Raising steam on an unprecedented scale

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Answers for energy.

SIEMENS

Raising steam on an unprecedented scale

To be made for Finland's Olkiluoto 3 nuclear plant, this extremely high output ST, a scaled up version of an existing Siemens design, will be the largest steam turbine ever constructed. What design problems, particularly those of scaling up, did this pose?

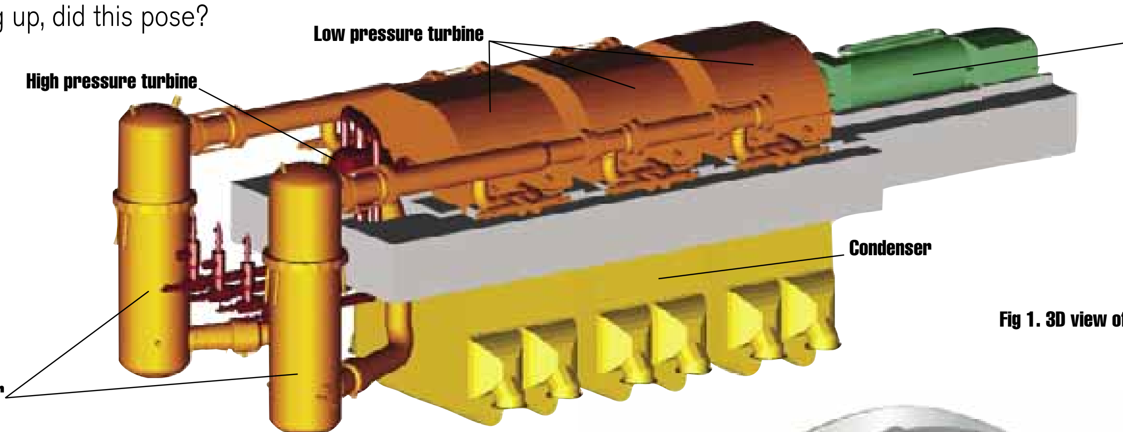
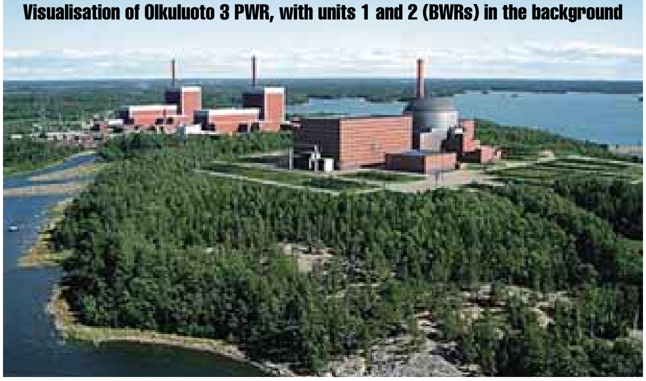


Fig 1. 3D view of the turboset

Visualisation of Olkuluoto 3 PWR, with units 1 and 2 (BWRs) in the background



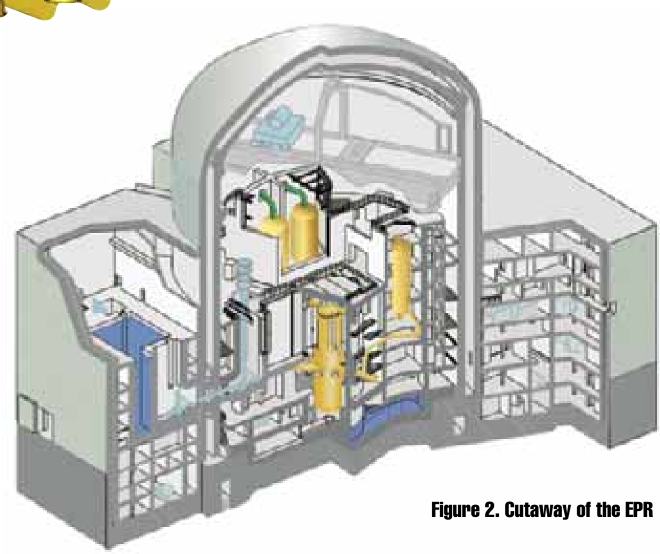


Figure 2. Cutaway of the EPR

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Finland's decision to build a new nuclear power plant – Olkiluoto 3 – was driven by three main factors, namely economics, reduction of carbon dioxide emissions and a desire to reduce dependence on electricity imports.

