TURBINE STEAM PATH

MECHANICAL DESIGN AND MANUFACTURE

Volume IIIb

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FOREWORD

As a companion text to his earlier two-volume set entitled *Turbine Steam Path Maintenance and Repair*, this book represents another valuable contribution to the power generation industry. Engineers involved in all aspects of steam turbine manufacturing, maintenance, and operation will benefit from Mr. Sanders' concise and detailed explanations of thermal and mechanical design principles. In this extensive work, Mr. Sanders covers much of the technical material included in his seminar titled *Turbine Steam Path Engineering.* This popular seminar has been developed over several years and presented to turbine engineers worldwide.

Pressures from industry deregulation and competition have forced many plants to operate beyond their original design life and with fewer resources available for maintenance. Turbine engineers have an increasing range of options available for undertaking steam path repairs, upgrades, or complete replacements. It has become a principle role of the plant turbine engineer to knowledgeably evaluate the options available. In that regard, education through technical resources such as this book will undoubtedly play an important role in this process in upcoming years. Likewise, this text will be an important resource for new steam path designers entering the field because they will benefit from the thorough explanation of all design aspects.

Mr. Sanders' more than 40 years of experience with steam turbines includes design/manufacturing in Europe and the United States as well as utility experience. For the past two decades, Mr. Sanders has been a valuable industry consultant, assisting in projects relating to performance improvement, blade repair options, steam path upgrade strategies, and component failure investigations. Those of us involved in the important field of steam turbine design, performance, and maintenance are indebted to Mr. Sanders for sharing his extensive experience in this text.

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PREFACE

As energy demands increase, utilities are faced with the responsibility of meeting them. To meet these demands, the providers of this energy are expected to make increased capacity available on their system or through purchases. The general consumers have little or no understanding of what effect increased demands have on those responsible for making power available. The providers of electric energy are not only responsible for making this power available but are also expected to provide this energy at a cost that is acceptable to the consumers. The power suppliers must be prepared to recognize and accommodate this.

The economic health of any community—country, district, or township—is directly related to its access to an adequate supply of electric energy at reasonable costs. The supply must be secure. This energy supply is essential for any industrial or commercial development.

Problems faced by electric utilities in meeting demand are many. First, and most difficult, is that they must be able to anticipate demand, which in a mature community is considerably easier than in a community that is developing and possibly trying to attract different forms of investment. The utility must plan to have adequate energy producing capacity available to support such development. This requirement can become an economic disaster for any community in the event capacity is provided and there is not sufficient demand for that energy.

Another problem is for utilities to determine how best to meet future demand. There are a number of options, each requiring some level of investigation. The alternates for increasing system capacity that need to be considered would include the following.

Installation of new generating capacity

This is ultimately the most expensive option, but it is also the most positive since it will make available on the system equipment that is new, and if selected properly, will comprise the latest technology and would therefore be expected to provide high efficiency and the best reliability available to the users at that time.

However, new capacity cannot be installed in the short term. The time to design, obtain licenses, let bids, and construct the plant will take many years. This is, therefore, the result of long-term planning based on a secure market demand once completed.

Addition of a gas topping unit

There are often a number of units on a system that can be converted to a combined-cycle application. This is an attractive and often cost-effective option for many steam turbine units that have operating life left in them but where other equipment such as the boiler or feed heaters have reached the end of their useful life.

Upgrade an existing base load unit

There are a number of large and mid range units that are currently operating and providing power to the system where unit capacity can be increased. There are two means of achieving this increase, such as redesigning portions of the unit with the installation of major components of improved design that will increase unit output.

It is also possible, if boiler capacity is or can be made available, to increase the amount of thermal energy supplied to the unit by increasing steam flow. This would produce a further increase in output. Unfortunately, such output increases will often result in decreased efficiency because the steam path was not optimized for the increased flow. Some design modifications could be made to improve efficiency; this is a matter of evaluation in terms of the cost of the modifications compared to the amount of increased output. It would also be necessary to evaluate the increase in stress levels of the components installed under the old rating.

