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## Variable-Pitch Axial Flow Fans for Thermal Power Stations

*Axial-flow fans with impeller blades adjustable under load have been designed and built for thermal power stations for about 30 years. The decision to develop this fan type was prompted not only by its easy design integration into overall plant configurations but also and primarily by the operating cost benefits it offers, specifically when compared with centrifugal fans with variable inlet vanes.*

Since the magnitude of the economic benefit obtained (reduced station power consumption) depends on the size of the generating station (block output), the fan operating regime (part-load operation), overall plant design and fuel costs, it took a number of years for axial-flow fans with variable pitch (VP) impellers to become established in thermal power station applications.

By now, this fan type has gained worldwide acceptance in forced draft, induced-draft, pulverizer air fan and flue gas desulphurization (FGD) service. A large percentage of these fans, specifically larger ones, goes to North American markets, where approx. 450 axial-flow fans have been deployed on power station blocks in the up to 900 MW range since 1974.

Among the most interesting plant types are the so-called “mono-block” systems which comprise only a single forced-draft, induced-draft, and pulverizer air fan per boiler.

The two induced-draft fans at the Weiher and Bexbach power stations, with their outside impeller diameters of 5.0 and 5.3 m and input power ratings of 13500 and 11500 kW, respectively, are among the world’s largest power station fans. They are also worth noting for the high tip speed of 162 m/s of their (nodular cast iron!) blades.

The decision to adopt a “mono” solution for blocks of this size had been preceded by several years of satisfactory experience gathered with the induced-draft fans of two coal-fired 350 MW blocks which were likewise operating with only one induced-draft unit per boiler.

Axial-flow fans with variable blade pitch angle may be of single-stage or multi-stage design. To our knowledge, only fans with up to two stages are in use in power stations today - with the exception of the three-stage forced draft unit shown in Fig. 1 which, in 1953, marked the start of this fan development at TLT (still named Dingler Werke at the time).

## Comparison of axial and centrifugal fan characteristics

It is evident from Fig. 2 that the iso-efficiency curve of variable-pitch axial flow run approximately parallel to the system resistance graph, implying good efficiencies throughout a broad operating range. In the case of centrifugal fans with variable inlet vanes, the iso-efficiency curves intersect the system resistance curves, meaning that their efficiency under part-load conditions is automatically lower than with axial-flow units.

Moreover, an axial-flow fan can be selected to ensure that the boiler design point will be located above the maximum efficiency range in the field of characteristic curves, the operating

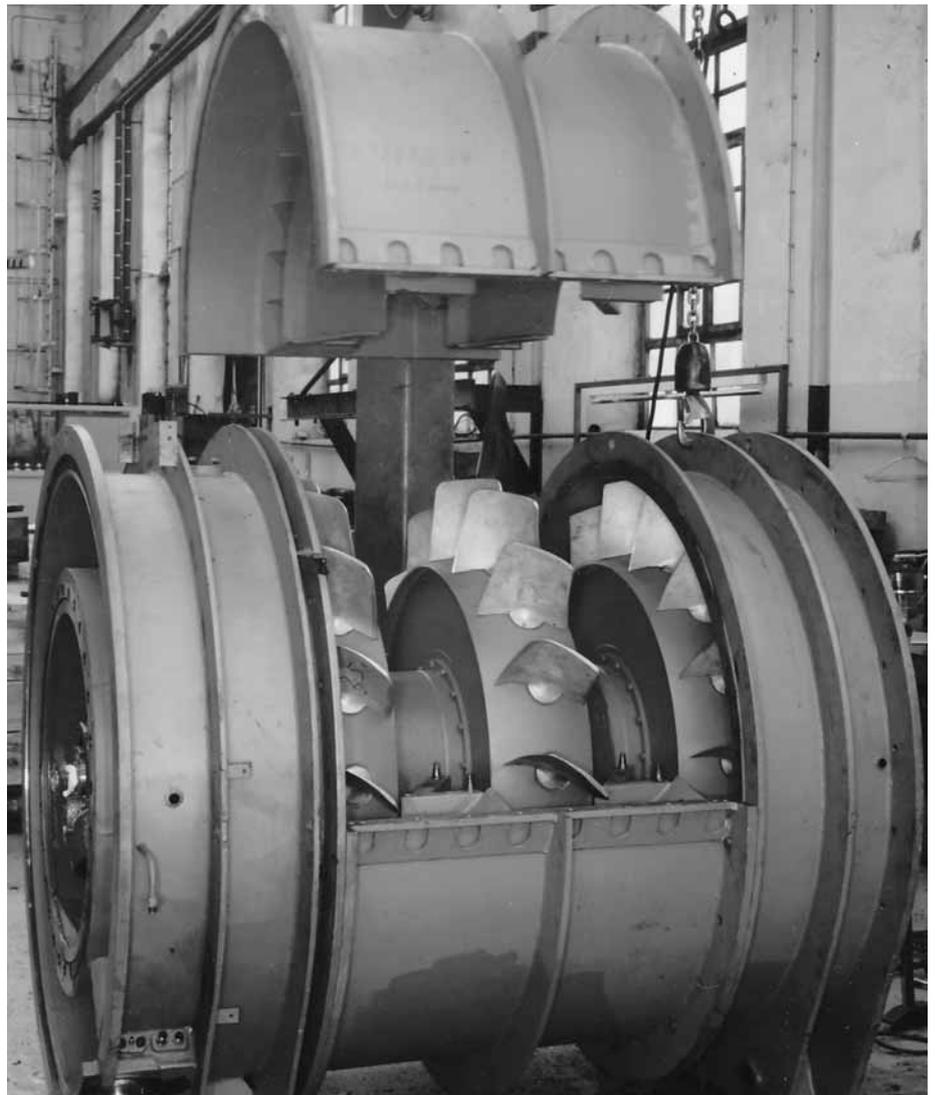


Fig. 1: Three-stage axial flow fresh-air fan

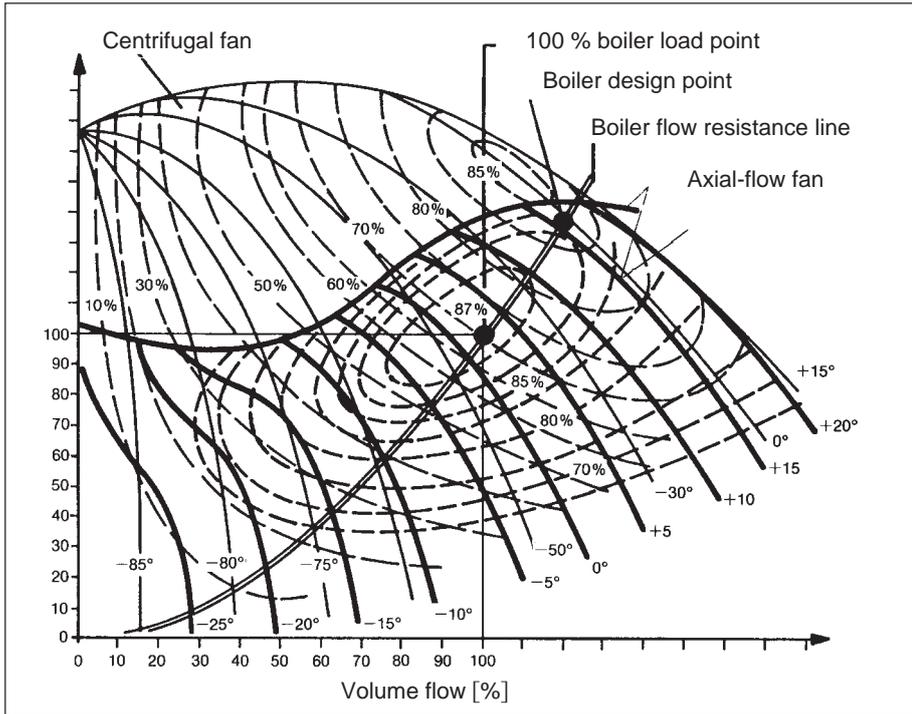


Fig. 2: Comparison between characteristic maps of axial-flow and centrifugal fans

points of maximum interest therefore falling into the highest efficiency spectrum.

**Fields of application**

Axial-flow fans in thermal power stations are used as fresh-air (forced-draft), induced draft and pulverizer air fans; in recent years they have also become more widespread in a flue-gas desulphurizing (FGD) context (Fig. 3). Their use is not contingent on the fuel type employed (coal, oil, gas, peat), although fuel type is naturally a design determinant, specifically with induced-draft units.

Regarding the installation of fans downstream of electrostatic precipitators, today's flue gas desulphurizing plants support various circuit configurations and hence, different arrangement of induced draft and FGD fans. In recent years, axial fans operating as "booster fans" on the wet-gas side downstream of the scrubber have gained particular importance. With these units, the choice of material, surface protection considerations and sealing towards the conveyed-medium circuit require particular attention.