The Finnish electric utility TVO (Teollisuuden Voima Oy) signed the contract with a consortium of Framatome ANP and Siemens to build an EPR (European Pressurised Water Reactor) at Olkiluoto. The nuclear island for the €3 billion turnkey project is to be supplied by Framatome ANP, and the turbine island by Siemens. The new plant, expected to perform at a net efficiency of about 37%, is due to start commercial operation in 2009. The net power output will be approximately 1600 MW.

Siemens are supplying conventional plant comprising the turbine building with its turbogenerator set and the water steam systems and all balance of plant facilities as well as electromechanical equipment and I&C.

The turbine generator is of tandem compound design and consists of a double flow high-pressure (HP) turbine and a six-flow low-pressure (LP) turbine rigidly coupled to a three phase synchronous generator with a directly connected exciter. The main data of the turbine generator are shown in Table 2, while the major steam system parameters at the steam generator outlet and inlet nozzles are summarised in Table 1.

Table 1. Major steam system parameters at steam generator outlet.

Reactor thermal power	4300 MW_{th}
Steam pressure	78 bar (a)
Steam flow	2443 kg/s
Steam temperature	293 °C
Feedwater temperature	230 °C

Table 2. Main data of turbine generator.

Operating speed	1500	rpm
Frequency	50	Hz
Generator output	1720	MWe
Power factor	0.9	
Voltage	27	kV±5%

Turboset

The design of the turboset for the new plant is based on an in-depth design study for the EPR basic design project initiated by the French EDF and started back in 1996 (Figure 2). The aim of the development work was a turboset design capable of achieving the highest power output, with best efficiencies and highest availability. This result will be realised in the saturated steam turboset for Olkiluoto 3.

The basis for development work on the steam turbine was the design of the standardised KONVOI saturated steam turbosets for nuclear power plants together with service and retrofit experience on large nuclear power plant turbosets. (See various publications compiled by Riehl, J.: Wirkungsgradverbessernde Maßnahmen an Siemens-KWU-Turbosätzen der großen Leistungsklasse in Kernkraftwerken, vorgestellt und erörtert vor dem Hintergrund einschlägiger Fachliteratur, Thesis, Hamburg 1999.)

A 3D illustration of the Olkiluoto 3 turboset is shown in Figure 1. The overall length of the shaft train is 68 m. Each turbine rotor rest on two bearings, so there is a double bearing between each of the turbine modules.

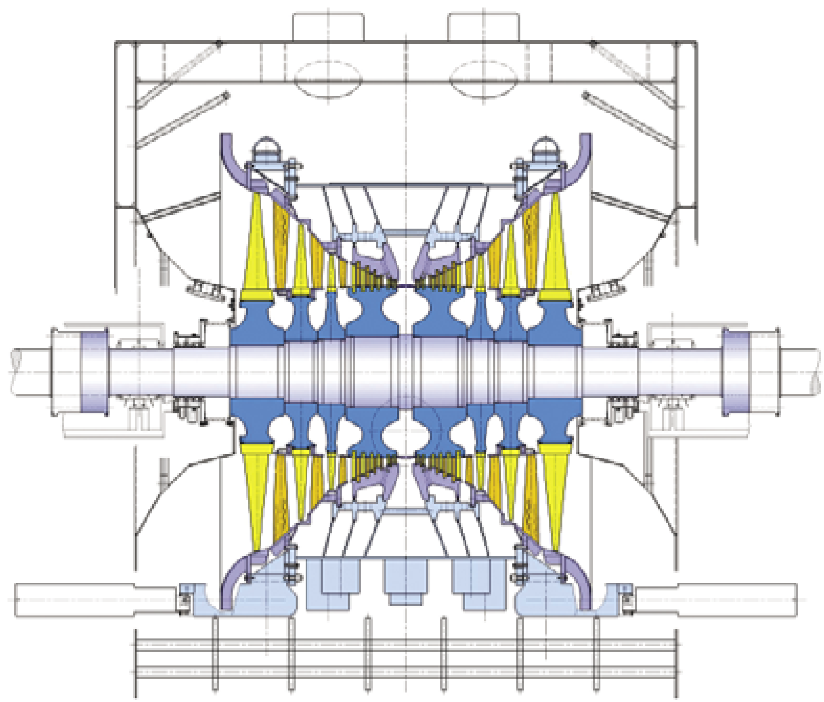
The steam turbine generator set is of rigid-coupled, tandem compound design consisting of one HP and three LP turbine cylinders. Because of the high power output and the relatively high volumetric flow rate a half-speed design was settled on.

