, shroud in tube bundle region, shroud in the flow distribution plate region, etc. are reachable through inspection openings, handholes or manways.

In order to ensure satisfactory performance of steam generators, inservice inspections and maintenance work have to be performed regularly. In spite of the fact that steam generators equipped with Incoloy 800 mod.[1)] tubing show very little corrosion, a complete arsenal of equipment for testing of steam generator tubes has been developed. A robot was developed for all kinds of steam generators tube inspections and maintenance. The robot basically consists of a support structure and two arms by with every position of the tubesheet can be reached. The robot can be used for inspection of the steam generator tubes as well as for the tube plugging, sleeving, welding, machining. In addition to the standard multifrequency eddy-current technique, special eddy-current and ultrasonic probes were developed. These probes are used to analyze tube defects and to obtain additional information on kind, size and depth of defects. A rotating combined ultrasonic and eddy-current probe is specially suited for the analysis of large volume defects resulting from wastage corrosion or fretting.

The most common repair technique is plugging. The former explosive plugs have meanwhile been completely replaced by superior removable mechanical. They are placed in the defective tubes by manipulators such as finger walkers or robots as described above. The sleeving technique developed by Siemens/KWU is characterized by welding of the sleeves at both ends. Advantages of this technique are absolute leak tightness and inspectability of the welds.

4.2 Cleaning Achievements

Cleanliness is one of the most important prerequisites for a steam generator's long life. Therefore emphasis was put on the development of cleaning techniques:

A tubesheet lancing equipment serves to further reduce the risk of corrosion by removing the sludge pile on the tubesheet by water blasting. The equipment is designed to be installed in the tube lane of a steam generator trough handholes above the tubesheet (see Fig. 2).

Several spray nozzles are arranged on a spray head, which moves along the tubes lane. The spray head can also be moved up and down covering with its water jet the whole region of crud drop-out. Because of the triangular pitch the whole circumference of the tubes can be reached by water jets.

Periodic tubesheet lancing in combination with measures such as replacing Cu-containing material from the steam/feedwater cycle and thus maintaining a high pH to reduce the transport of corrosion products into the steam generators results in a minimum build-up of crud. After removal of usually less than 10 kg per steam generator the tubesheet is clean as it was demonstrated by fiberoptic inspections.

In case there are big amounts of crud in a steam generator at locations which cannot be reached by water jets, chemical cleaning of the tube bundle is an alternative for crud removal. The Siemens/KWU technique for chemical cleaning is able to remove copper as well as corrosion products from a steam generator without affecting the tubes or other structural materials. This method has been applied to the steam generators of numerous units in Germany and abroad. Up to 500 kg of crud could be removed per steam generator.

5. INTEGRATED SERVICE CONCEPT

The Integrated Service Concept includes the preparation, performance and documentation of the above mentioned services as well as the engineering activities necessary for an integrated evaluation of the steam generator.

In former times the decision about the particular service activities at the SGs such as eddy-current testing of SG tubes, optical inspections, tube sheet lancing or repair works was taken based on individual separated aspects and optimizations. On the contrary the integrated service concept is directed to the over-all optimization of all above mentioned service activities by recording, evaluating and judging of results from operation and from inspection. Thereby not only the behavior of the specific plant with their SGs will be considered but also other similar plants. The goal of this concept is an optimized maintenance depending on the SG status as well as an optimized availability of the SG considering safety related and economical aspects (see Fig. 3).

The engineering part of the concept consists of the modules component monitoring, assessment of results from other plants, maintenance advice and recommendation as well as other special evaluations or considerations.

With the evaluations not only the trouble free operation of the SGs is assured but it also can get a contribution to the plant safety status analysis which has to be performed later on.

Performance of SG is continuously evaluated and fixed in lifetime databases. The main indicator for SG integrity still is the eddy-current testing of SG tubes. SG tubes which have shown indications at the eddy current tests are rated with lifetime threshold values to assure a safe and trouble free operation till the next outage without an unplanned shut down for tube repairing.

The steam generator operating experience is recorded with special consideration of tube damage due to material removal at points of contact with tube supports (anti vibration bar (AVB) fretting) and foreign objects (loose part (LP) fretting). This information is used to determine an enveloping fretting wear curve, which can be used to determine wear criteria and/or define examination cycles for initial indications. The safety-related verification of tube integrity is also developed for subsequent indications.

