MODERN TURBINE-GENERATORS FOR SMALLER STANDARDIZED NUCLEAR POWER PLANT

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INTRODUCTION

There is an emerging interest in small standardized nuclear power plants for worldwide commercial application (ref. 1) and these are of a size for which well proven, compact steam turbines are ideally suited.

Considerable experience has, over the past 30 years, been gained in the power plant industry with the supply and operation of large turbines for wet-steam nuclear applications. The first such GEC ALSTHOM machines entered service in the early 1960's and the total now deployed is over 80 with a number having achieved over 100,000 hours service. The experience embraces machines associated with different types of water cooled reactors, with some machines designed for half rotational speed using 4 pole generators and others designed as full speed machines with 2 pole generators.

In the past decade or so, the main thrust has been towards large machines rated at more than 1000 MW(e) for which half-speed turbine-generators are generally found appropriate. The progress is typified by the steps in output rating applied in the extensive French programme where machine sizes have increased from 1000 MW(e) to 1350 MW(e) and now on to the 1500 MW(e) machines supplied by the author's company at Chooz 'B' Power Station (ref. 2).

Other recent applications at lower ratings have involved full-speed 3000 RPM machines for both the 985 MW(e) plant at Daya Bay Nuclear Power Station in the People's Republic of China and the twin 630 MW(e) machines for the first commercial PWR in the United Kingdom at Sizewell 'B' Power Station.

With such experience GEC ALSTHOM is well placed to provide turbines for small standardized nuclear systems of up to the 600 MW(e) rating currently envisaged. At this low power level full speed turbines are the appropriate choice and the following sections describe the relevant experience with these machines and the corresponding thermodynamic cycles.

THERMODYNAMIC CYCLE PARAMETERS

General Thermodynamic Requirements

Thermodynamic considerations dictate the basic design of the turbine and associated plant for water-cooled reactor systems and this has evolved to the modern plant arrangement shown in simplified form in fig. 1a. The expansion of the steam through the various components of the turbine cycle is illustrated in fig. 1b. The live steam conditions are moderate compared with modern fossil-fuelled plant but the mass and volumetric flow rates are correspondingly increased for the same electrical output.

Live steam, initially at dry-saturated or slightly-wet condition, is expanded in the high pressure (HP) cylinder and an increase in wetness occurs during expansion. An external water separator is applied after the HP cylinder outlet to remove moisture from the wet steam flow and to restore the steam to virtually dry-saturated condition. This is followed by steam-to-steam reheating using either live steam or both live and bled steam in order to reduce the wetness level in the subsequent low pressure (LP) expansion. Expansion of this superheated steam follows in the low pressure cylinder and the lower wetness level achieved as a result of reheating reduces blading losses and improves overall thermodynamic efficiency. Suitable provision is made in the turbine feedheating system for utilization of the high temperature water drained from the water separator and from live and bled steam reheaters to maximise efficiency.

Turbine Terminal Conditions

Turbine stop valve pressures in water-cooled plant range from 45 bar in CANDU installations up to 70 bar with light water plant, both with initial steam quality at a small fraction of one percent wet. Final feedwater temperatures required for return to the steam generator are typically 187°C for CANDU reactors and about 225°C for other types, requiring extraction pressures of about 13 and 25 bar respectively for steam tapped to the top heater.

Moisture Separator Reheater (MSR)

Modern large turbines for use with wet steam cycles employ moisture separation. This is followed by live steam reheating which results in performance improvement and gives a low pressure expansion line which, at the thermodynamically optimum levels of pressure chosen for water separation, is close to that used in a typical high temperature reheat cycle (fig. 1b). This enables standard LP cylinder designs, service-proven on fossil-fuelled plant, to be used subsequently under almost identical conditions on wet nuclear plant.

The addition of bled steam to share the reheating duty improves the cycle efficiency by reducing the amount of live steam required. Nowadays it is generally found that a bled steam reheating section in the MSR is economically attractive.

Cycle Arrangement

A typical cycle arrangement applicable to wet steam plant incorporates three or four LP feedwater heaters, a deaerator and the HP feedtrain. For CANDU plant the HP train will consist of one or two feedheaters whereas two or three feedheaters are used to achieve the higher final feed temperature on light water reactors. The water quantity removed in the separator depends primarily on the reheat pressure and is typically 10% of the total flow to the turbine stop valve. It is essential to utilise fully the heat available in the drain water and this is normally achieved by pumping it to the deaerator. Similarly the heat in the drains from the live and bled steam reheaters is utilised in the HP feedheater train.

Reheat Pressure Optimisation

The design reheat-pressure level, selected between HP and LP cylinders, affects both the mean length of the blades and the mean wetness level in the HP and LP expansions and, in consequence, controls the balance of efficiency between the two cylinders. The optimum reheat pressure for best cycle efficiency, taking account of such changes in blading efficiency, is in the region 5 to 8 bar. The variation of cycle efficiency with reheat pressure is not great over this region, so that small departures from the optimum do not involve much penalty. The pressure can, therefore, be chosen such that the same standard LP cylinders may be used in either fossil or nuclear applications. The steam conditions and last blade erosion levels are the same as those at which service experience has already been gained.

Other Factors Affecting Cycle Efficiency

In addition to the factors discussed above, many other internal parameters associated with the plant have an effect on the cycle efficiency. They include the total number of feedheating stages, terminal temperature differences for bled steam and live steam reheaters and pressure drop of the heated steam in passing through the MSR.

Each of these parameters can be modified so as to increase efficiency, but in each instance only at additional cost. Whether such improvements are worthwhile can only be determined by an economic assessment.

SELECTION OF LP EXHAUST CONFIGURATION

Mass Flow, Condenser Pressure and Exhaust Area

The matching of exhaust volumetric flow by suitable selection of the LP last stage exhaust area is of paramount importance in configuring the turbine for a particular application. The choice may be between either a larger LP frame or the use of an extra LP cylinder of smaller size to give the required area.

The steam mass flow rate in nuclear plant is between $1\frac{1}{2}$ to 2 times greater than that for equivalent output fossil plant, leading to high LP volumetric flows at the turbine exhaust. The volumetric flow is also dependent on condenser pressure, which in turn is related to the cooling water temperature available at the site. These temperatures vary considerably at differing sites around the world and, in general, have a profound effect on the configuration of the turbine. However, for the smaller standardized reactor the choice would usually be an HP cylinder with two or three double flow LP cylinders.

<u>Exhaust Velocity and Leaving Loss</u>

The optimum LP exhaust condition, resulting from the choice of exhaust area to match the volumetric flow, is characterised by the steam exhaust velocity and corresponding kinetic energy. Because the overall turbine enthalpy-drop available in nuclear plant is less than fossil plant, 1 kJ/kg extra kinetic energy loss in the exhaust is worth up to twice the corresponding proportion of power loss on fossil plant.

<u>Last Stage Blade Design and Rotational Speed</u>

Modern blades are designed and selected to operate with steam velocities of about 250 m/s for optimum exhaust loading, being neither too high to give excessive loss of kinetic energy nor too low to lead to choice of oversize and costly turbine configurations.