**Disposition**

Axial-flow boiler fans may be fitted horizontally or vertically. Fresh-air and pulverizer air fans are preferably installed horizontally, while induced draft units are also known to perform well when fitted in an upright position in the stack. In flue gas desulphurization systems, fans serving on the wet-gas side downstream of the scrubber are likewise designed for vertical operation and are even so-

metimes configured with integrated motors.

An overview of these installation principles is given in Fig. 4. The inlet box opening may have any orientation, up to 360 deg., relative to the fan axis.

Vertical solutions may provide the following benefits:

- simplified flue gas ducting;
- reduction of pressure losses due to fewer deflection points;
- no need for sound insulation or special silencer structures (with in-duct fans);
- no need for separate installation space as unused space is available;
- easier assembly and disassembly through optional "lateral offset" of active components, i.e., the housing and rotor (i.e., these can be moved sideways without requiring any change in the position of adjoining components).

**Mounting configurations**

Fig. 5 summarizes the main installation arrangements that have found to be viable in practice. For fans mounted at floor level, buried concrete block foundations were primarily employed in former years (refer to sub-figure a).

14

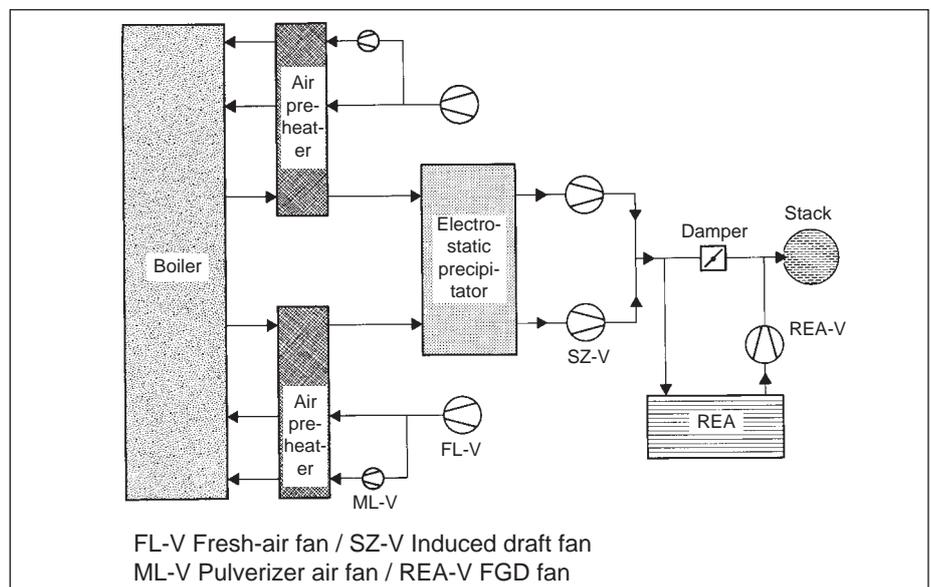


Fig. 3: Axial-flow fans in thermal power plants

Solutions illustrated in sub-figures b) and c) are preferred nowadays since they are associated with a less complex oscillation behaviour. Put simply, a configuration of this type may be viewed as a two-mass oscillation system.

**Mass 1:** Rotor, consisting of the impeller and main bearing assembly

**Spring 1:** Overall spring stiffness of the main shaft, bearing assembly and fan housing

**Mass 2:** Concrete block

**Spring 2:** Spring stiffness of the anti-vibration mountings

Given the mass ratio of approx. 20 : 1 between the concrete block and the rotor and the resulting low frequency response of the foundation, the two-mass oscillation system may be considered decoupled for the purposes of oscillation modelling. At this mass ratio, the foundation's influence on the

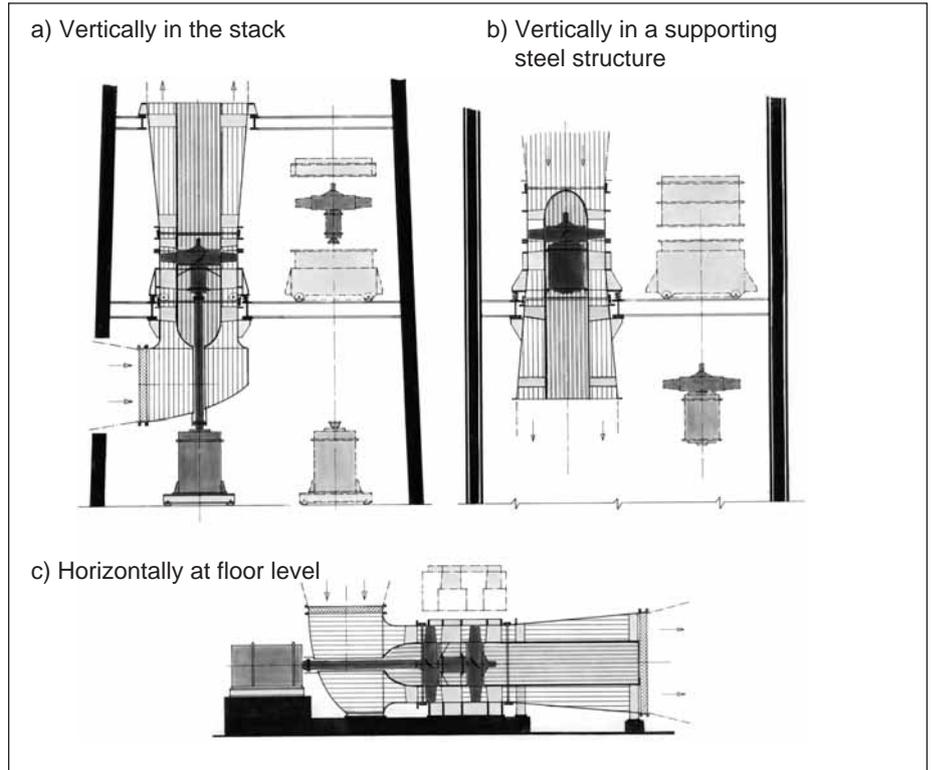


Fig. 4: Arrangement of axial flow fans

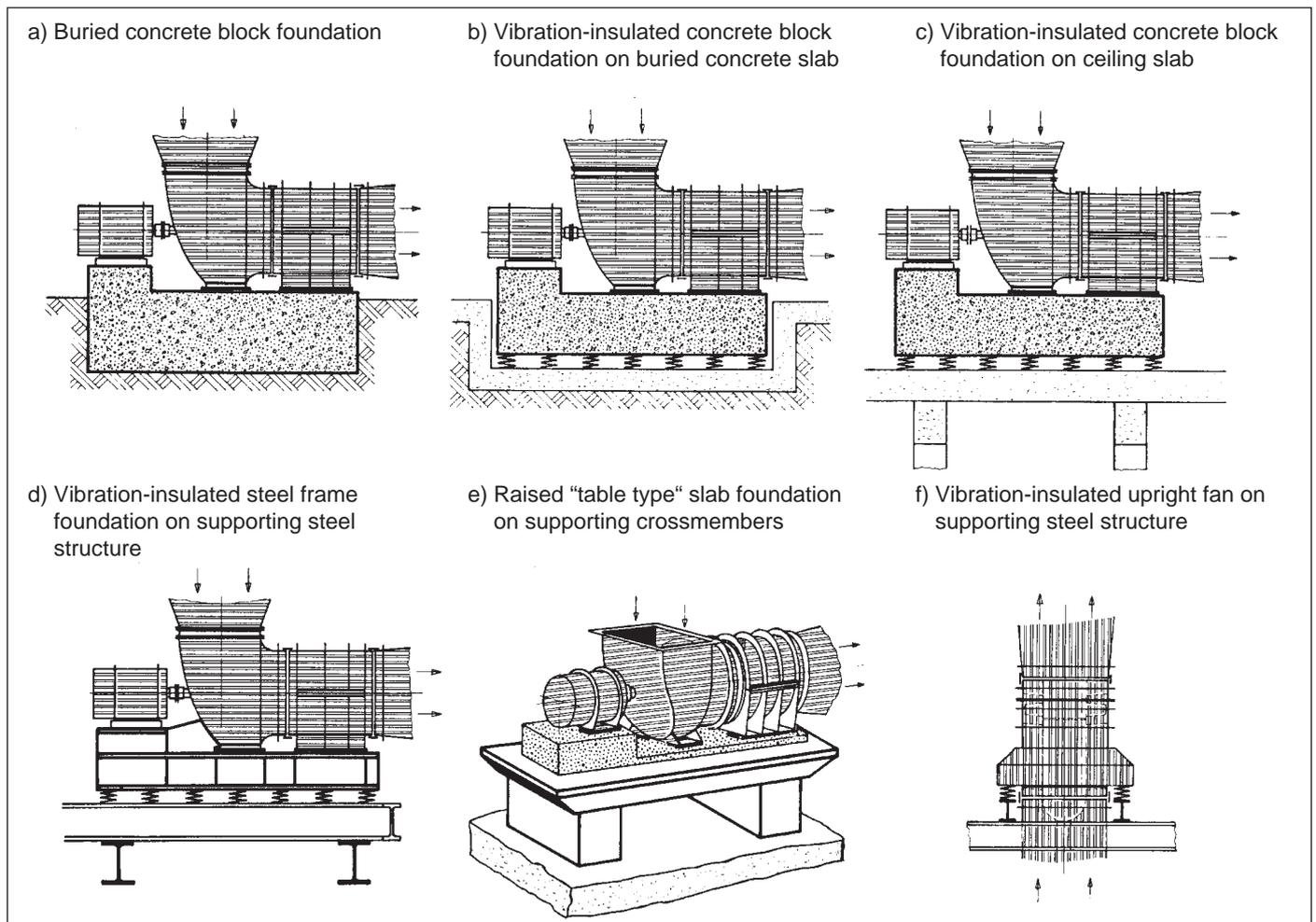


Fig. 5: Axial flow fan installation configurations

natural bending frequency of the rotor system is negligible.