For LP fretting, foreign-object specific wear curves are described and the determination of wear criteria demonstrated. For verification the enveloping curve for AVB fretting has been compared with experimental results.

The Integrated Service Concept provides the possibility to agree and bundle the individual activities, to optimize the personnel assignments and by this assure a safe and reliable operation of the SGs at low cost.

6. OPERATING EXPERIENCE

As of the end of 1997 a total of 80 Siemens/KWU steam generators were in commercial operation worldwide. This number includes also 6 replacement steam generator for Ringhals Unit 2 and 3 with Inconel 690 TT tubes.

As far as SG tubes made of Incoloy 800 mod.[1)] are concerned, phosphate wastage was in the past the only mechanism of significance experienced in the Siemens/KWU plants operating under phosphate treatment. In addition to several secondary system improvements and the modifications to the water chemistry, annual cleaning of the steam generator (tubesheet lancing) during refueling has proven a suitable means of restricting the progress of wastage. Since 1985 wastage corrosion is no more an issue for old Siemens/KWU SGs.

Apart from corrosion of this type after more than 25 years there has been only one instance of SG tubes developing intergranular crack within the sludge pile region on the secondary side of the tubesheet and two tubes with traces of pitting. With SG tubes made of Incoloy 800 according to Siemens/KWU specification there have been no indications of PWSCC, IGA, or chloride-induced SCC.

Operation experience with the stainless steel grid-type tube supports and vibration restraints in the U-bend region has verified that unacceptable tube vibration, which could lead to fretting, is effectively suppressed by this design. Extensive eddy-current examinations carried out in all PWR nuclear power plants constructed by Siemens/KWU produced following results (see Fig. 4):

- No fretting of SG tubes at the grid in the straight tube sections
- Minimal fretting in the U-bend region in a few older plants
- No fretting in the U-bend region in plants with standard vibration restraints. This design is operation in since 1978.

Fretting damage to the extent discovered in preheater steam generators of other vendors can be excluded on the grounds that Siemens/KWU already from the beginning

- installed flow distribution boxes in order to achieve uniform distribution of feedwater flow at a moderate velocity level which is sufficiently below values inducing unacceptable tube vibrations. Eddy-current inspections showed neither indications of fretting attack nor any other kind of tube wall degradation.

There were only 13 instances of SG tube leakage, of which half led to non-scheduled outages. This resulted in a plant availability forfeit of less than 0.1 %. Numerous publications deal with the effects of steam generator problems on plant availability. The figures quoted range from less than 2 % for 1986 to over 4 % for the years between 1980 and 1984. These percentages do not include outages for steam generator replacement. Comparison of the availability figures confirms the effectiveness of the Siemens/KWU design and operating concept of steam generators in PWR nuclear power plants.

Neither at this time nor in the next future any replacements of steam generators have to be anticipated in Siemens/KWU designed nuclear power plants.

[1)] modifications due to a better corrosion resistance: lower content of carbon, increased stabilization ratio and additional degree of cold working

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SG Life Time Assessment with respect to

SG Feeding

- Minimisation of
  - Cold feedwater shocks/Fatigue
  - Stratification / Fatigue
  - Voiding / Water hammer
- Continuous update of fatique status (FAMOS)

SG Inspection

- Eddy Current Inspection (Tubes)
- Visual Inspection
  - Tube Bundle
  - SG Internals, Primary chamber
  - SG Tube Integrity

SG Heat Transfer Capacity

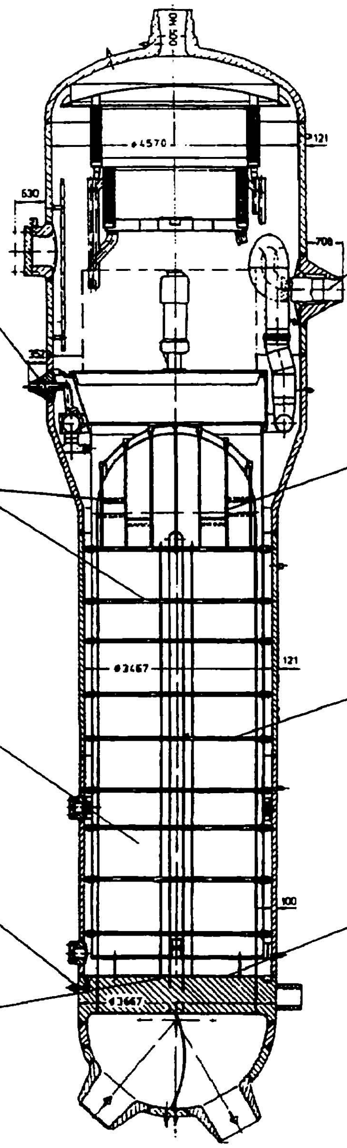
- Fouling Measurements

SG Water Chemistry

- Ingress of contaminants
- Hide-out, hide-out return behaviour
- Online corrosion monitoring

