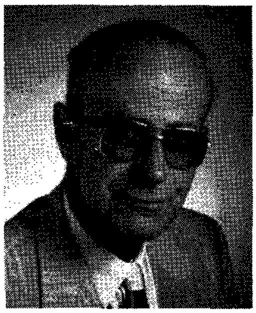 

Reliability of Large Low-Pressure Steam Turbine Rotors

- A State of the Art Review -

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Introduction

In the world of large steam turbines 1986 has seen a remarkable new first event. On February 7 the 1040 MW Zion Unit 2 belonging to Commonwealth Edison in USA was resynchronized after refitting with complete new LP rotors, blades and inner casings which were supplied by Brown Boveri in a different technology, to that of the original equipment supplier.

The decision to make this replacement followed a history of stress corrosion cracking (SCC) problems on the original rotors, which proved to be inherent in their design and in fact part of a widespread reliability problem affecting many nuclear units throughout the world. With the main goal of permanently solving these problems, the decision involved a switch in rotor technology in favour of the "welded rotor" construction which in both theory and practice is demonstrably immune to SCC. This article looks at various reliability-related aspects of steam turbine LP rotors, considering all major modern designs, in particular their susceptibility to SCC.

In the case of the Zion machines, the benefits of introducing welded rotor technology did not stop with the achievement of better reliability. Despite the restrictions of retaining the original outer casings, the improved blading and exhaust design has brought a measured output improvement of 20 MW compared to the original design. This represents 2 percent on heat rate!

Status Review

Until recently all large nuclear LP rotors were either of the built-up design, according to the two major US manufacturers, or of the welded design propagated by Brown Boveri. Both "solutions" avoided the difficulties of manufacturing the very large one-piece forgings which would otherwise be necessary for these rotors.

These alternative configurations are shown in Fig. 1.

Since 1982 it has become apparent that LP rotors of the built-up design suffer from serious cracking problems. (See Table 1). The cracks identified as "Stress Corrosion Cracking"(SCC) have been found at the key-way, the bore surfaces, the web face and at the disc-rim blade attachment area, (steeple cracking) as shown in Fig. 2.

All of these built-up LP rotors must be inspected periodically to check for rotor integrity and crack growth. These inspections are both time consuming and costly to the utility. Along with the constant danger of an LP rotor disc rup-

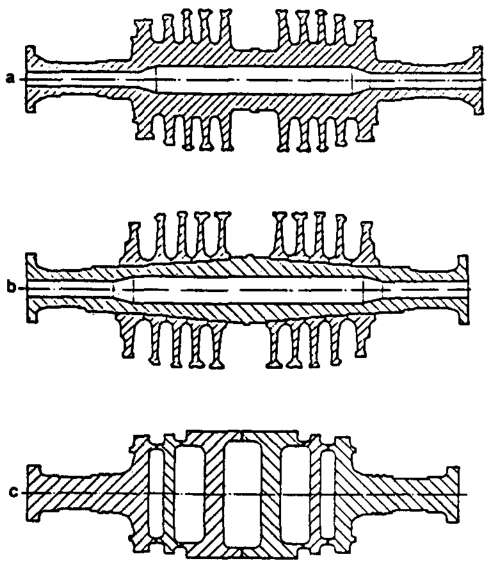


Fig. 1 – Designs of steam turbine rotors

a: Solid rotor
b: Rotor with shrunk-on discs
c: Welded rotor according to BBC design

ture there is also a risk of an unpredicted blade failure.

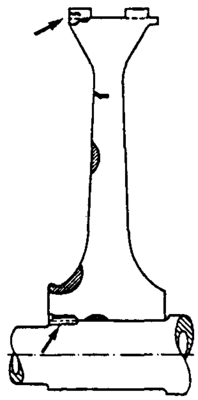
At least three rotor disc ruptures have occurred in nuclear plants. Along with various blade failures resulting in forced outages of the unit this is continuing to contribute to lower availability in several nuclear power plants.

Stress Corrosion Cracking

The occurrence of stress corrosion cracking is dependent on three factors:

1. Material susceptibility to SCC
   This generally increases with increasing yield strength.
2. Stress levels
   The higher the stresses the greater the danger. Stresses at or near the yield point are very detrimental (stress concentration at notches such as key-ways, blade attachments, etc.)
3. Environment
   Corrosive environment.
   Condensate with feedwater/steam impurities in ppm levels is enough to initiate SCC when concentrated in crevices.

Fig. 2 – Crack formation in low-pressure turbines of 700/900 MW nuclear power stations in the USA



All three of these factors must be present to produce SCC. Thus if only one factor can be eliminated or sufficiently reduced, SCC can be prevented or retarded. As it is difficult to predict the initiation and subsequent propagation of cracks under normal service conditions one must strive for a solution which completely eliminates SCC, rather than retarding it.