The appropriate type of turbine generator is a four-pole arrangement including its brushless exciter set. The condensers are welded rigidly to the outer casings of the LP turbine cylinders and mounted on multi-ball bearings. The LP outer casing features free expansion without causing any changes of clearance between internal stationary and moving components of the turbine.

Four combined main steam stop and control valves are arranged below and in front of the HP turbine cylinder.

The combined moisture separator/reheaters are installed in front of the turbine in upright position. They each rest on four pendulum supports with axial guidance mounted on foundation beams.

Fig 4. Longitudinal section of LP turbine



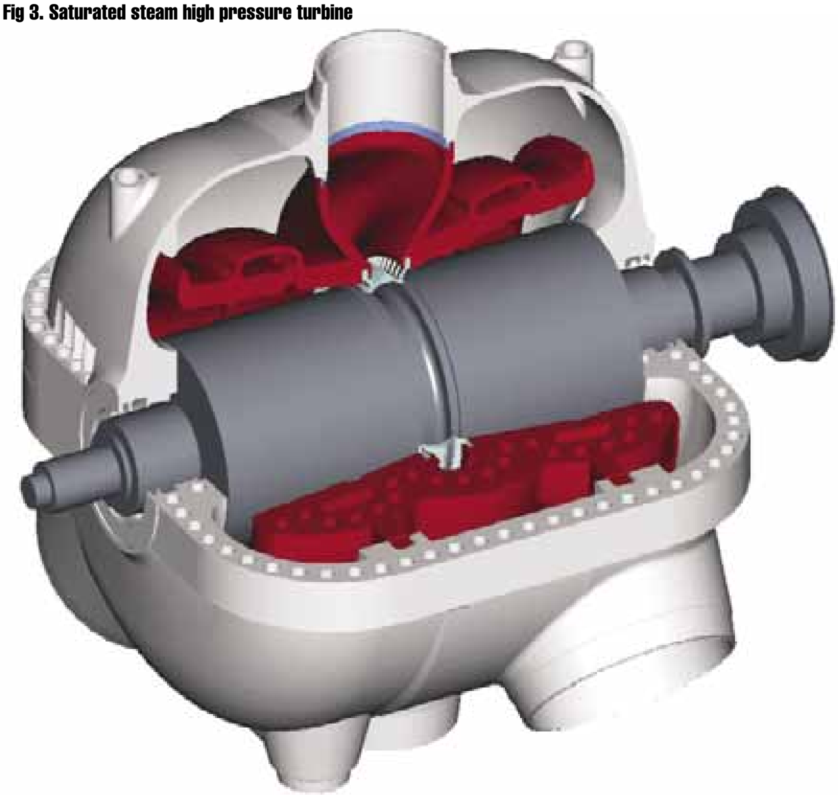
HP turbine

The HP turbine is of double-flow, double shell design with horizontally split outer and inner casings (Figure 3). An important feature is the double flow design which gives raise to symmetrically arranged stages and nozzles and results in the elimination of random thrust changes during operation. As a result an optimum number of turbine stages can be installed, and small radial clearances between stationary and moving blades are feasible, assuring a high HP turbine efficiency. Owing to the relatively low pressure in the outer casing, the employment of small flanges is possible. The advantage is high flexibility during transient operation, and short start up times.