SG Cleaning

- Tubesheet lancing
- Chemical cleaning



SG Areas of Concern

- Feedwater Inlet
  - Cold water shocks
  - Stratification
  - Water hammer
- U - Bends
  - FIV Fretting and-wear
  - Tube corrosion
- U - Tube Bundle
  - Deposition of crud, Contaminants
  - Tube Fouling
  - Tube Corrosion
- Tube Bundle above tubesheet
  - Crud accumulation
  - Tube corrosion
  - Loose parts

Steam Generator Life Time Assessment

Figure 1

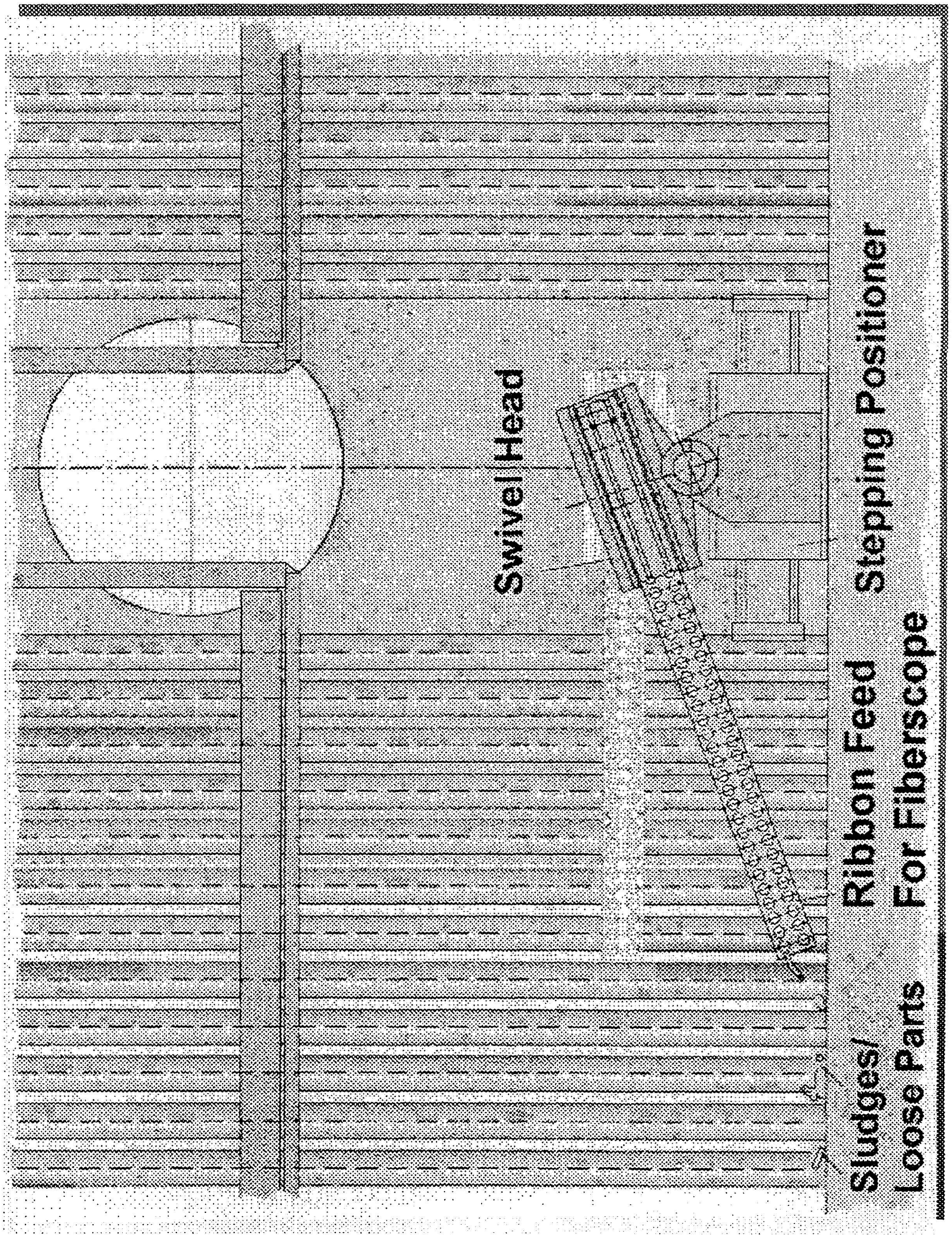

Swivel Head
Stepping Positioner
Ribbon Feed
For Fiberscope
Sludges/
Loose Parts

Figure 2

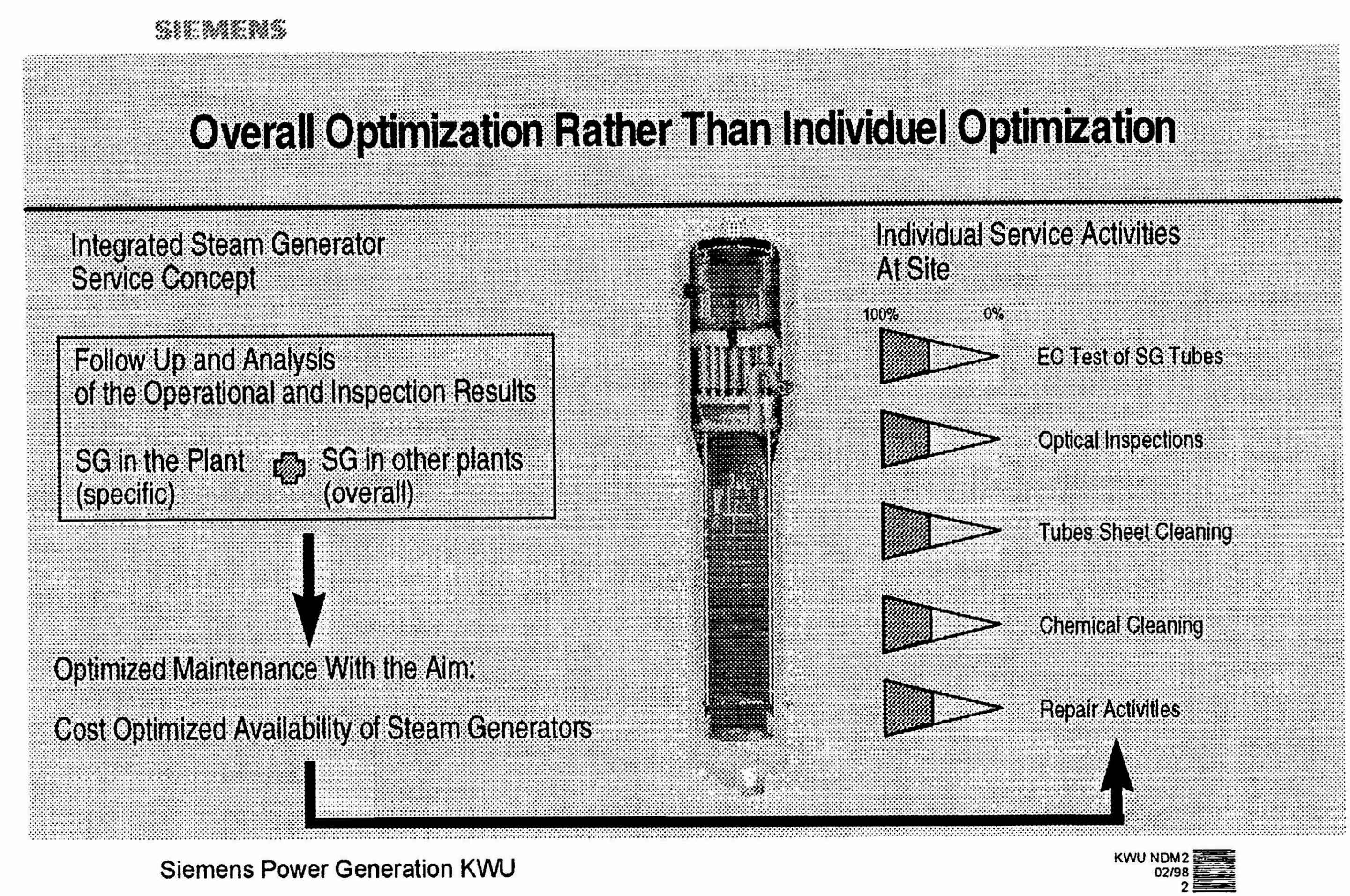

SIEMENS
Overall Optimization Rather Than Individuel Optimization
Integrated Steam Generator
Service Concept
Follow Up and Analysis
of the Operational and Inspection Results
SG in the Plant
(specific)
SG in other plants
(overall)