Blades are limited in their design length and exhaust area by the centrifugal loading which can be tolerated, but continuing advances based on experience, refined design techniques and use of better materials have produced long blades (ref. 3) suitable at full speed for nuclear applications. At half-speed longer blades are possible due to less onerous centrifugal loading, but these are not necessary for the smaller standardized reactors.

Two families of standard exhaust blades and LP cylinders are available in the author's company: one set for 3000 RPM applications and the other for 3600 RPM. The top-end of the range of exhaust area, when used in a 6 flow arrangement, is adequate to deal with the turbine exhaust volumetric flow of small reactor plant at the coldest envisaged cooling water conditions. At less demanding volumetric flows, either smaller standard LP's may be selected or 2, rather than 3, LP cylinders could be employed.

It is possible that suitable LP cylinders, of similar exhaust area and last blade length, could be selected from the standard families at both 3000 and 3600 RPM. This would permit turbines to be configured with similar overall dimensions for application with the same reactor and cooling water conditions, but in countries with different electrical system frequencies.

EXPERIENCE

Wet Steam Erosion

As described earlier, steam conditions in the LP cylinders of wet steam turbines using moisture separation and live steam reheating are very similar to those on high temperature turbines. It is evident, therefore, that there are no special erosion problems.

However, in the HP cylinder conditions are quite different. The progressive increase in wetness through the cylinder at relatively high pressures has a powerful potential for causing erosion damage. With the velocities of the moisture droplets and main steam not differing widely at the relatively high steam densities applying, coupled with the use of stainless steel for the whole steam path, blading erosion is not a significant problem. Potential for erosion damage is highest in the casings and associated pipework and valves, either where there are changes in flow direction or across joint surfaces of pressure seals.

Operating Experience with Nuclear Wet Steam Turbines

It follows from the above that experience with nuclear wet steam turbines has greatest relevance to the design of the HP cylinder, valves and pipework, with particular reference to erosion problems due to steam wetness. In considering these problems for high speed wet turbines experience at both full speed and half speed and operation with different types of reactor is fully relevant. Service experience with many turbines with ratings up to 1300 MW(e), including CANDU, PWR, BWR and SGHWR applications, amounts to several hundred machine years, with individual machine operating times beyond 150,000 hours.

Earliest experience included a small machine of 22 MW(e) rating running at 3600 RPM with a CANDU reactor. This was followed by two larger machines, a 100 MW(e) machine running at 3000 RPM using SGHWR steam and a 220 MW(e) machine running at 1800 RPM with a CANDU reactor. A number of erosion problems were initially encountered on these units, for which design solutions were evolved and changes made in materials used, and these were proved by subsequent service. Later machines incorporating these features have now achieved considerable success, with service experience in excess of 100,000 hours, for both full speed and half speed construction.

Material Selection

The above experience allows confident selection of materials for components in a wet steam environment (ref. 4). The selection depends on the steam pressure and wetness and the nature of the steam flow associated with the particular design features of the components involved.

For the HP casings and diaphragm carriers, where the wetness levels are significant, a low chromium alloy steel is used. For welded diaphragms a fully stainless steel blade path is employed, including nozzle blades and spacer bands forming the nozzle annulus boundaries at inner and outer diameters. On the faces of joints sustaining pressure differences either stainless materials or a deposit of stainless steel cladding is applied to prevent any significant wire drawing erosion.

No special protection is applied to the body of the low alloy steel HP rotor, nor to the interstage gland regions. However, because of the high degree of exhaust wetness, the rotor end glands are packed with dry steam obtained by throttling live steam.

The overall HP experience has, therefore, been with only minor problems of material selection and detail design on the first generation turbines, followed by successful experience on all subsequent generations of machines. The success with LP applications results from prior service on fossil plant before application to nuclear plant. The vast experience on the more demanding large units sets good store for the reliability of future small standardized units.

HIGH SPEED TURBINES

Of the recent applications to wet nuclear plant, the 985 MW(e) machines at Daya Bay represent the top end of the construction range for high speed turbines. The general design features are described as follows:

<u>High Pressure Cylinder</u>

The cylinder consists of two flows, each with five stages of blading as shown in fig. 2. Because the inlet pressure and temperature are only moderate the casing can be essentially of single shell construction, with bled belts arranged between groups of diaphragms to permit ease of extraction of steam to feedheaters. The four steam inlet pipes are attached directly to the casing. To ease the arrangement of external pipework on this cylinder supplying steam to two HP heaters, steam tappings from two different stages are bled asymmetrically, one from each flow. Steam exhausts through eight exhaust pipes, located symmetrically in the top and bottom halves, with four outlets at each end of the casing.

As on high temperature cylinders, disc and diaphragm construction is employed. The moving blades are shrouded and are attached to the monobloc rotor using pinned roots. The diaphragms are kinematically supported so as to remain concentric whilst permitting relative thermal expansion. The diaphragms carry the rotor interstage spring-backed glands and also, on an extension ring, the tip seals, which co-operate with circumferential ribs on the moving blade shrouding. This type of construction ensures that small effective radial clearances are maintained over long periods of operation. Arrangements are made at the blade tips for moisture separation and drainage at each stage where this is not automatically effected at bled-steam tapping points.

Low Pressure Cylinders

Three low pressure cylinders are applied to accommodate the large exhaust volumetric flow at Daya Bay and these are of a standard modular construction employing 945mm last row blades as shown in fig. 3. This module is identical to that used on a large number of high temperature machines over a wide range of outputs. The five stages of blading in each flow are carried on a monobloc rotor. The diaphragms are mounted in a single shell inner casing supported in a fabricated outer casing. Steam is admitted through two inlets in the top half casing and steam exhausts downwards to an underslung condenser.

Overall Arrangement

The HP cylinder is shown in tandem arrangement with the three standard LP modules on site assembly in fig. 4. Each rotor is supported on two journal bearings and the rotor-line thrust bearing is mounted in the bearing pedestal between the HP and the first LP cylinder.

The moisture separator/reheater vessels are normally mounted horizontally at turbine floor level on each side of the turbine alongside the low pressure cylinder. These can be seen during site erection in fig. 4 and the overall plan view "footprint" of the installation, including the electrical generator, is shown in fig. 5.

DESIGN CONSIDERATIONS FOR SMALLER OUTPUT

Single-flow Principle

Smaller output ratings substantially reduce the mass flow level throughout the turbine and this leads to worsened aspect-ratio blading and reduced cylinder efficiencies. This trend may be offset by configuration with single-flow rather than double-flow sections wherever possible. The principle, as applied to an HP expansion, is shown in fig. 6. The doubling of volumetric flow per end substantially increases the blade heights and so leads to reduced end-wall (secondary) losses and reduced leakage-proportion losses; particularly for short height stages. The gain is offset to some extent by the introduced thrust balance-piston leakage, but generally for small flows the overall effect is a significant improvement in cylinder efficiency.

Similar consideration can be applied for low volumetric flow to double flow LP cylinders. For applications where two or three double flow LP's are applied, the flow at inlet is divided four or six ways respectively and the resulting early-stage blade heights can become very short. Introduction of a single flow section into the centre of each LP cylinder, as shown in fig. 7, to form an 'optiflow' arrangement, doubles the blade heights on the early stages and so, again, improves the overall expansion efficiency.