The rotor of the HP turbine consists of a forged, mono block shaft with forged-on coupling flanges and with the moving blades held in slots; the critical speed of the rotor is above the operating speed. The rigid HP rotor has operational advantages over flexible rotors in maintaining the relatively small clearances, and giving rise to no instabilities owing to resonance zones during startup, no power limitation caused by steam turbulence and no self-excited oil film vibration. The blading is of variable reaction type with about 40-50% reaction. All the moving and stationary blades are integrally shrouded and tightly fitted together. The integral shrouding has an excellent damping characteristic in service, which has been proved effective since its introduction many years ago.

The HP turbine operates in the wet steam region. Erosion/corrosion problems are taken care of by appropriate material selection and surface protection. Use is made of steels with chromium content of about 2% and 13%, and chromium steel claddings, which have sufficiently high resistance to erosion corrosion.

Fig 3. Saturated steam high pressure turbine



LP Turbine

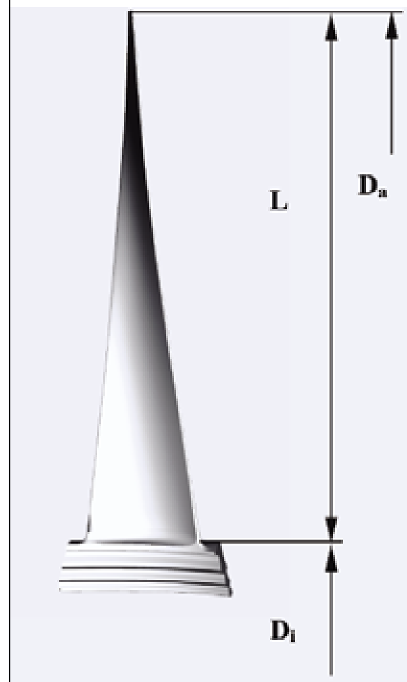
The LP turbine casings are welded structures of horizontally split, double shell design; the LP turbine cylinders are also of the double-flow type (Figure 4). The exhaust area of the last blade stage is to be 30m^2. This will be achieved by an end stage blade with 1830mm profile length. The six-flow configuration reaches a total exhaust area of 180m^2.

The rotors of the LP turbine are built-up-type rotors with the moving blades held in slots. The individual rotor segments and coupling flanges are shrink-fitted to the shaft core (Figure 5). Siemens designed LP shrunk-on disk rotors have a high resistance to stress corrosion cracking achieved by choice of materials, quality, stress limitation design, and control of steam purity. Millions of disk service hours have been accumulated without any indication of stress corrosion cracking.

The first flexural critical speed of the LP turbine rotors is below the operating speed. The drum stages are provided with about 50% reaction, integral shrouded blading being used. The final stages are standardised, well proven, twisted moving blades. Their degree of reaction differs over the length of the blade in line with the speed of rotation, which also in-

Fig 5. Shrunk-on-disk LP turbine rotor

Fig 7. Final stage blade, LP turbine with exhaust area of 30 m²



Hub diameter D_i - 3060 mm, tip diameter D_a - 6720 mm, blade length L - 1830mm, blade weight (including root) - 340kg.

creases sharply over the length of the blade. The last three standardised blades have the main advantages of guaranteed vibration frequencies with a wide margin between the natural frequency at rated speed and resonance. The moving blades are locked in place by means of curved 'fir-tree' roots.

Impact erosion through water droples striking rotor blades at high relative velocities is prevented during all operational modes by a special design based on long-term experience. The steam path of the LP casing also has special design features for water extraction.

Efficiency features

Turbine efficiency is determined primarily by the blading, because this is the component that actually transforms the available energy of the steam into useful work. Research on blade design improvement on turbines for fossil steam power application was started many years ago. The results gained have been transferred to the nuclear steam turbine design to achieve the maximum thermodynamic benefit.

For the drum stages of the HP turbine Siemens' newest drum blading technology called 3DV™ (3D variable reaction) will be applied (Figures 6 and 7). This new type of blading eliminates the need for a 100-year-old decision, namely, what percentage reaction to apply across each row of blades [3].