Optimized Maintenance With the Aim:
Cost Optimized Availability of Steam Generators
Individual Service Activities
At Site
100%
0%
EC Test of SG Tubes
Optical Inspections
Tubes Sheet Cleaning
Chemical Cleaning
Repair Activities
Siemens Power Generation KWU
KWU NDM2
02/98
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Figure 3

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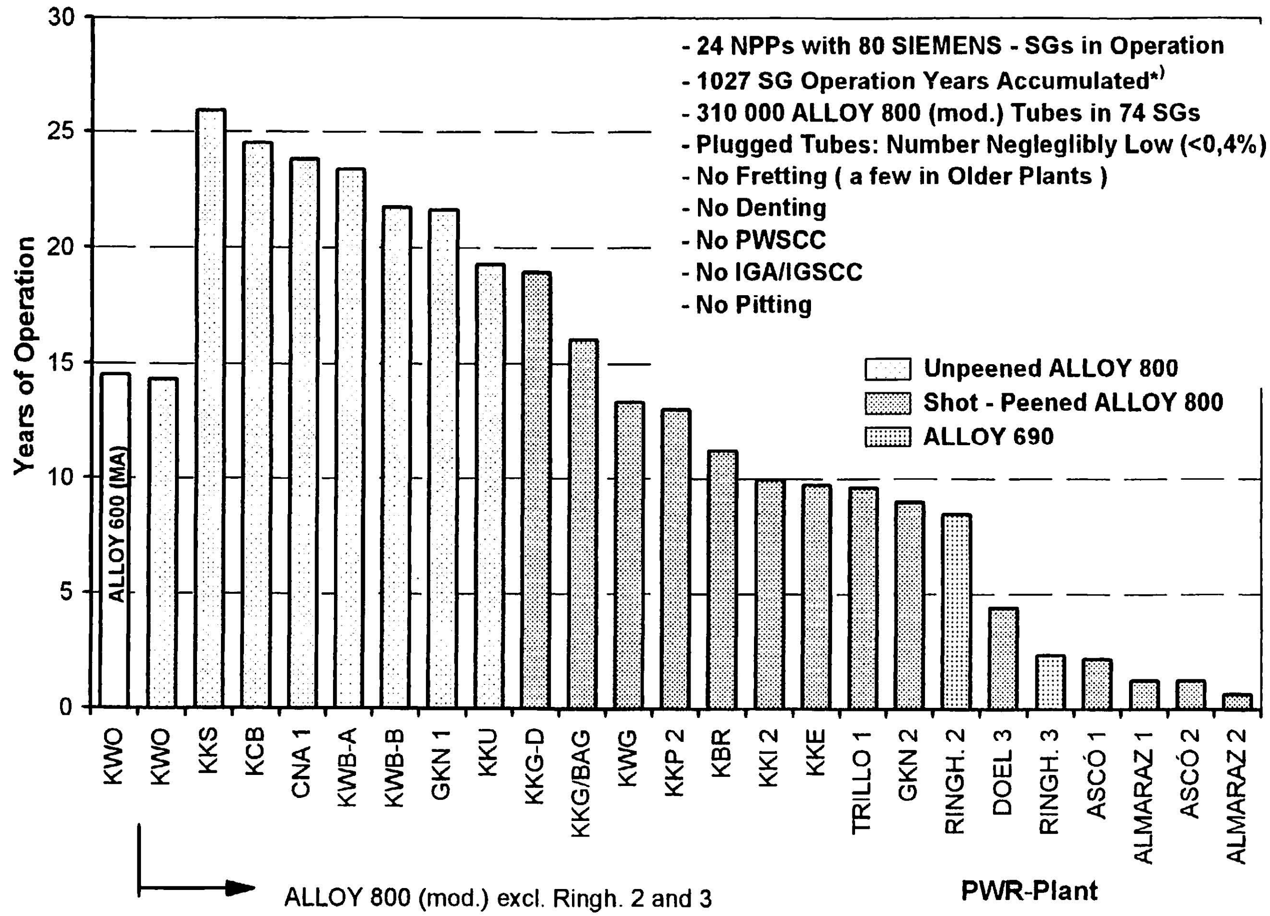