Application to HP Cylinders

For small output sizes of wet nuclear plant, the HP cylinder construction can be executed as a conventional single-flow cylinder as shown in fig. 8. The doubled aspect ratio blading plus the available rotor length to apply more stages at a smaller base diameter, gives a worthwhile gain in cylinder efficiency. Arrangements of this single flow type are widespread on conventional fossil-fuelled plant and have given good service on high speed nuclear machines in the range up to 400 MW(e).

Application of Optiflow LP cylinders

The low volumetric flow to the LP cylinders of small output machines can benefit from an initial single flow section. In the application of optiflow LP cylinders the last three long blades remain in double-flow configuration, but an inner cylinder with single-flow configuration is introduced to increase the length and hence efficiency, of the early stage blades. An arrangement of this type is illustrated in fig. 9 and fig. 10 shows an optiflow rotor for a 500 MW(e) PWR unit.

TURBINE GENERATOR RANGE FOR STANDARD SMALL NUCLEAR PLANT

General Requirement

By way of example, a scheme of turbine-generator frame designs for standardized small nuclear plant is outlined based on the CANDU 3 (450MWe) system. The scheme described highlights the benefits of organising the turbine frame design to cover the range required by the use of a number of standard cylinder modules.

The CANDU 3 system provides a versatile and compact installation at the lower end of the nuclear plant range and offers the adaptability to match individual requirements of different utilities at varied sites. As a compact, modern plant, the CANDU 3 system aims at quick installation times, competitive costs and lower investment risks which should be attractive to smaller utilities and developing countries. Standardization and pre-engineering of modular arrangements aims at providing suitable plant for diverse worldwide sites without the need for significant change to design or documentation.

Other water-cooled reactor technologies may also see the opportunity for ratings at or below 600 MW(e). From the turbine-generator viewpoint these are likely to have similar volumetric flows to the CANDU 3 system and the advantage of the same standard turbine range would apply.

The standardization of the nuclear steam supply system itself is largely independent of the station site whereas the turbine-generator considerations, although not affected by the pressurised components external to the cylinders (e.g. pipework, valves, MSR, feedheaters, etc), do have to account for the alternative 50 and 60 Hz operating speeds and are more fundamentally affected by differing cooling water conditions for turbine exhaust and condenser selection.

Selection of LP Frames

The full-load LP turbine exhaust steam flow for the CANDU 3 system will be virtually independent of site conditions with a value of about 400 kg/s. However, different site cooling water conditions will have a profound effect on the exhaust selection. Taking 10°C and 20°C as typical design cooling water (CW) temperatures for cold and warm sites, the corresponding condenser pressures should be of the order 33 mbar and 55 mbar respectively. Combining the exhaust mass flow and the specific volume of the condensing steam gives the exhaust volumetric flow at the design point. To deal with this efficiently, the exhaust velocities should be near the optimum value and in this case, the total exhaust areas required are $60m^2$ and $40m^2$ respectively. Standard LP modules of modern high speed design are available for both 50 and 60 Hz systems with exhaust areas up to about $10m^2$ per flow, so that the appropriate machine configurations are with 3 double flow LP cylinders for cold sites and 2 double flow LP cylinders for warm sites. For sites with still warmer cooling water a suitable configuration would be with 2 cylinders of a smaller LP module.

This selection has given, by fixing the LP cylinder configurations, the basis for the practical layout of the range of turbine frames to cover possible sites at 50Hz and 60Hz for cold and warm cooling water conditions.

Overall Turbine Layout

For the relatively low capacity involved at 450MW(e) a single flow HP cylinder is appropriate to be used in conjunction with the selected LP's. The resulting overall general configuration is shown in fig. 11 and the alternative applications in a rational range are illustrated in fig. 12. The arrangement for cold CW sites, with an HP cylinder in tandem with three double flow LP cylinders, follows established practice. The overall installation of a 985 MW(e) at Daya Bay, at the top-end of the range for this configuration, is shown in fig. 13. The smaller units envisaged for CANDU 3 applications lie well within this experience.

The reheat design pressure level is maintained at about the same near-optimum level for the differing applications so that the MSR capacity and cold reheat pipework can also be replicated. Two different arrangements of hot reheat pipework are required for distribution of steam to the alternative 2 or 3 LP cylinder configurations. Similarly provision is required to accommodate the options for 2 or 3 condensers corresponding to the relevant turbine option.

The 'footprint' of the turbine-generator frames of fig. 12 and associated equipment is thus available for general layout of the turbine hall. The plan-form similarity of the different application frames provides the opportunity for commonality of architecture.

CONCLUDING REMARKS

A set of turbine-generator frames, based on extensive satisfactory experience, is available for application with standardized nuclear steam supply systems at the lower end of the power range. Pre-engineered modules incorporating fully developed and established components allows the Plant Architect-Engineer to pre-plan arrangements of turbine halls in standard form to give benefits in installation time and costs. Similar overall turbine arrangements for different sites are envisaged which accommodate the effect of alternative grid frequencies and encompass diverse cooling water temperatures found at sites worldwide.

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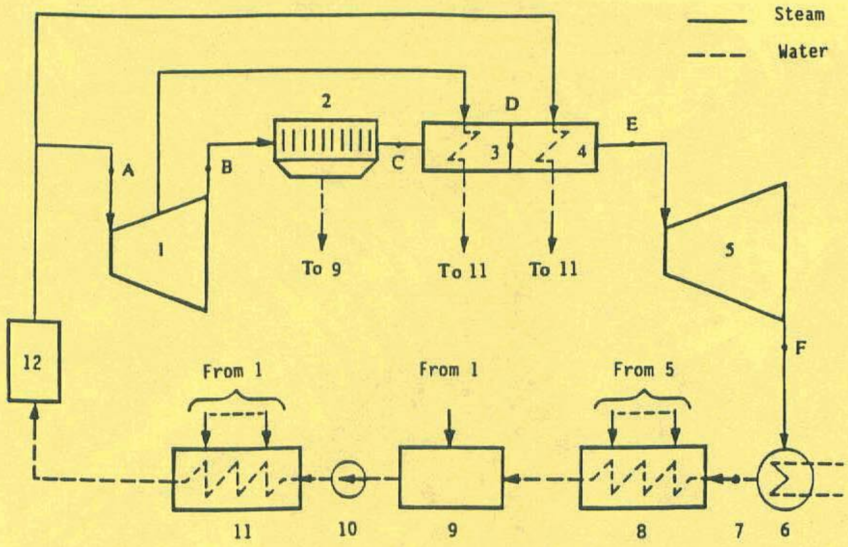
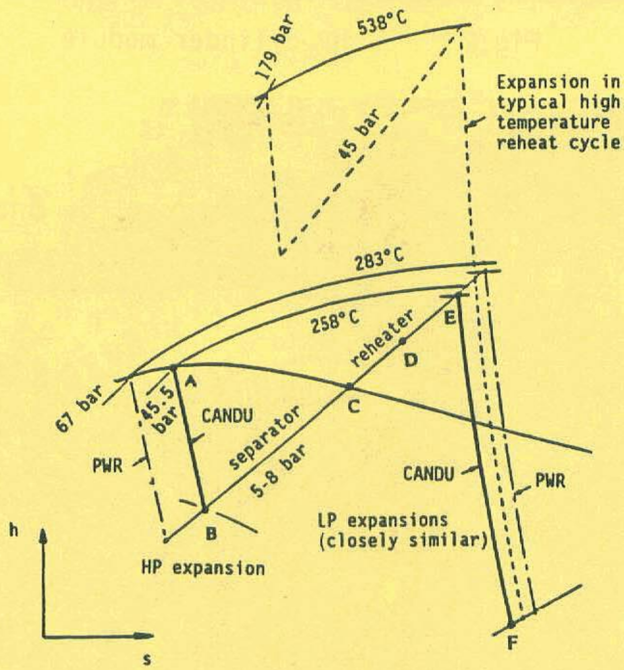