With isolated frame foundations of the type illustrated in sub-figure d), the natural vibration behaviour of the frame must be included in the analysis. Frequency criteria generally used for isolated foundations must be applied to the natural frequencies of the frame as well.

When fans are placed on ceiling slabs, as shown in sub-figure c), care must be taken to ensure that an appropriately sized girder extends under both the fan and the motor.

Raised slab foundations of the "table" type, illustrated in sub-figure d), have to be supported by strong crossmembers under the motor and fan at the main force transmission points.

For fans erected directly on anti-vibration mounts (e.g., upright induc-

ted-draft units fitted in the stack or vertical FGD fans mounted on supporting steel structures) as depicted in sub-figure f), the natural oscillation behaviour of the frame structure must be taken into account, just as with horizontal fans mounted on isolated foundations.

Computing models for the block and frame foundations are usually available today for both anti-vibration mounting and direct floor installation. The natural oscillation frequencies can be determined for such foundations with up to 6 degrees of freedom, including translational motion and rotation about the three main spatial axes, plus the most frequent coupled modes.

A few other boiler fan installation methods exist but are of minor significance and shall therefore not be discussed here.

## Design

Induced draft, forced draft, pulverizer air and FGD fans do not differ greatly in terms of their basic design. The focus of the present article is on axial-flow induced draft fans. The horizontal fan type shall be considered for the purposes of our further comments.

In line with the design objective, variable-pitch axial flow fans were developed with the following main criteria in mind:

- good access to rotating parts through an appropriate separation of housings and suitable arrangement of access doors;
- possible avoidance of inlet and outlet side duct displacement in the event of a rotor change;
- minimum shut-down times, achieved through a replacement of entire

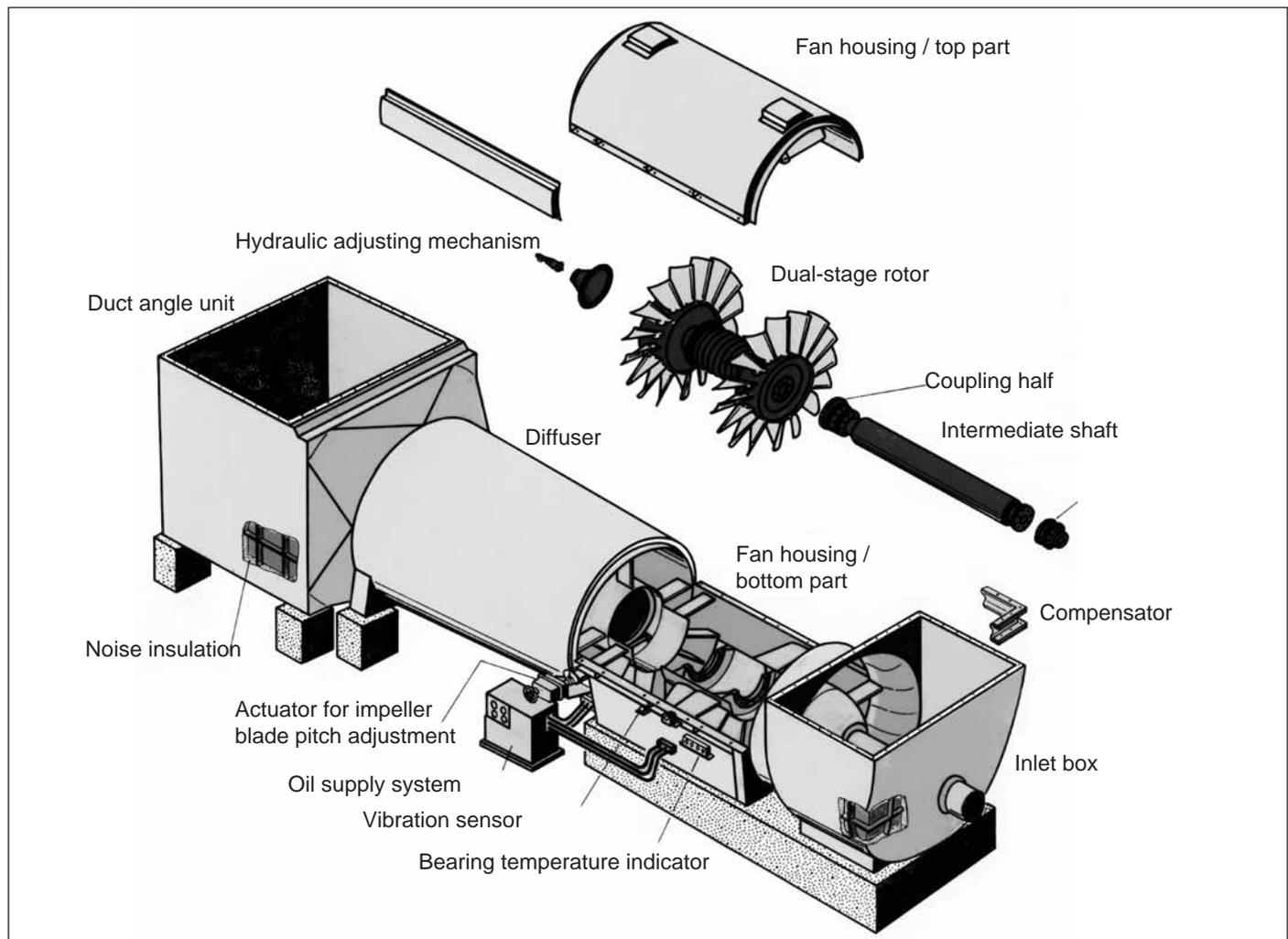


fig. 6: Axial-flow boiler fan

components (e.g., rotor, main bearing assembly, actuating mechanism);

- high availability and longevity through selection of appropriate materials and sealing systems, in conjunction with rugged design;
- maximum standardization of components to speed up the accumulation of operating experience.

Fig. 6 clearly illustrates how the above design requirements are met in practice. The rotor - consisting of the impellers, the main bearing assembly and the blade adjustment mechanism - can be installed and removed as a complete subassembly on both single-stage and dual-stage fan models.

The fan housing with its removable top portion is connected to the diffuser and inlet box via a quickly removable non-metallic bandage held down by a steel strap.

With this design, a rotor replacement on the induced draft fan of a 600 MW block can be accomplished in about three shifts.

The induced draft fan shown in Fig. 7 has a two-stage rotor whose blades are adjusted simultaneously by the actuating mechanism provided on the impeller outlet side.

The fan is powered by a constant-speed electric motor normally arranged outside the fan itself. The motor is connected to the rotor via a hollow shaft with a torsionally flexible cur-

ved-tooth or multiple spring disc coupling. Basically, an integration of the drive motor into the fan housing hub is likewise conceivable. This design was adopted for the flue gas desulphurization fans in three NWK power stations; these fans are all arranged on the wet-gas side.

Due to the temperature loads acting on induced draft fans, the interior of the hub is thermally insulated in order to protect the rotating components.

Cooling air is supplied into the hub through the hollow bracing and blades by a set of separate external fans. It is important that the cooling air-carrying ducts are insulated to prevent temperatures below the dew point.