With 3DV blading the stage reaction and the stage loading for each row can be numerically optimised to gain higher HP and IP efficiency than was possible with previous blading-types.

3DV blading also incorporates the well-known advantages of 3DS blade technology where reduction of secondary losses in the side-wall area at the hub and tip region is of primary importance. The secondary losses contribute significantly to an efficiency deficit in some HP blades due to the relatively small blade heights.

To allow for the low temperature of cooling water available in Finland the design back-pressure is about 25 mbar. A large exhaust area of 180 m² provides the optimum concerning exhaust loss reduction and power output gain. It will be achieved with a 6-flow LP turbine with an end stage size of 30 m², ie a blade of 1830 mm profile length (Figure 8). This blade is a fully scaled version of the well proven 8m² full speed blade with 911 years of module ser-

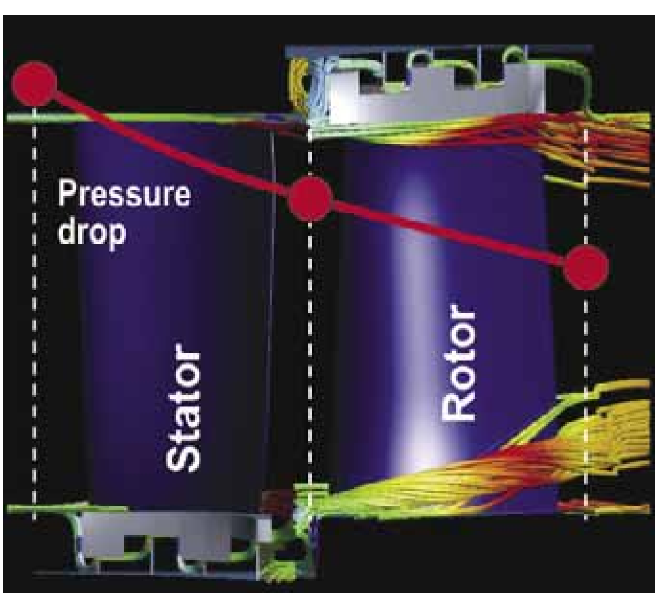


Fig 6. 3D flow field analysis

Fig 7. 3DV-optimised-blade profile

Fig 9. Finite element stress analysis of first disk

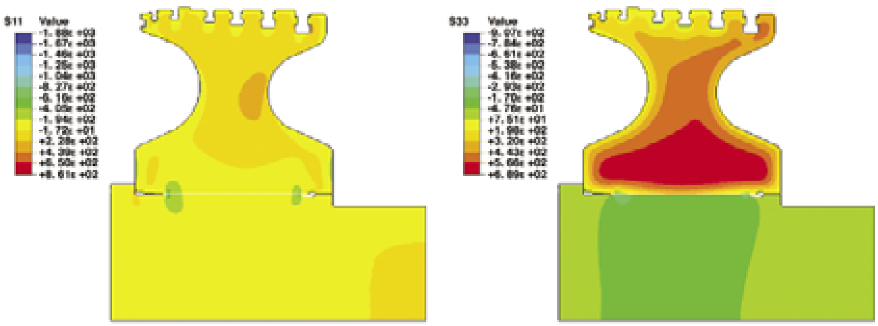


Fig 10. Non-linear fracture mechanics analysis for hypothetical worst-case scenarios

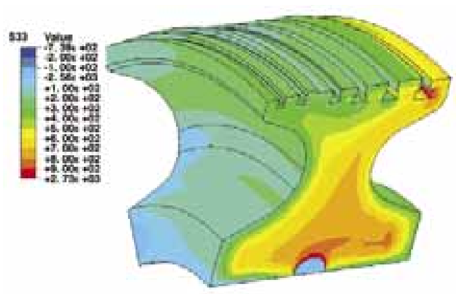
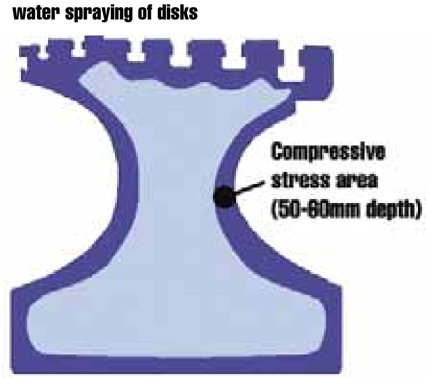


Fig 11. Residual compressive stress area after water spraying of disks



vice life experience. The mechanical and aerodynamic properties of the 8 m² and 30 m² last stage blades are the same.