1	HP turbine cylinder	5	LP turbine cylinder(s)	9	Deaerator
2	Moisture separator	6	Steam condenser	10	Feed pump
3	Bled steam reheater	7	Condensate pump	11	HP heaters
4	Live steam reheater	8	LP heaters	12	Steam generator

1(a) Cycle Components



1(b) Expansion lines for typical water-cooled reactor plant (CANDU and PWR) compared with high temperature reheat turbines.

Fig.1 Simplified steam cycle.

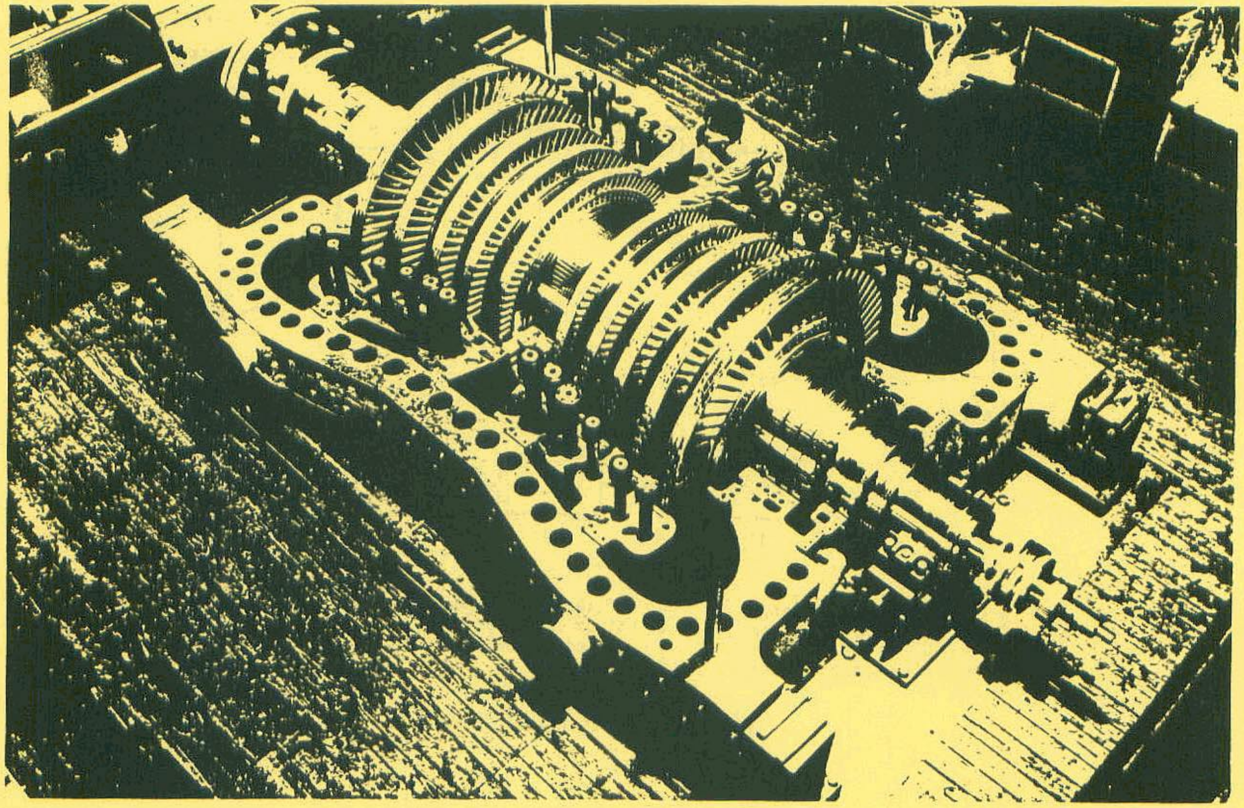


Fig.2 HP cylinder module

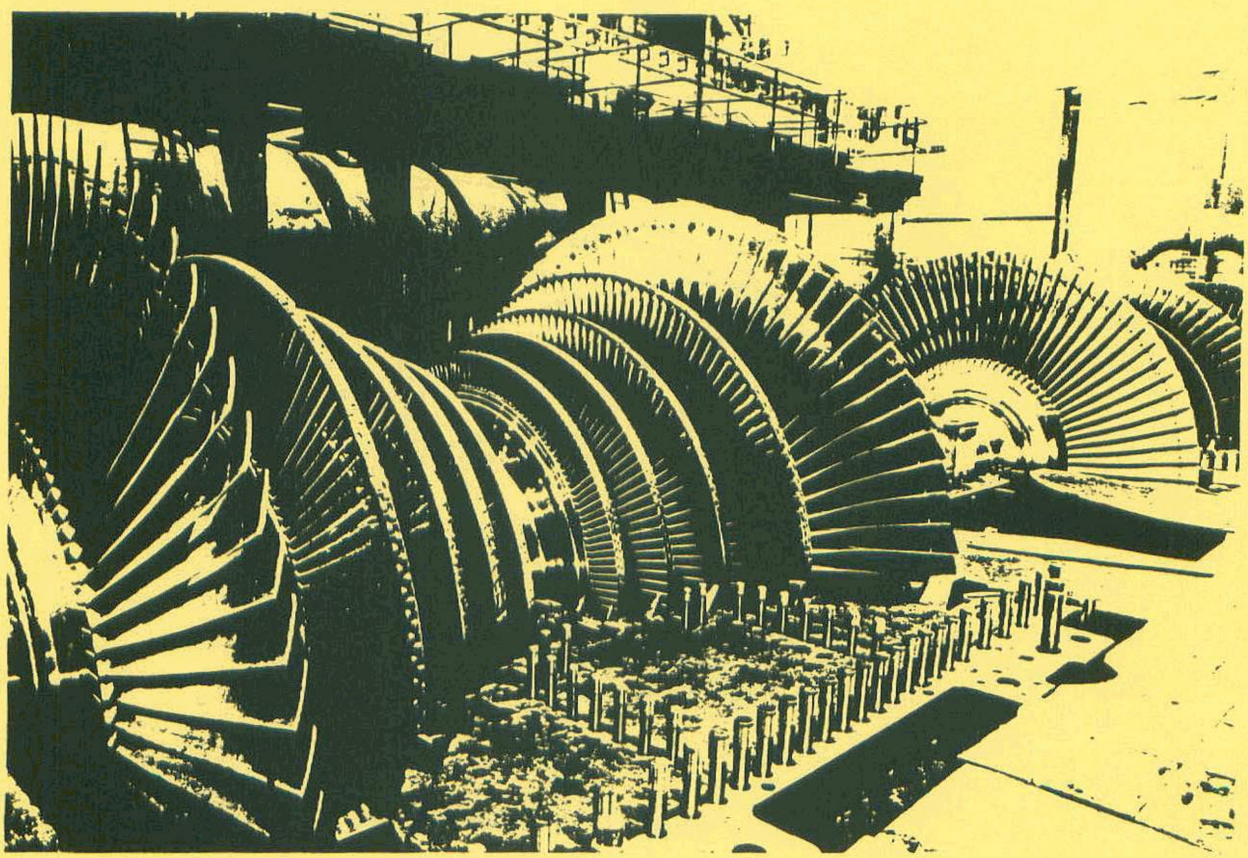


Fig.3 Standard LP cylinders

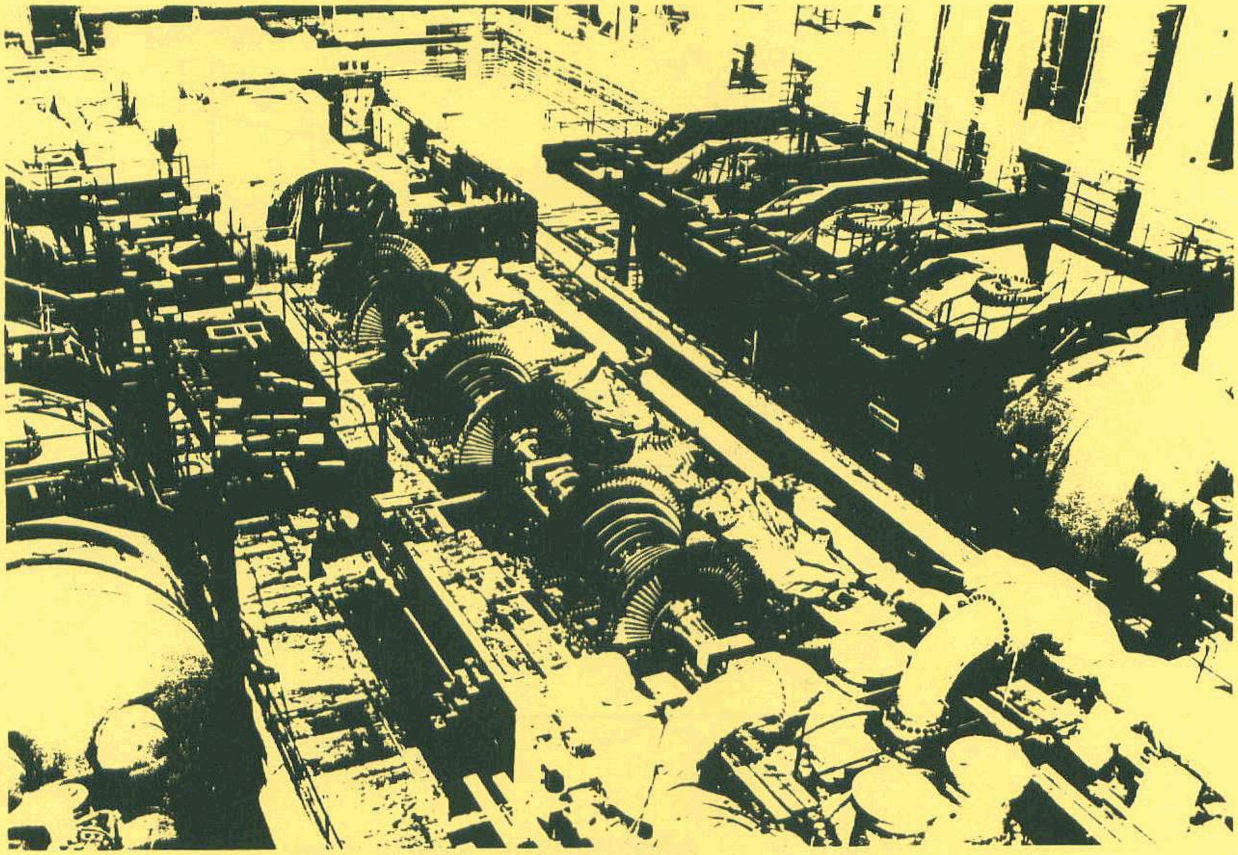