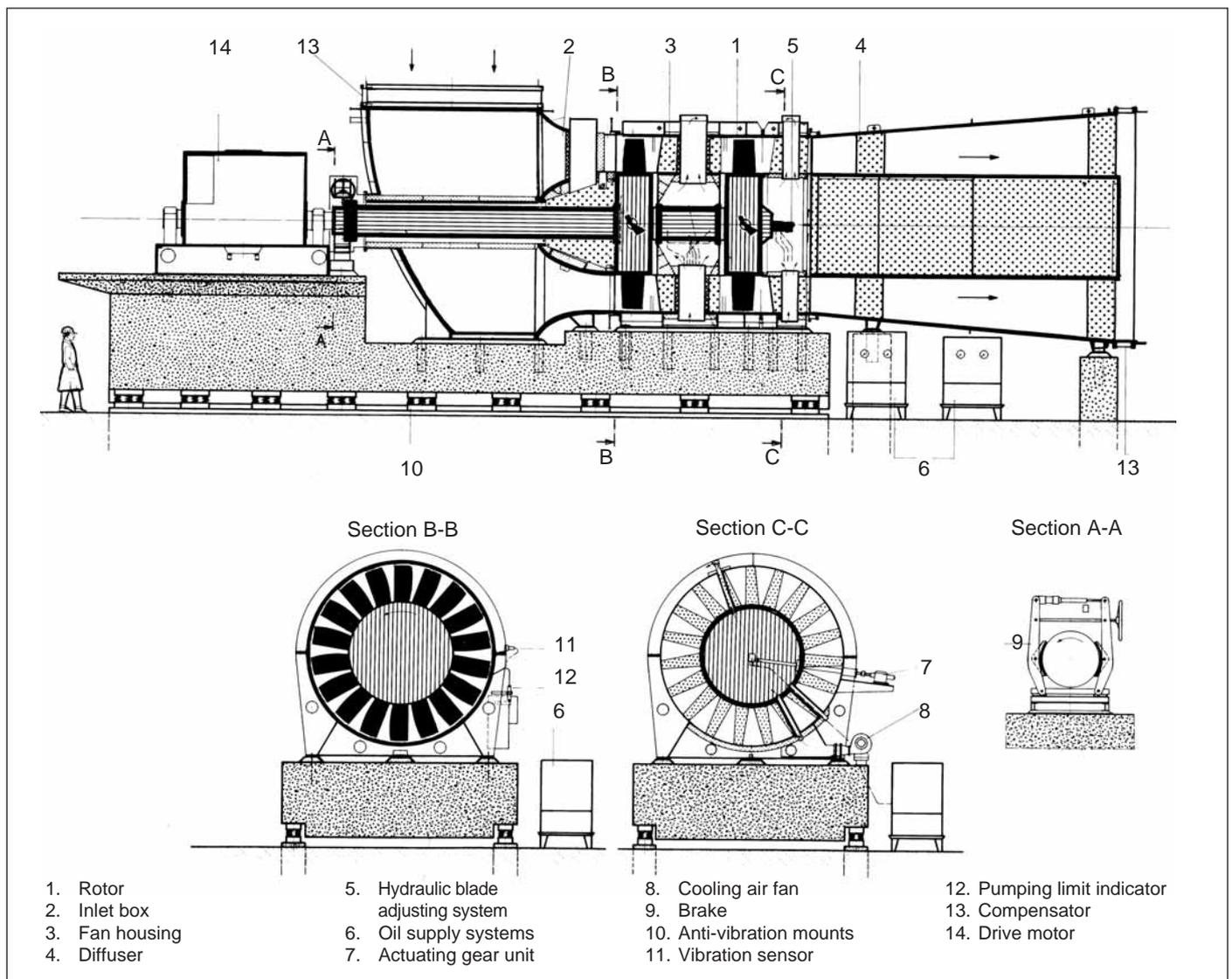


Fig. 7: Dual-stage induced draft axial flow fan with blade pitch adjustment

If the rotor is supported in sliding bearings, a brake is fitted on the drive-side coupling to protect the bearings against running in mixed-friction conditions and to prevent rotor spinning once the motor has been de-energized.

Lubricating oil for the main bearing and hydraulic oil for the hydraulic actuating mechanism are supplied by oil supply units mounted outside the fan (Fig. 8). These are normally equipped with two pumps of approximately equal output, of which one is a stand-by pump brought on stream by a pressure monitoring switch when the first pump fails. To prevent bearing damage when the fan coasts to a stop after a power failure, the second pump is sometimes connected to an uninterruptible power supply, specifically on fans with sliding bearings.

Forced lubrication oil is fed to the point of use via a dual filter and an air-oil or water-oil heat exchanger. If the bearings of the main drive motor are likewise lubricated off this system, an accurate distribution of the oil flow to the various bearing points must be ensured.

Fig. 9 is a cross-sectional view of a single-stage rotor. It consists of the impeller with blades, the main bearing assembly, and the blade control mechanism.

**Impeller body**

In this design the impeller body is entirely of welded construction. The centrifugal forces are absorbed by a ring arranged inside the hub.

This welded design has proven highly advantageous, particularly on indu-

ced-draft fans, since a cost-efficient casting for the load levels encountered would be difficult to produce with any degree of reliability.

The welded hub design makes it possible to select induced draft fans of higher speeds, which in turn permits reduced fan sizes and the use of single-stage instead of dual-stage units (examples include the induced-draft fans in the Weiher, Bexbach and Mannheim power stations).

**Blade shaft bearing assembly**

In a variable-pitch axial flow fan the blade shaft bearing assembly is one of the most critical components.

In the design illustrated on page 7, centrifugal forces are absorbed by hermetically sealed deep-groove ball thrust bearing while the transverse