The built-up rotor compared to the welded rotor

In the built-up design, forged discs with a centre bore and key-way are shrink fittec to a shaft or spindle as illustrated in Fig. 1b. The shrink fit must hold high centrifugal loads from the large discs with

Table 1 : Stress corrosion cracks in the l.p. turbine rotors of US nuclear power stations

Manufacturer A: July 1980	61 turbines inspected	36 had stress corrosion cracks
Manufacturer B: July 1982	Total inspected 1111 discs 72 rotors 34 units	Number with indications of keyway cracks 131 (12%) 50 (69%) 25 (74%)

(Stress corrosion cracking only occurred in rotors with shrunk-on discs.)

blades attached. This demands materials of high yield strength (ASTM A 471 Y.S.122ksi) It is use of a high yield strength material along with the high stresses at the bore and key-ways or blade root fixation which causes the problems of SCC, even at normal nuclear power plant water/steam puritiy levels.

The welded low pressure rotor design consists of "solid" discs circumferentially welded together at their periphery where the stress levels are at their lowest. BBC has over 50 years of experience with this technology.

As there is no shrink-fit or centre bore in this design, materials of lower yield strength, less susceptible to SCC, can be used.

A comparison of the welded rotor design with the built-up rotor design is as follows:

Although both rotor types have to carry nearly the same centrifugal loads, the stress level in the shrunk-on wheel or disc design is higher than in the welded rotor.

It is, of course, this stress level which determines the required yield strength of the material for each design. For the welded rotor stress levels are first calculated. A safety factor is then applied so that plastic deformation of the material selected does not take place under any circumstances or modes of operation. This factor considers the total stress, i.e. the sum of radial, circumferential and axial stress (the axial stress component being zero in both designs).

The yield strength of the material employed in the welded design is 92 ksi at room temperature. This results in a safety factor of 2.8 in the centre of the welded disc.

The corresponding safety factor of a shrunk-on disc is 1.53 with a material similar to ASTM A 471 having a yield point of 122 ksi. [1]

As mentioned above stress corrosion cracking results principally from 3 factors: material, stress and environment. Comparing the two rotor designs on the basis of these three factors:

Material: The welded rotor uses a relatively low yield strength material with high fracture toughness (K_{IC} at least 170 ksi in at 35°C). Experience in the U.S. indicates that yield strength is one of the major factors determining growth rates of cracks in LP/ turbine discs. [2]

Crack growth rates for high yield strength steel are significantly faster than those for a lower yield strength steel as employed in welded rotors. The high fracture toughness assures greater safety against rotor rupture than can be offered by the shrunk-on disc or even monoblock design materials.

Stress: Crack initiation is dependent on the ratio of applied stress/yield strength. Probability of cracking and crack growth may be reduced or eliminated by reducing the stress level. The fact that BBC's welded LP-rotors exhibit no SCC, demonstrates that the combination of material and stress level gives good resistance to crack initiation. Cracks and their growth are not observed.

Environment: Crack initiation and growth rates are influenced greatly by the environment in existing plants, in particular chemical disturbances in the water-steam system (improper operation of condensate polishers, air-in-leakages, condenser leakages).

Meticulous control of the water chemistry is essential to ensure the lifetime of shrunk-on discs. Since the welded rotor by its design and choice of material is not susceptible to SCC, the environmental requirements are less stringent. For example:

- no restriction on air-in leakages is required to minimise SCC (other than economic considerations).

At present those units which have built-up rotors with generic SCC are subject to stringent control of feedwater/steam chemistry since it is not possible to change material or stress to retard SCC.

The Integral or Monoblock Rotor compared to the Welded Rotor

This solution which employs a one-piece forging is now being offered by the manufacturers of built-up rotors as a replacement and cure both in the case of cracks in their original equipment and on new units.

This design constitutes a new development on large nuclear half-speed rotors and as such is not backed by any references. Only very few forgers in the world are capable of producing the necessary 500 to 600 ton ingots in anything like the necessary quality.

Monoblock rotors have of course been in service for many years on full-speed (3000 and 3600 r.p.m.) machines, where they are naturally much smaller. Even here they have suffered occasional cracking problems, mostly due to SCC at rather sharp notches. Particularly at larger diameters, it has been found to be necessary to employ 3.5% Ni steels (ASTM A 470, Class 5&7), in order to provide the necessary through-hardening, uniform mechanical properties and an adequate toughness level at the centre of the forging.

A number of comparisons have been made of the SCC resistance of steel for the monoblock (3.5% Ni steel) and the welded rotor (1% Ni steel), e.g. by independent EPRI-funded tests on crack initiation [3] and on crack propagation [4].

These references conclude that

a. crack initiation is significantly faster even on the best commercially available monoblock steels than on the 1% Ni steel used for the welded rotors. In house tests have confirmed these findings.

b. In 10% NaOH solution the propagation rates of cracks in 1% Ni steel are much lower than in the 3.5% Ni steel. Such corrosive conditions can arise in crevices or at the condensation line, during chemical disturbances in the steam/water chemistry. Under milder conditions such as pure deaerated water, there is no large difference in growth rate. The steel for the welded design thus provides a far greater margin of safety at critical locations, such as blade fixings, and particularly when operating under abnormal conditions with impure steam.