Fig.4 Assembly of HP and LP cylinders at site

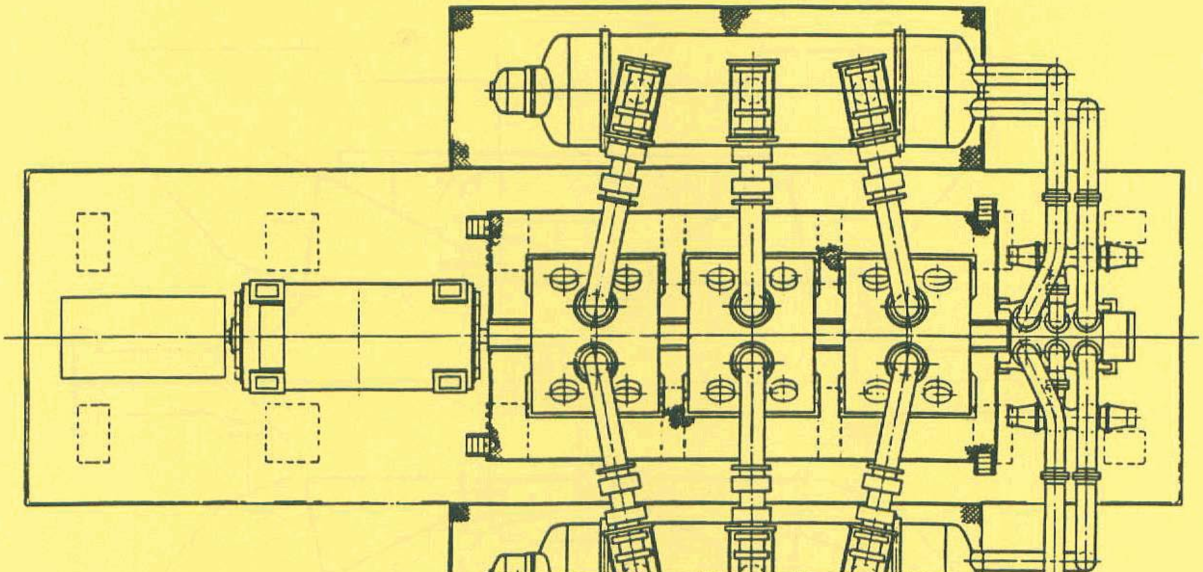


Fig.5 General arrangement of turbine-generator and MSR vessels

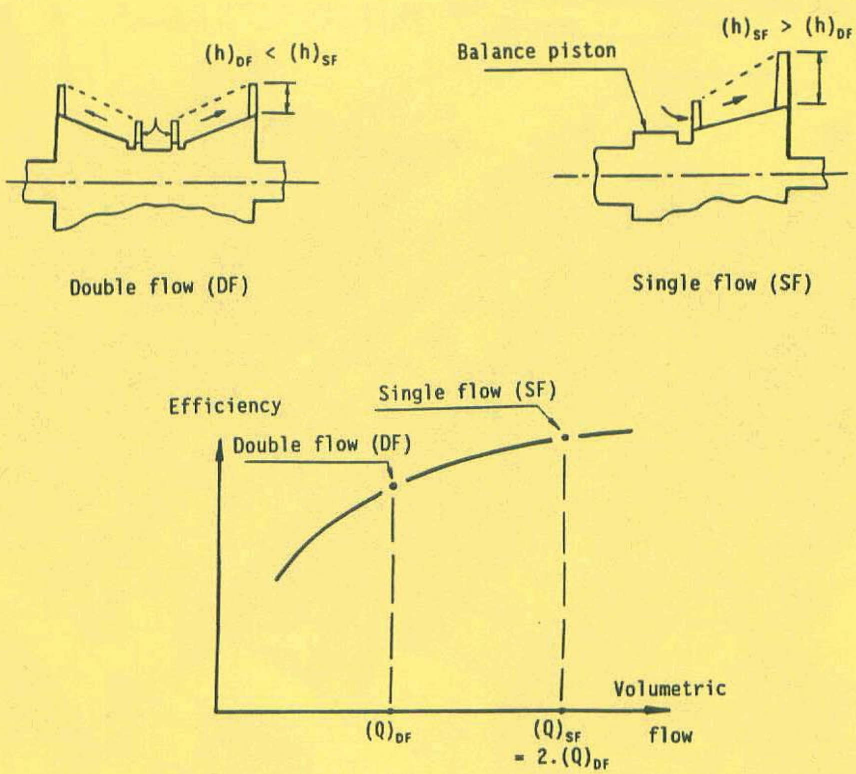


Fig.6 Advantages of single flow

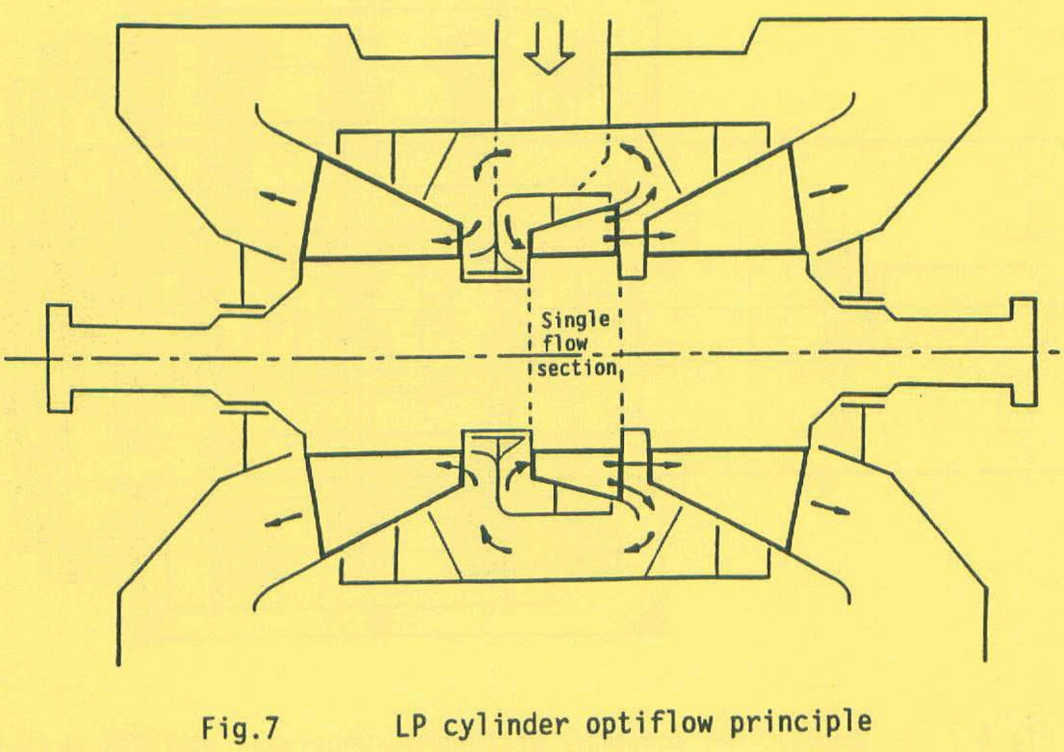


Fig.7 LP cylinder optiflow principle