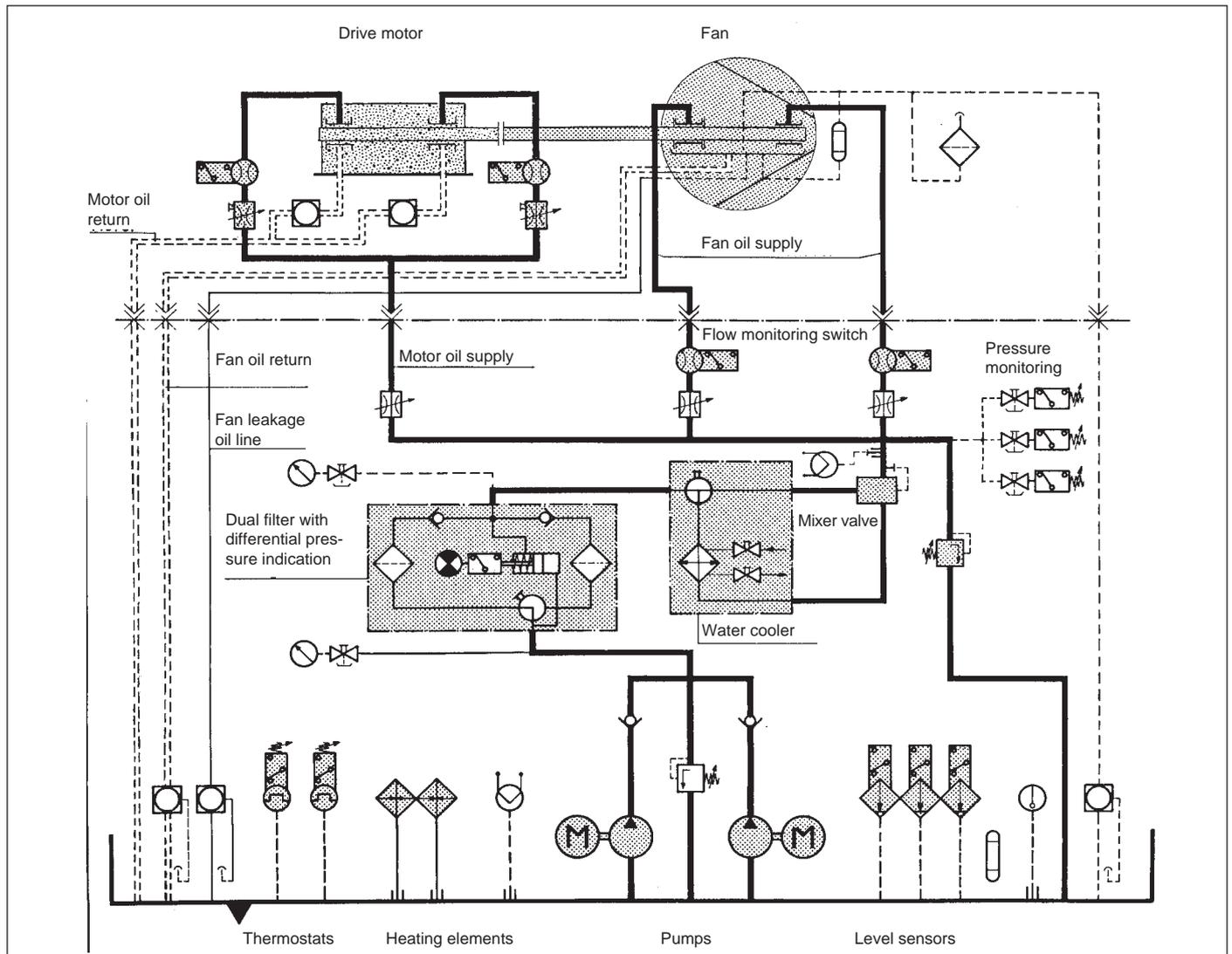


Fig. 8: Bearing lubricating oil circuit schematic

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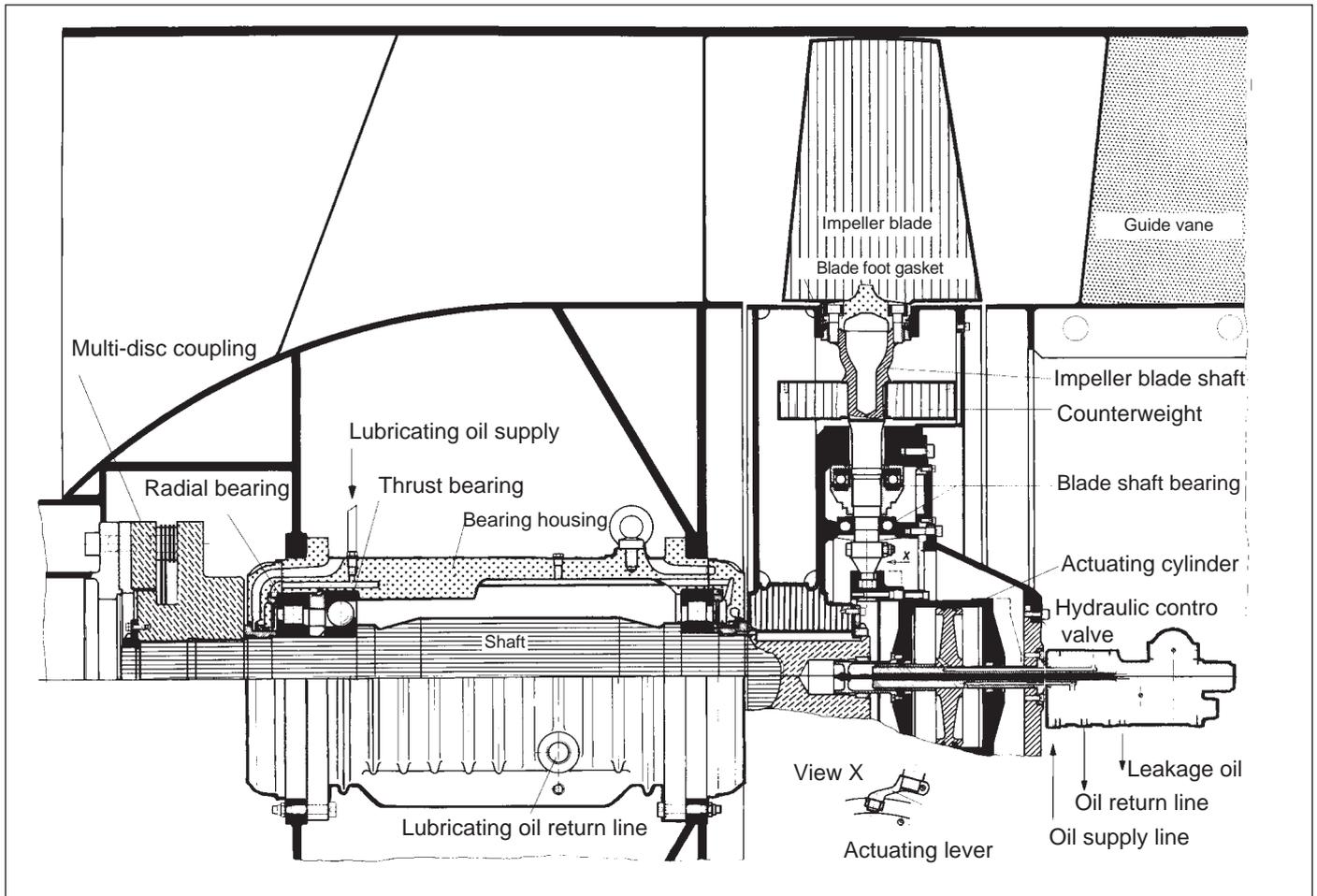


Fig. 9: Rotor of a single-stage axial-flow fan

forces resulting from the adjustment function are handled by an angular-contact ball bearing.

Anti-friction bearings are by definition intended to rotate; however, in the present application they serve merely to accommodate the blade pitch angle adjustment. Proper design, lubrication and sealing of the blade shaft bearing assembly are therefore of outstanding importance.

The bearings may either be greased or oil-lubricated. Operating tests and development trials have shown that only a few grease types will retain their lubricating properties over an extended period under the prevailing temperature loads and centrifugal forces. A fully enclosed design of the thrust bearing was therefore adopted; this has greatly increased the service life of the bearing assembly compared to the solutions used in previous years. Since the anti-friction bearings will not fail suddenly, the bearing sta-

tus can be monitored "on-line" from outside the fan by measuring the requisite oil pressure for the blade angle adjustment.

#### Blade foot sealing

Tightness of the blade shaft passage through the hub casing is a major reliability criterion, specifically in the design of induced-draft axial flow fans.

Experience has shown that the sealing system employed ensures a 100% tight shaft entry into the hub chamber.

#### Impeller blades

Impeller blades are screwed onto the blade shafts. Individual blades can thus be replaced without removing the entire rotor. Proven blade materials include aluminium alloys for fresh-air (forced draft) and pulverizer air fans, and cast steel or nodular cast iron for induced draft fans in coal-fired boiler duty.

Although the performance and separating efficiencies of today's electrostatic precipitators are much improved and dust loads on the clean-gas side have dropped significantly as a result, the accumulated experience suggests that cast steel or nodular cast iron remain the materials of choice.

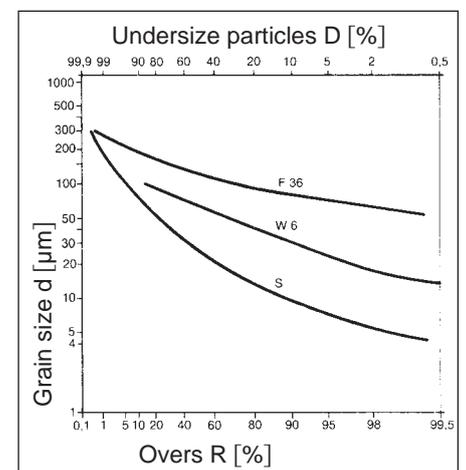


Fig. 10: Particle-size distribution of various dust types

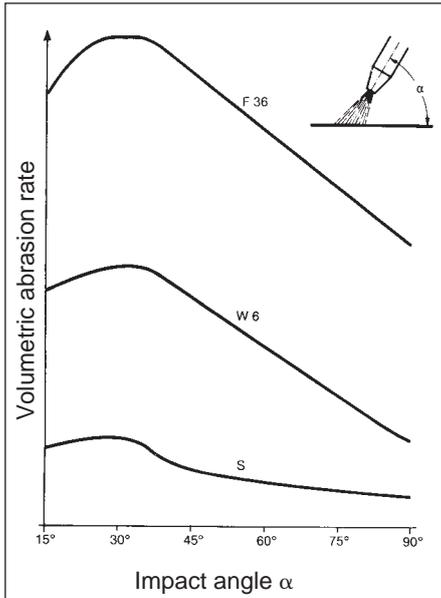


Fig. 11: Volumetric steel abrasion as a function of dust particle size

It has been found that short-time filter failures give rise to high wear rates; moreover, in the case of an air-preheater failure, temperatures in the fan area may reach 300°C.

Since the endurance strength of aluminium alloys drops very quickly at temperatures over 200°C, the use of aluminium blades on induced draft fans in coal-fired boiler service implies significant operating reliability and safety hazards.

**Impeller blade wear**

Abrasive wear of the impeller blades is a function of the following:

- relative speed of dust particles impinging on the blade surface
- impeller blade material
- angle of impact
- dust concentration
- grain size distribution
- dust load distribution
- hardness of dust particles

Only the first two parameters are controllable by the fan manufacturer.

Extensive trials have shown that there exists an approximately square correlation between the relative speed of the dust particles and the rate of blade abrasion. Under otherwise equal conditions, the granulometric distribution of the particles also has a significant influence on blade wear, as illustrated for three dust types in Fig. 10. As will be appreciated from Fig. 11, the volumetric abrasion rate (cm<sup>3</sup> of material removed per kg of impinging dust) is much higher with "F36" dust than with "S" type particles. Knowing the dust particle size distribution is therefore a key prerequisite for any correct advance evaluation of impeller blade service life under wear conditions.

Extensive wear tests conducted over many years, supported by field experience gathered with induced draft fans, have led to the development of a computing method whereby the service life of impeller blades can be projected if the values of the above parameters are known.

**Rotor main bearing**

The illustration on page 9 shows the "compact design" bearing system which has given good results in single- and dual-stage axial flow fans for years. This design approach minimizes the necessary removal, refitting and alignment work (particularly the latter), since the flanges in the bearing mounting area are handled simultaneously with the blade running surface of the outer fan housing shell. In addition, this bearing design allows for the selective use of sliding and anti-friction bearings without any change in exterior diameter.

Both systems have proven their value in many installations for years. The anti-friction bearings are oil-lubricated, with an external oil-supply unit recirculating the oil sump in the bearing housing. Moreover, this oil sump allows the fan to remain in operation for quite a while if the forced circulation system should fail.