Secure a purchase agreement with a neighboring utility

The advantage of this option is that it does not involve any significant and immediate expenditure. However, it is also possible that the costs paid for this energy will be the generating costs of the oldest and most inefficient generators on the system from which the power is being purchased. This could in the long-term result in excessive costs.

This could however, be a suitable solution while a new modern plan is being constructed.

Development of alternate sources of renewable power

The possible development of alternate fuel sources can be considered, such as wind, incineration, hydro, or solar energy. However, several of these concepts are in their infancy of development, and total economics are at this time far from established.

Another problem the utility must address is the need to finance new capacity. This often proves to be the most difficult matter involved in adding capacity. Fortunately, this is beyond the scope of this book, because it would require the wisdom of Solomon to address in any meaningful form. Of the power producing systems available, steam turbines are the most abundant producers in the world today; they are also important motive units in both industrial and marine applications. However, their installation requires the inclusion of considerably more peripheral equipment than the gas turbine or many other possible options. Therefore, their selection may prove to be a more expensive option to providing required power. They can, however, be installed as very large generating units.

A steam turbine generating plant is expensive as a new installation. However, it can be particularly attractive if older units can be upgraded and used in conjunction with a gas turbine in a combined-cycle application.

The development of steam turbines has taken place in a little more than a century. The initial units were built as a consequence of the foresight and pioneer work of engineers such as Parsons, Curtis, and Ljumstrom working independently and each producing a unit that was able to convert thermal potential to rotational kinetic energy. Rotational energy was preferable to reciprocating, which to that time was the most commonly used. Rotational units offered certain advantages. The units are considerably more compact and able to be balanced with a greater accuracy than a reciprocating motion. Although the steam turbine units of these pioneers performed the same function, details of their designs were quite unique. These early efforts laid the groundwork for the preparation of a unit that has now been able to produce outputs up to 900,000 kilowatts (kW) in a tandem compound arrangement and up to 1,300,000 kW in a cross compound configuration.

Many of the units currently in service are contained in power generating plants or industrial installations and continue to operate for years without being shut down for inspection or maintenance. These extended operating periods do not represent negligence on the part of operators. Designers designed units to be opened only every 4 or 5 years for inspection and maintenance. Now, there is a growing tendency within industries to increase this operating period to 8 to 10 years. These extended operating periods are a conscious decision made possible due to advancing technology, particularly in terms of improved materials and the ability of designers to more accurately predict stress levels and the remaining life of components whose failure could force a unit from service.

These extended operating periods have a number of important implications for the operating engineer, including the need to make an exhaustive examination when the unit does become available. To examine these units in greater detail requires they be removed from service and opened for inspection. Reparative actions may have to be undertaken that could have been delayed for a 4-year operating cycle, but cannot for 8 to 10. The cost of opening a unit is high and, more importantly, while these units are open, they are not producing power. Therefore, at those planned outages when units are open it is a responsibility of the plant engineers to ensure all actions identified and required to make the unit suited for another extended operating period are taken.

The extended operating period between maintenance outages provides certain advantages to the owners. They do not require as much reserve capacity, and the cost of opening and taking maintenance activities has in the short-term been reduced. At this time in the evolution of the industry, it is not clear whether, in the long-term, any additional degradation in efficiency during this extended period of operation will cover the cost of the one outage that has been missed. Much of this gain or loss will depend upon the manner in which the plant is operated.

Therefore, the operating staff at any plant is now charged with the additional responsibility of operating the unit to maximize its efficiency and minimize any operating regime that could diminish its reliability or force it from service. Unfortunately, there are limited actions operators can take to achieve these performance goals once the unit has been returned to service. Those positive actions that operators can take include careful monitoring and maintenance of water quality, and helping ensure that the unit does not experience any unjustified or avoidable transients. Many such transients of speed or thermal conditions have the potential to cause deterioration in efficiency and to compromise structural reliability.