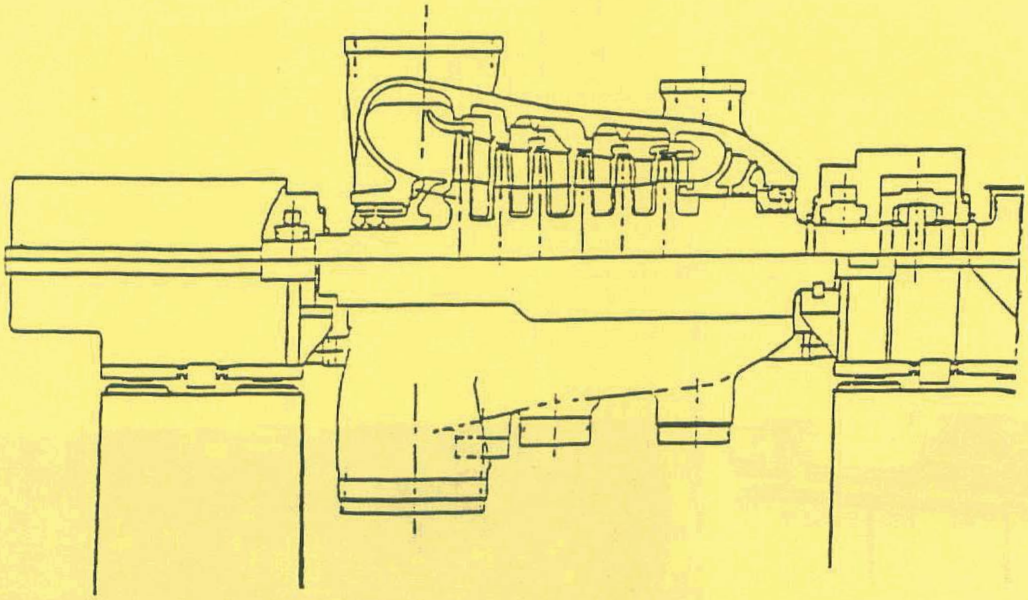


Fig.8 Single flow HP cylinder module

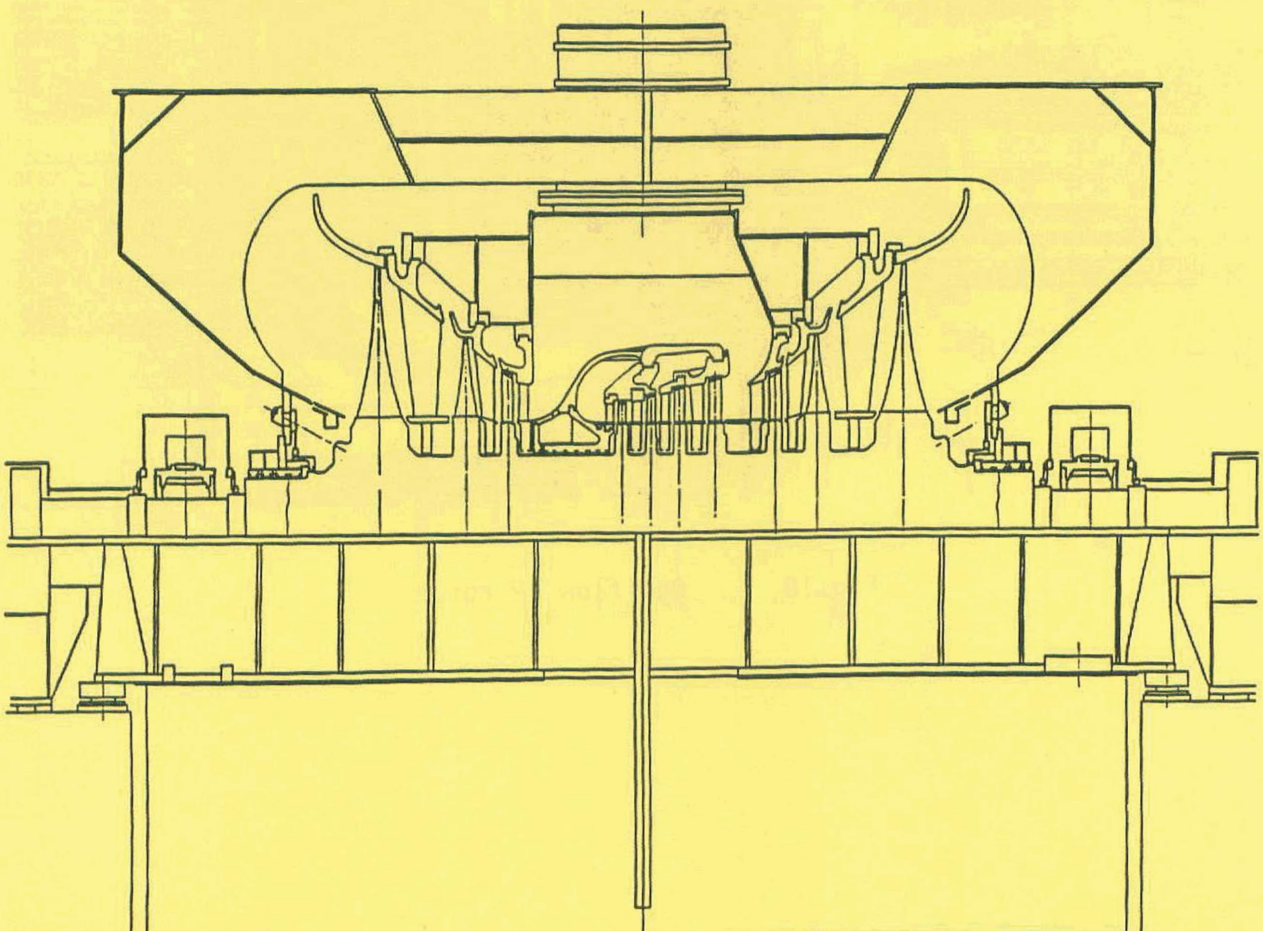


Fig.9 Optiflow LP cylinder module

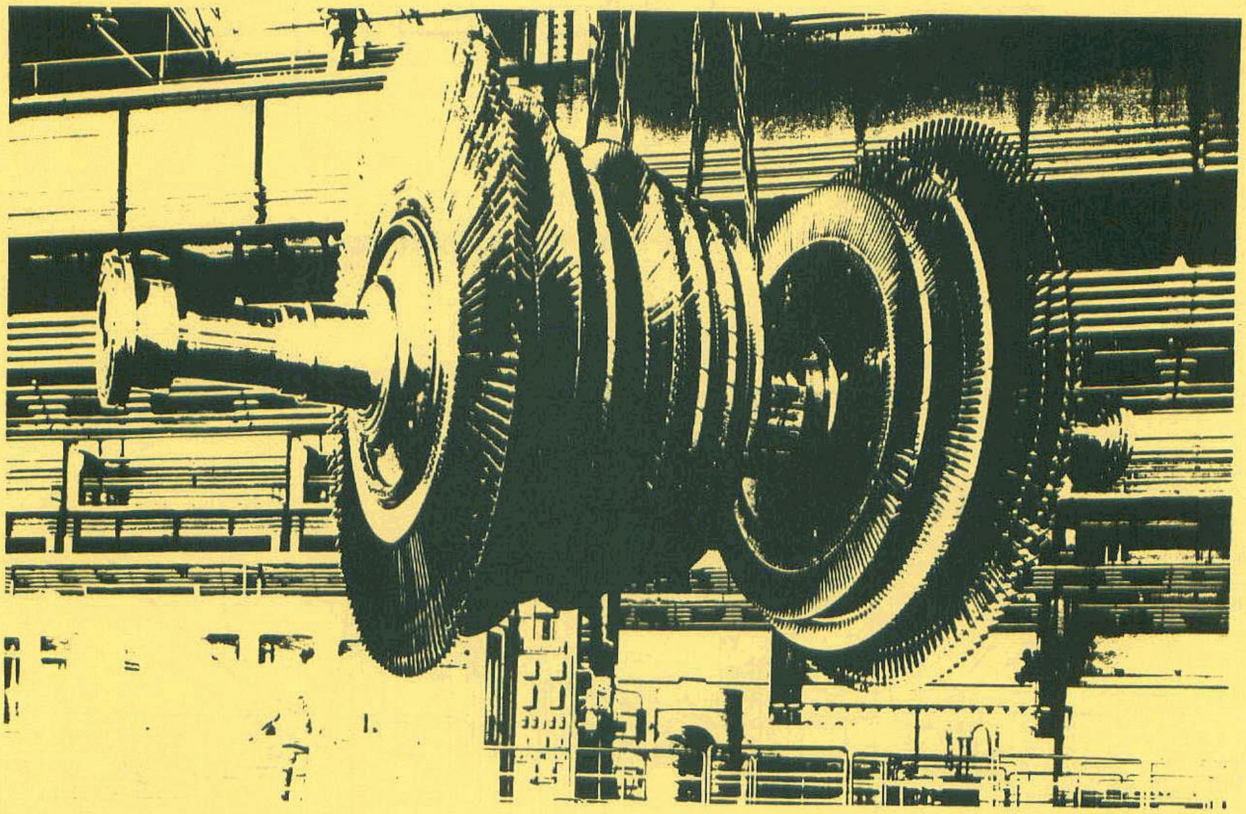


Fig.10 Optiflow LP rotor

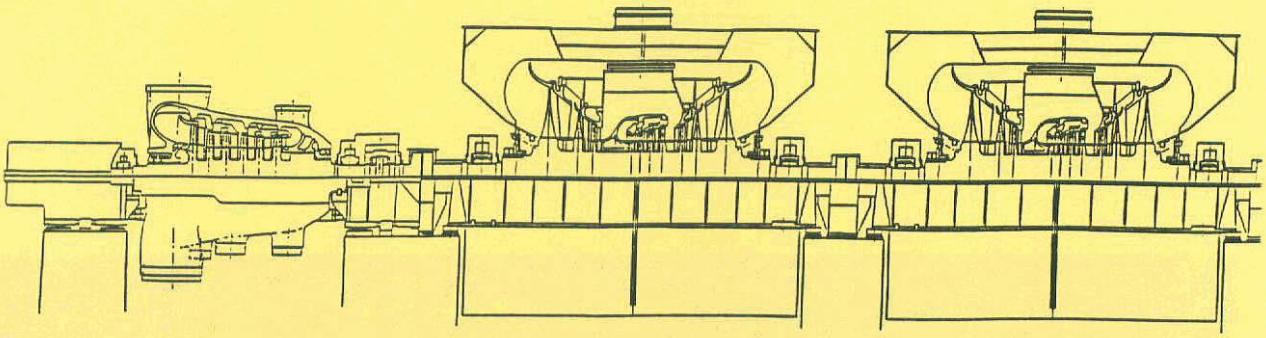