**Sliding bearings**

The sliding bearing assembly (Fig. 12) consists of tilting-pad radial bea-

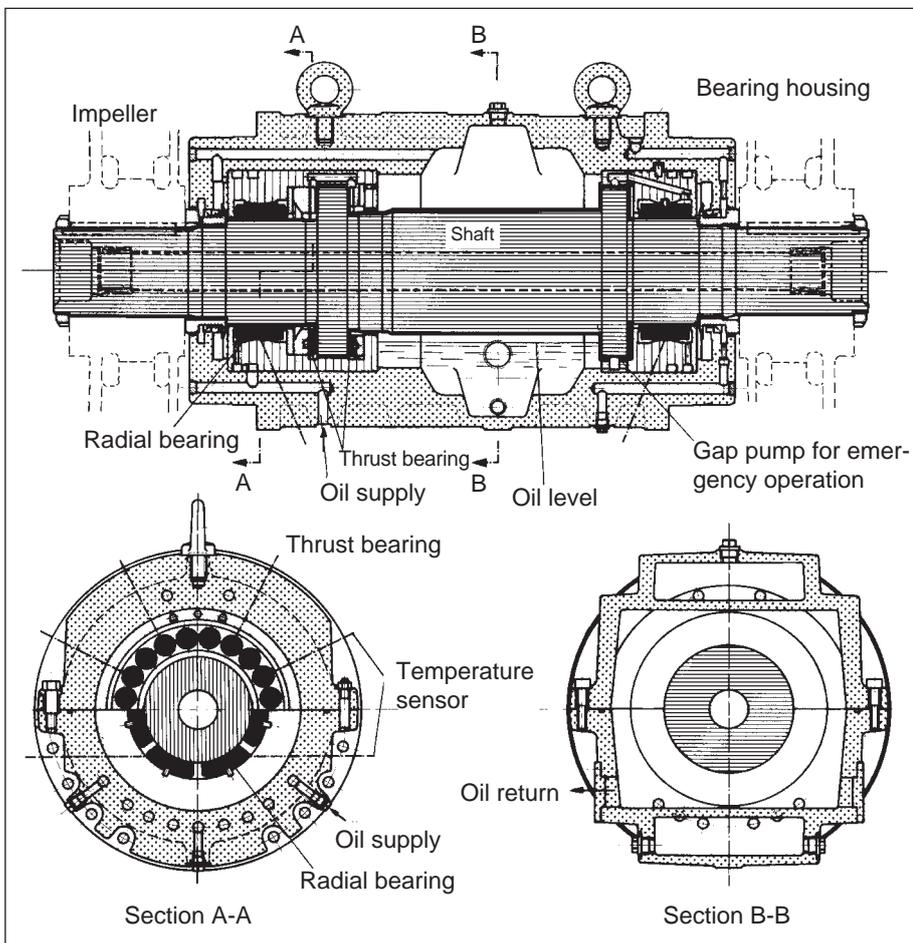


Fig. 12: Sliding bearing assembly

14

rings and thrust bearings with self-adjusting circular sliding pads arranged circumferentially on both sides of a shaft collar. The bearing housing is split horizontally, allowing bearing parts to be inspected or replaced without having to remove the impellers from the shaft.

Bearings are lubricated by an oil supply system mounted outside the fan. Emergency lubrication after an oil-supply failure is ensured by a "gap pump" fitted directly onto the main shaft. This pump draws oil from the sump in the bearing housing and feeds it to the point of use. The system is effective only briefly under full load, but permits an extended coast-down cycle.

The decision between sliding and anti-friction bearings is often a philosophical one, at least in part, since both bearing types have proven their merit over the years. It may be observed that split-type sliding bearings offer advantages with large and therefore heavy rotors, and may yield an unlimited service life when combined with a reliable lubricating system.

The tilting pads of the radial bearings are adjustable both longitudinally and transversely and will therefore adapt to possible shaft deflections.

A properly rated sliding bearing, unlike an anti-friction bearing, is not a "wearing" part requiring periodic replacement if used with appropriate oil-quality.

Moreover, bearing failures will develop over much longer time spans and can thus be forecast, and hence avoided, via temperature and oscillation monitoring.

Anti-friction bearings, on the other hand, provide superior emergency operating characteristics due to the existing oil sump in the bearing housing. Nevertheless, a premature failure of such bearings can never be ruled out.

### Hydraulic blade pitch adjustment

For controlling the impeller blade pitch setting and hence, the fan's volumetric throughput and outlet pres-

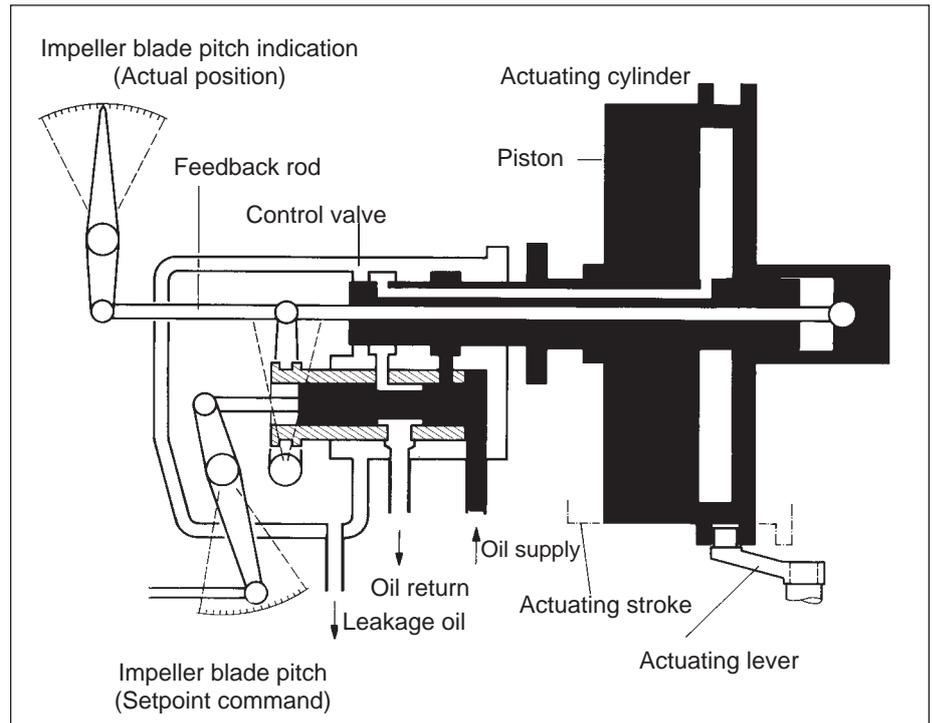


Fig. 13: Schematic view of the hydraulic blade pitch control system

sure, the following actuator systems are available:

- pneumatic
- electromechanical
- mechanical
- oil hydraulic

Pneumatic and electromechanical systems play virtually no role in power plant fan engineering, while mechanical blade pitch control systems used to be employed specifically on smaller units. Oil-hydraulic control systems have emerged as the most suitable solution for this purpose. They operate with less hysteresis since they use fewer mechanical power transmission elements; in addition, they are capable of transmitting higher actuating forces of the magnitude required in over 300 kW blocks.

Systems embodying the principle illustrated in Fig. 13 have been built with only minor changes for more than 30 years.

An actuator system of this type comprises the following main elements:

- an actuating cylinder moving axially along the fan axis and turning with the rotor;

- a piston within the actuating cylinder which is axially fixed and rotates with the same speed as the cylinder;

- a feedback rod

- a stationary control valve which receives the command to change the blade angle via an actuating gear unit outside of the fan housing and converts it into a hydraulic signal. Pressurized oil will thus be directed to the appropriate cylinder side, imparting an axial movement to the cylinder. This axial displacement causes the impeller blade to turn, due to the geometry of the levers attached to the end of the blade shafts which engage the actuating disk. The movement is carried out simultaneously, even on multi-stage fans.

The actual position of the impeller blades is indicated outside the fan housing and can be transmitted to a control center.