Though these difficulties and complexities in generating power exist, the general public has no idea of the difficulties involved in securing an adequate supply of electrical power. Similarly, they cannot comprehend what the possible consequences would be if the engineers responsible for the maintenance and care of power plants were to fail to keep these units running efficiently, reliably, and safely.

There are today many facilities generating with units that were installed more than 40 years ago and that have exceeded their design life. These units are still generating power as required, and this power is fed into the distribution system. Many of these older units are still required to meet peak demands, and this type of duty places a heavy burden on them because the start/stop-type of operation is more destructive as the units are continually cycled. Therefore, while the operating hours may be relatively low, the requirements of maintenance can be high.

In many instances, there may have been significant advances in design methods, manufacturing, and installation since the units being considered were designed. If replacement components are to be purchased, there are often alternate designs or design features available that can either increase efficiency or improve reliability or both. These manufacturing changes can either increase or decrease manufacturing costs. In such instances, it is for the plant engineer to evaluate the advantages of incorporating new components since they always seem to have a higher purchase price. However, the return on investment could well pay for the additional cost within a very short period of operation.

W.P.S.

AUTHOR'S NOTE

In 2001/2002 PennWell published a two-volume set entitled *Turbine Steam Path Maintenance and Repair.* These volumes were based upon a portion of the seminar I present on "Turbine Steam Path Engineering."

This two-volume work covers the remaining portion of that seminar and considers the design options available to the manufacturer and the challenges faced in selecting and arranging the components to optimize unit performance efficiency, reliability, and safety.

The engineer responsible for the health and operation of steam turbines is often faced with the difficult task of selecting between options for repair; these matters are covered in the earlier volumes. This work provides insights into the design options, challenges, and decisions that were originally made by the designers and selection from among these options for the manufacturing facilities at his disposal.

In selecting the information to include, I have tried to anticipate what information a turbine engineer requires when he has to decide what is influencing the performance of his unit or when he is involved with making a decision concerning new components to be incorporated into an existing unit to refurbish or upgrade it for continued use.

Also, I have tried to make these volumes as user-friendly as possible by eliminating as much as possible extensive mathematical treatments. There are a number of excellent volumes that already do this and these are referenced. I have tried to concentrate instead on the practical aspects of the unit—its design and manufacture—to the extent that when problems are encountered or decisions must be made, this reference is available.

For instance, the steam turbine is a thermal machine; it works as a result of expanding high-energy steam and generating rotational energy that is then used to drive some other piece of equipment. For this reason, I have included an introductory chapter in this volume discussing those aspects of thermal design that are of interest to the plant engineer. However, the chapter is not a treatise on thermodynamics.

What I have tried to do is select those thermal considerations that go into designing and arranging the steam path components of the turbine so that it will provide the greatest utility and flexibility to the plant engineer.

There are two departures from this simplified approach, and these are in the areas of steam path efficiency (chapter 3) and rotating blade design (chapter 4). I have elected to provide a more intensive treatment in these areas because rotating blades tend to be of greater concern in the operating unit than any other single group of components and because of the various influences of the geometric stage arrangement and how these differences influence the efficient expansion of the steam.

Turbine manufacturers determine the expansion efficiency of units by establishing the losses that occur as a consequence of stage geometry and steam parameters. Each manufacturer has a methodology for making these assessments. Also, if these methods are compared, there appears to be a degree of variation in them; manufacturers place different weight on the various factors of design, including some and ignoring others. For these reasons, I have provided a greater detail of the factors that influence expansion efficiency. I expect these to be of value primarily to engineers responsible for the thermal performance of the turbine units. I hope this will assist them in determining why any unit appears to be deficient in its performance after some period of operation and enable them to identify some remedial factors that will assist with the restoration of its condition.

Manufacturers' decisions regarding what to include and the weighting of factors is also influenced by field experience and internal research and development. It is surprising but true that if the guaranteed efficiencies of manufacturers are compared, they all tend to finish with a very comparable result.