Improvements in materials

In addition to flow-related modifications, special attention was paid to minimising the risk of stress corrosion cracking of the new low-pressure turbine cylinder. (See Oeynhausen, Rottger, Ewald, Schleithoff, Thermuehlen: *Reliable Disc-Type Rotors for Nuclear Power Plants.* American Power Conf., Chicago, April 27-29, 1987.

Stress corrosion cracking is likely to occur if the following three factors coincide:

- Steam/condensate impurities (electrical conductivity)
- Material susceptibility to stress corrosion cracking (high yield strength)
- High tensile stresses at the surfaces of the disks (stress concentration)

All the types of forged steels used in low-pressure rotors exhibit broadly the same behaviour with respect to stress corrosion cracking and crack growth rate. It is therefore impossible to make parts more resistant to stress corrosion cracking merely through choice of materials. Siemens uses a forged steel with a 3.5% nickel and 1.5% chromium content for all its shafts and disks. This steel has excellent through-hardening characteristics, even given the large diameters used here. Good fracture toughness and notch toughness can be achieved across the entire cross section with consistently high yield strength.

The third factor that can trigger stress corrosion cracking is the only one which turbine manufacturers can take steps to prevent, by ensuring that only compressive stresses or low-magnitude tensile stresses act on the surfaces of the disks.

Siemens uses the finite element method to determine disk stresses caused by centrifugal force and shrink fit. The disk contour and shrink fit are optimised such that the hub area is only subjected to consistently low tensile stresses (Figure 9). Also nonlinear fracture mechanics analysis will be performed on all highly loaded components to ensure reliable operation in all hypothetical load cases and worst case assumptions (Figure 10).

In addition to these design measures, special heat and surface treatment processes further increase the resistance of disks to stress corrosion cracking. These are:

- Spraying with water after heat treatment in the steel mill; this causes the hub and outer rim areas to cool faster than the inside of the disk with the result that surface zones of residual compressive stresses occur once the entire component has been properly cooled (Figure 11).
- Shot peening of the hub, web areas and blade grooves of the disks; this eliminates tensile residual stresses resulting from machining operations and produces compressive stresses at the surface (Figure 12)
- Rolling of all shaft radii, axial keyways and LP blade root radii with highest stress (Figure 13)

Particularly careful and precise machining techniques that have been optimised in manufacturing tests are used for all four disks.

For the anti-rotation bolts, a method which has been used successfully for many years is to provide the keyways with a circumferential stress-relief groove outside the shrink fit area. After reaming and honing, the keyways are rolled with a special tool and honed a second time.

This process produces such high compressive stresses at the surface of the keyways that tensile stresses cannot possibly occur in the low-pressure rotors, even in operation.

Advanced design

The Finnish decision to build the new nuclear power plant Olkiluoto 3 suggests that nuclear energy will be an option in the future of electricity production worldwide. It can show economic superiority at a certain level of power output compared to fossil fuels and can also make a significant contribution to reducing carbon dioxide emissions.

The design of the advanced saturated steam turboset for a net power output of approximately 1600 MW is a result of long operational experience with nuclear power plant at Siemens, and incorporates the latest engineering expertise gathered from service experience of, and creating, large scale fossil fuel steam turbines. Special care has been taken to achieve a heat balance which is optimised overall, based on optimal efficiency of individual turbines. The last stage blade of the LP turbine will have a profile length of 1830 mm. Despite its dimensions and greater size it is a well proven profile scaled from existing full speed applications.

The prevention of erosion, corrosion and stress corrosion cracking has been achieved by appropriate material selection and advanced design methods employed at the first stage of design development. MPS

Fig 12. Shot peening of disk web area

Fig 13. Rolling of LP blade root radii

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