Effective sealing in the joint areas between stationary and rotary components is an essential requirement with such actuator systems. Seals may consist of plastic or metal elements. The control delays for the relevant pitch adjustment range usually vary between 30 and 45 seconds. Ho-

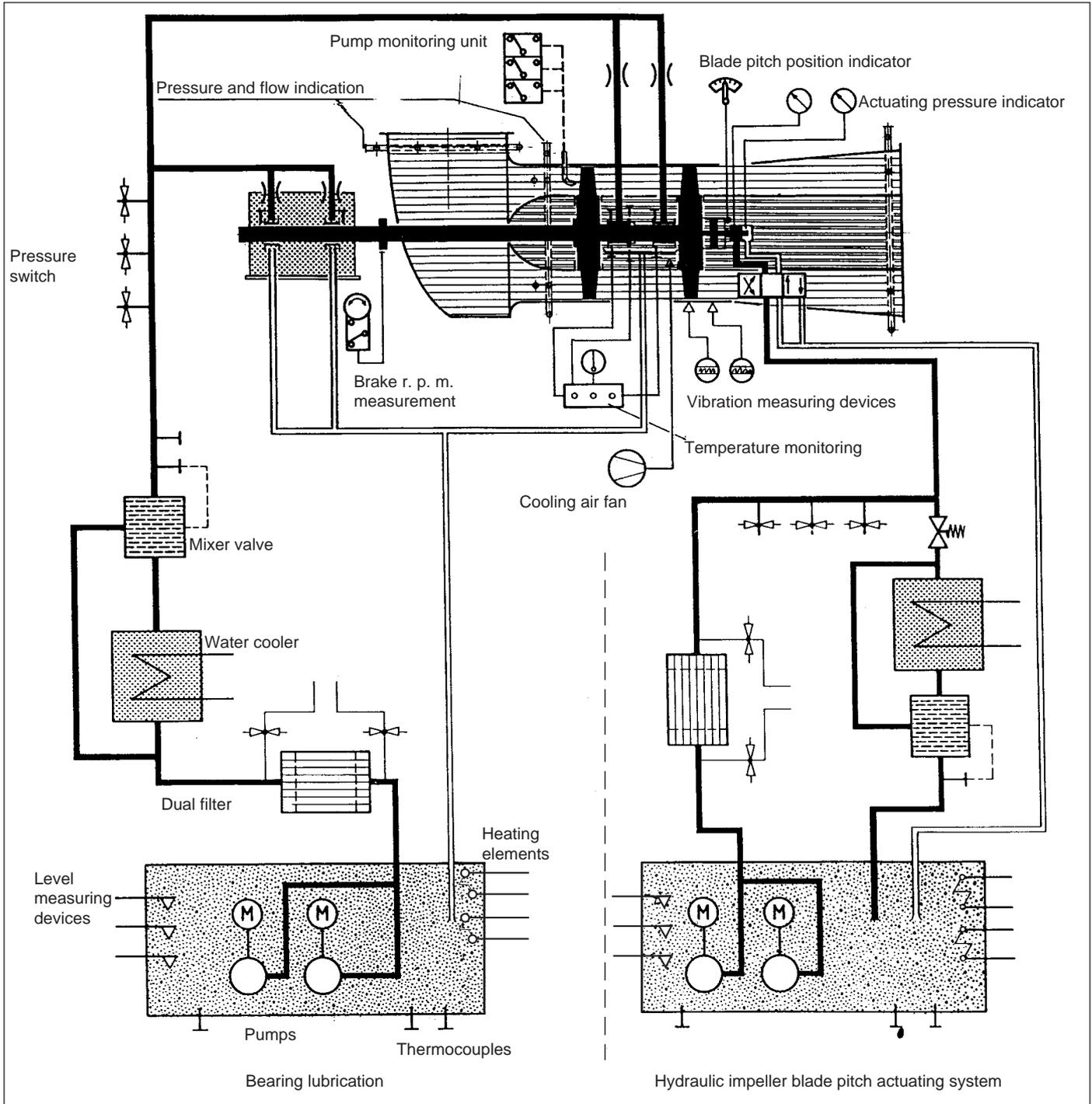


Fig. 14: Schematic instrumentation diagram

wever, faster responses can be achieved through appropriate dimensioning of the actuating system.

**Instrumentation**

The choice of instruments and monitoring devices are major factors in the design of variable-pitch axial flow fans.

The complexity of the instrumentation system is increased primarily by the

frequent request for a “2v3” solution to be implemented in the fan monitoring system for integration into the automatic operating control environment.

Fig. 14 summarizes the main instruments provided on a variable-pitch axial flow fan in induced-draft service and its peripheral equipment.

**Fan protection**

To ensure the safe and reliable operation of an axial flow fan, the relevant key parameter values (readings) must be continuously known.

By continuously recording all changes in fan operating behaviour, specifically oscillations and current operating point positions (pumping limit monitoring), it is possible to ensure an

14

advance detection of dangerous operating states and imminent failures.

In addition, reliable monitoring of the fan allows the appropriate maintenance and overhaul steps to be scheduled so as to be carried out upon attainment of defined limits, instead of upon completion of a defined number of operating hours.

Figs. 15 to 17 show examples of the switchgear and control schematics with protection system criteria for induced-draft axial flow fans.

### Operating experience

From the experience gathered to date, it emerges that operating campaigns of six years and more are definitely realistic with variable-pitch axial flow units representing state-of-the-art technology.

However, extensive prior development work was necessary to achieve this outstanding performance. Improvements at the level of fan monitoring and control equipment were a necessary part of this effort.

The following paragraphs give a description of the operating experience gained with key fan components.

### Impeller blades

The problem of blade wear had long been a priority issue in induced-draft fan engineering. Through the selection of improved blade materials (steel, nodular cast iron) and higher filter efficiencies it has been possible to reduce wear rates substantially.

More recently, increased blade wear has been reported only where units were operated significantly above the

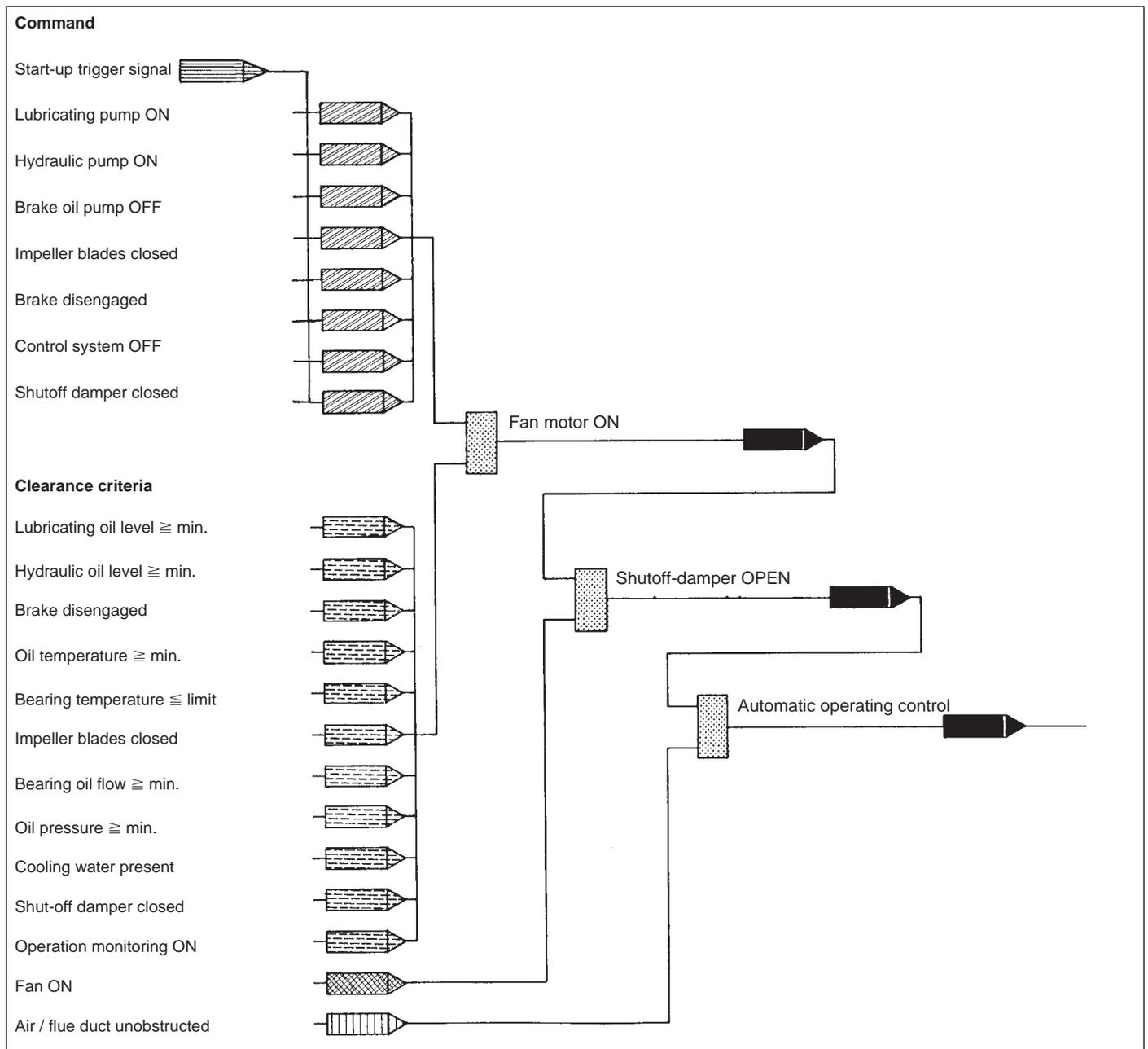
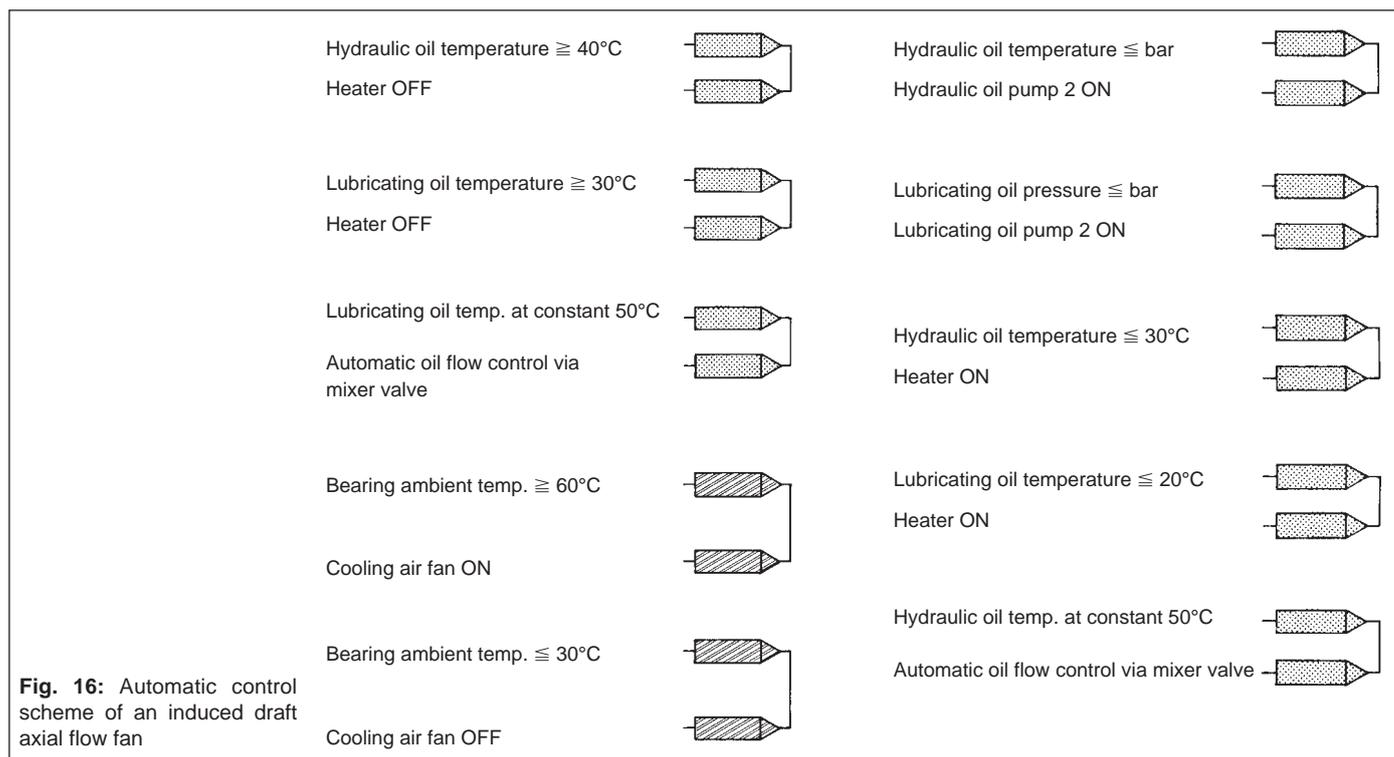