It is generally accepted that temper embrittlement and enhanced susceptibility to SCC are associated with the segregation of impurity elements such as phosphorus to grain boundaries. The results show the grain boundary concentrations of phosphorus in the 1% Ni steel to be lowest, even though this steel happens to have the highest overall P-content. Clearly with similar heat-treatment conditions, this steel shows less tendency to grain boundary segregation than the monoblock steel, so that embrittlement and stress corrosion sensitization are low.

Enhanced grain boundary segregation occurs during slow cooling after heat treatment. On account of their large size, monoblock rotors experience particularly slow cooling rates at positions where gashes are subsequently made, allowing opportunity for grain boundary segregation at highly stressed regions. Results of [5] show considerably increased sensitivity to SCC in slow-cooled (step-cooled) 3.5% Ni steel.

Since P segregation continues thousands of hours into service, [6], this will still not represent the worst condition on monoblock rotors. Susceptibility to the initiation of stress corrosion cracks will go on increasing during operation.

Although it is known that clean steels with reduced P and impurity content show less tendency to temper embrittlement, preliminary results of crack growth rate tests show no improvement in SCC properties of the clean steel (clean steel forgings are not yet commercially available in large LP sizes) [7].

Summarising: The steel used for the welded rotor shows greater resistance to both the initiation and propagation of stress corrosion cracks. Slow cooling of the monoblock rotor, may further increase the susceptibility to SCC, particularly at highly stressed locations in contact with impure steam. Safety margins may be further reduced by grain boundary segregation during operation.

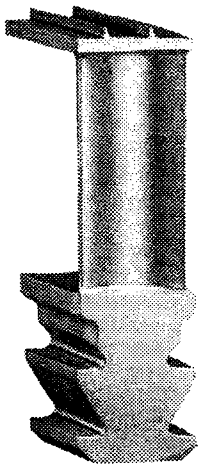


Fig. 3 - BBC design one-piece LP rotor blade with integral shroud.

Blading and Blade Attachments

These important components have been major trouble sources and the causes of numerous forced outages on US designed LP rotors.

The main problems have resulted from
1.Rivetted shrouds which lead to local high stresses and stress concentrations, and introduce crevices. This is all fertile ground for SCC.
2.High stress levels in blade attachments which also favours SCC.

These designs are very inconvenient to repair, e.g. it may be necessary to sacrifice many undamaged blades just to extract a single failed blade. On account of their record they are also subject to regular inspection of the rivetted tenons.

In contrast to the above blade designs BBC nuclear LP rotor blading is of a very simple and robust design which gives SCC no chance.

These BBC blades are all completely solid, i.e. manufactured from one piece. LSB and L-1 are precision forged and all others machined from the solid with integral root and shroud. (See Fig. 3)
3. The blade attachment is designed and dimensioned to give low stress levels. The payoff is clear from the statistics -no forced outage on BBC nuclear turbines- and has been confirmed by many independent studies (eg EPRI [1]) of blading problems.

When maintenance is required BBC's simple blade arrangement without tie-wires (free standing blades) makes blade replacement very fast and easy - LSB's can even be replaced individually without removing the LP hood!

Conclusions

The present state of the art on large "half speed" steam turbine LP rotors may in conclusion be summarised as follows:
1.conventional shrunk-on disc/wheel design has higher operational stresses, requiring a higher yield strength material than the welded rotor design.

High yield strength material and high operational stresses result in a marked susceptibility to SCC, especially at critical areas (key-way bore surfaces, blade attachments). There is a high sensitivity to steam chemistry. This is borne out by the statistics in Table 1, which have substantially worsened since the investigations were carried out in the early 80's.
2. The monoblock or integral rotor being offered as a solution to the problem still has disadvantages:

Table2: Evaluation of the most important factors determining the availability of l.p. rotors

	Shrunk-on discs	Solid rotor	Welded rotor
Loading at the critical locations in the rotor	High	Medium	Low
Yield strength of the material	High	Low	Low
Access of corrosive environment to highly loaded locations	Yes	Medium	No
Susceptibility to stress corrosion cracking	High	Medium	Low
Fracture toughness	Low	Medium	High
Operating experience	Poor	None	Good
Lifetime	Short	Unknown	Long

- Impurity segregation from the steelmaking and heat treating process for such large forgings results in an increased susceptibility to SCC compared to material used for the welded rotor design.
- No operational behaviour statistics are available to demonstrate the reliability of this solution. This is in stark contrast to the reference situation on large welded LP rotors where Brown Boveri's 11 million flow-hours on nuclear LP turbines has been entirely without a cracking incident
- Few steelmakers are able to supply the necessary large forgings and this could result in long delivery times. Often a "back up" forging will be required for the case that a forging does not pass ultrasonic inspection.

This situation is summarised in Table 2.

3. The only established reliable LP rotor technology available today is the welded rotor, conceived, developed and proven by Brown Boveri and backed with 50 years' experience.

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