Fig.11 Overall turbine configuration for warm CW site

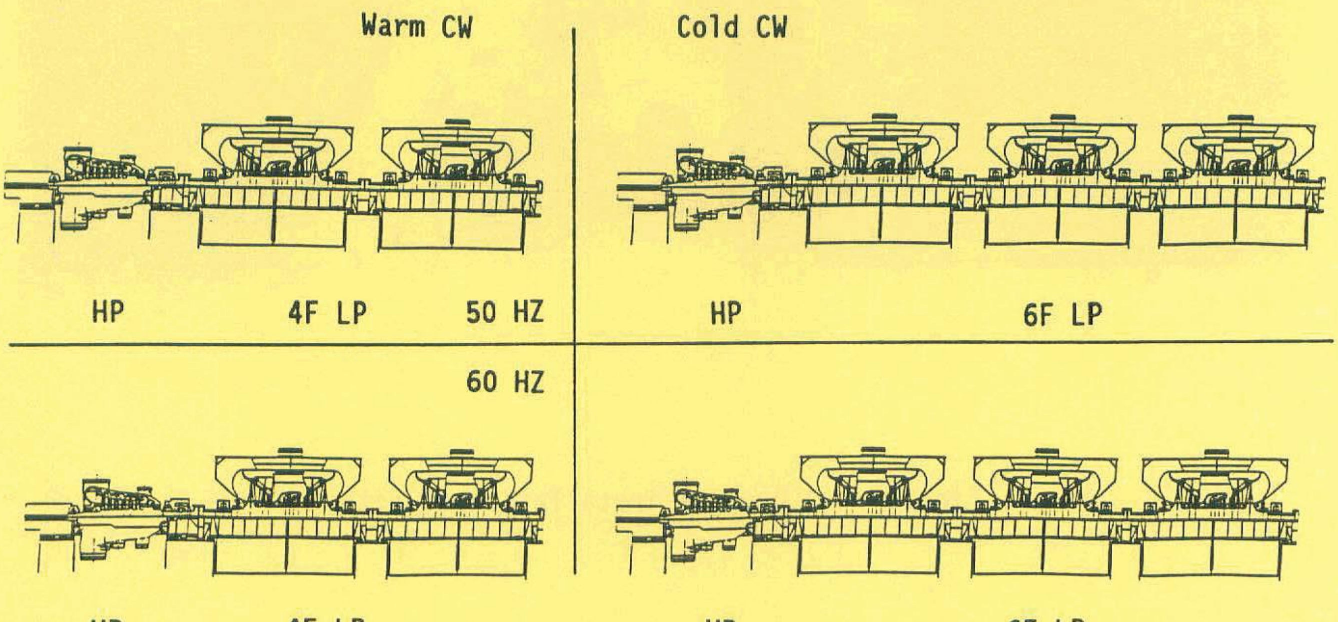


Fig.12 Range of full speed turbines for small reactor plant at different system frequencies and cooling water temperatures.

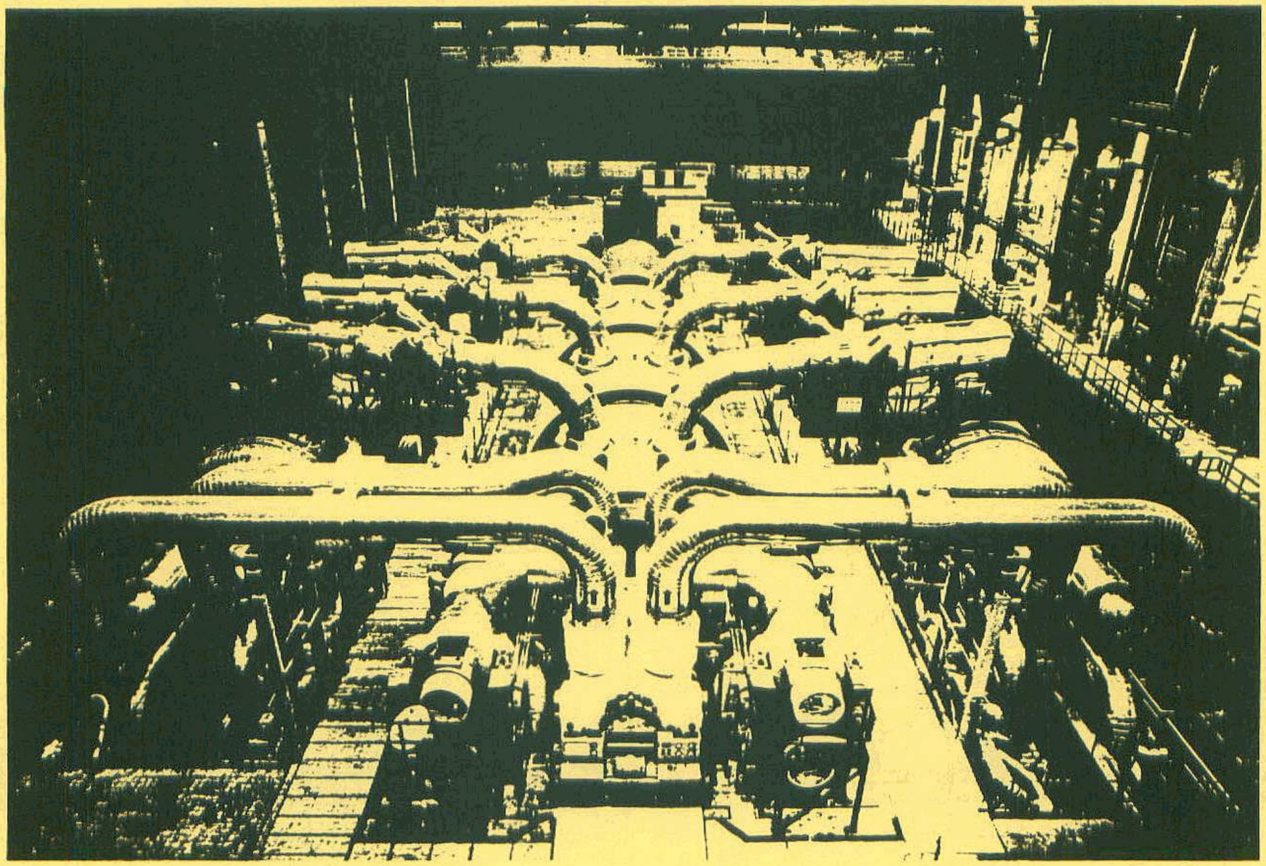


Fig.13 Overall installation at site