Fig. 15: Start-up program of an induced-draft axial flow fan



**Fig. 16:** Automatic control scheme of an induced draft axial flow fan

load levels assumed at the design and rating stage.

### Blade shaft bearings

The difficulties observed in this respect in previous years were attributable to unsuitable lubricants and inadequate sealing of the bearing assembly.

Service life deficiencies have been vastly improved through selective design improvement in conjunction with laboratory and field trials.

Today, service lives permitting a boiler campaign of more than 4 years' duration are no longer uncommon. In individual cases, service periods in excess of 60,000 operating hours have been reached.

### Hydraulic blade-pitch adjustment

An analysis of past failures of this subassembly has revealed that the seals in the joint area between its stationary and rotating components used to constitute a "weak link". These problems have been overcome through dedicated design optimization (use of metal sealing elements) supported by laboratory and operating trials. As a result of these efforts,

the campaign durations now commonly expected will be reliably reached.

### Rotor main bearing

Anti-friction bearings

Exceedingly frequent operation at zero load with thrust reversals (frequent start-ups) or exceeding the pumping limit may reduce the service life of the bearings. Fretting corrosion associated with the anti-friction bearings and individual failures due to alternating stress situations that could not be anticipated at the time of design have been ruled out through new bearing design approaches and expanded calculation methods.

### Sliding bearings

No serious problems have occurred to date with the sliding bearing configuration outlined above. The tilting-pad bearings employed accommodate operating deflections of the fan shaft, thus avoiding edge loading effects.

A reliable distribution and monitoring of oil flows to the bearing points and advanced anti-seizure features (ensuring performance after a failure of

the lubricant supply) ensure a long service life.

Only minor improvements have been made to the shaft seal system.

### Summary

Summing up, it may be stated that these variable-pitch axial flow fans have performed well in thermal power station service. A further intense information-sharing process between the operator and fan manufacturer and ongoing product development focused on critical components will yield further improved results in the future.

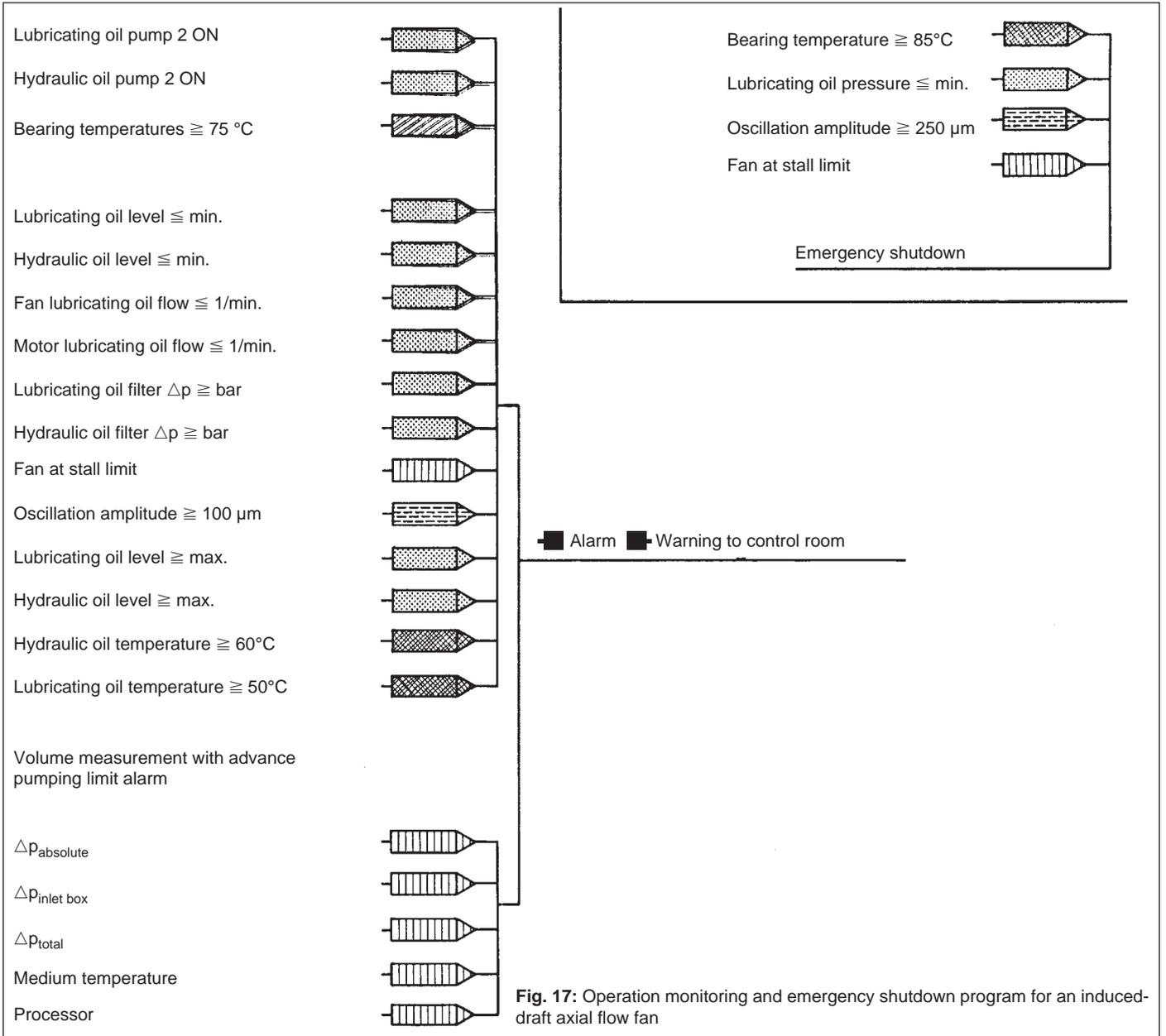


Fig. 17: Operation monitoring and emergency shutdown program for an induced-draft axial flow fan