*) including 32 SG Operation Years for Alloy 690 (TT)

Operating Experience with SIEMENS Steam Generators in PWR-Plants as per 31.12.97

Figure 4

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PWR-Plant *)	Year of Start-up	No. of SG's	No. of Tubes	No. of Tube Leaks	No. of Plugged Tubes	No. of Plugged Tubes and Causes: Wastage	Fretting: AVB	Fretting: LP	Fretting: SCO	P	SCC: OD	SCC: ID	D	Other 3)
Stade	1972	4	11,972	1	318	314	1	-	-	-	-	-	-	3
Borssele	1973	2	8,468	1	125	113/2 2)	10	-	-	-	-	-	-	-
Atucha I (D2O)	1974	2	7,890	5	140	3	130	-	-	-	-	-	-	7
Biblis A	1974	4	16,240	2	605	33/448 2)	49	-	-	-	-	-	-	75 1)
Biblis B	1976	4	16,084	1	61	7	50	-	-	2 5)	1 5)	-	-	1
Neckarwestheim 1	1976	3	12,063	1	19	4	6	5	-	-	-	-	-	4
Unterweser	1978	4	16,084	0	0	-	-	-	-	-	-	-	-	-
Goesgen	1979	3	12,318	0	15	1	-	13	-	-	-	-	-	1
Grafenrheinfeld	1981	4	16,344	0	0	-	-	-	-	-	-	-	-	-
Obrigheim (new)	1983	2	6,020	0	0	-	-	-	-	-	-	-	-	-
Grohnde	1984	4	16,344	0	1	-	-	-	1	-	-	-	-	-
Philippsburg 2	1984	4	16,424	0	0	-	-	-	-	-	-	-	-	-
Brokdorf	1986	4	16,344	0	0	-	-	-	-	-	-	-	-	-
Isar 2	1988	4	16,472	0	0	-	-	-	-	-	-	-	-	-
Emsland	1988	4	16,472	0	0	-	-	-	-	-	-	-	-	-
Trillo 1	1988	3	12,258	2	14	-	1	9	2	-	-	-	-	2 6)
Neckarwestheim 2	1989	4	16,472	0	0	-	-	-	-	-	-	-	-	-
Ringhals 2 4)	1989	3	15,390	0	0	-	-	-	-	-	-	-	-	-
Doel 3	1993	3	15,390	0	0	-	-	-	-	-	-	-	-	-
Ringhals 3 4)	1995	3	16,284	0	0	-	-	-	-	-	-	-	-	-
Ascó 1	1995	3	15,390	0	0	-	-	-	-	-	-	-	-	-
Almaraz 1	1996	3	15,390	0	0	-	-	-	-	-	-	-	-	-
Ascó 2	1996	3	15,390	0	0	-	-	-	-	-	-	-	-	-
Almaraz 2	1997	3	15,390	0	0	-	-	-	-	-	-	-	-	-
		80	342,893	13	1298 = 0.38 %									

*) Plants with Alloy 800 (mod.) tubed SG's, without 4)

[shaded] SGs starting under High-AVT

W = Wastage
P = Pitting
D = Denting

SCC = Stress Corrosion Cracking
OD = Outer Diameter
ID = Inner Diameter

AVB = Anti Vibration Bar
LP = Loose Part(s)
SCO = Structural Component

1) 63 tubes plugged as precautional measure due to installation of additional AVB's
2) /n: Wastage in the innermost U-bend area
3) Most of them not inspectable, excl. Biblis A
4) Tubing Alloy 690 (TT)
5) Pulled Tubes
6) 1 Tube Pulled for Fouling Investigations, 1 precautionary plugged

Plant Status Summary of SIEMENS Steam Generators (SGs) as per 31.12.1997

Figure 5