So, while this work should be considered companion to the earlier PennWell publication *Turbine Steam Path Maintenance and Repair*, certain aspects and subjects covered in the earlier publication are revisited, in outline if not in detail so these two volumes are complete within themselves.

In Volume IIIa, chapter 1 discusses those aspects of thermal design that are required to understand component selection and unit arrangement. Chapter 2 gives a brief outline of the mechanical design and development process. Chapter 3 provides information on steam path performance and chapter 4 considers performance testing—not from a how-to-do perspective but rather from a how-to-organize-and-prepare approach.

In Volume IIIb, chapters 5 through 10 consider individual components. Chapter 11 reviews certain aspects of rotating blade manufacture. This is of value because if blades are not manufactured to design specification, they will not operate as intended.

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Chapter

5

Mechanical Design Considerations for High- and Low-Pressure Casings

INTRODUCTION

The turbine casing is essentially a cylindrical vessel and the main stationary portion of each expansion section. This casing encloses the rotating elements of the unit and at the same time locates the stationary blades, either directly, or through the location and support of an inner casing, which itself carries the stationary blades and/or diaphragms. The principle components of the casing are the shells, which provide the mechanical strength of the element and carry and locate other elements such as packing heads, diaphragms, and the inner casing or blade carriers.

The casing is normally split along its horizontal joint at the centerline to facilitate assembly and provide access to the rotor and internal stationary portions of the unit. The shell halves are normally

If steam flow quantities are such that a single-flow section does not provide sufficient discharge area, it is normal to arrange the low-pressure portion of the unit to employ a single or multiple double-flow low-pressure sections. It was common at one time to employ designs with three exhaust flows, with the one single expansion connected to the intermediate or reheat pressure section discharge. This concept is not used extensively in the majority of modern units, as it is more cost effective to develop modular designs of double-flow units, with specific arrangements for steam extraction. These modular low-pressure designs also permit a better mechanical arrangement of the low-pressure sections.

It is, therefore, becoming less common to employ an arrangement of three exhaust flows. There are, however, still in successful operation a number units in which a single-flow low-pressure section is connected directly to the intermediate section. This intermediate-pressure/low-pressure (IP/LP) section can then be used with a single double-flow section to provide a three-flow arrangement. In the three-flow arrangement, the first stationary blade row of the low-pressure sections is set so that steam admitted to each of the three flows is controlled so that with possible different steam extractions patterns in each. The exhaust flow from each expansion last-stage blade row is the same.

The pressure range across the low-pressure sections is small when compared to the high and reheat sections at one-fifteenth to one tenth their range. However, the energy extracted from the low-pressure section can produce an output comparable to the sum of the output from the other two expansions. Because of its large physical size and the fact that the space between the outer hood and inner casing is maintained at vacuum pressure, there is a large downward force resulting from the pressure differential between the inner hood and atmospheric. This total pressure is sufficient to deflect the total casing vertically downward.

defect excavations. Discontinuous linear indications are considered acceptable where the separation between adjacent indications is at least four times the length of the larger of the two indications.

Surface Linear Indications

Location	Critical Areas Length in Inches	Noncritical Areas Length in Inches
Rough Machined Surfaces	0.125	0.125
Repair weld (greater and less than 50% of the wall thickness)	0.125	0.125
Unmachined Surfaces	0.250	0.375

Table 5–3 Acceptable Magnetic Particle Inspection

If as a consequence of this magnetic particle examination unacceptable defects are found, then they should be excavated and weld repaired. After weld repair the casting should be subjected to a stress relief cycle.

Defects in machined areas. The casting must be free from subsurface defects which would be exposed on machining. Defects classified as being greater than ASME schedule 1 found by radiography in scheduled weld regions are not acceptable. Any such defects in this area should be repaired by welding.

Welding repairs. If it becomes necessary to weld repair defects in the cast shells, the faults must first be excavated by some suitable means such as grinding and/or chipping, machining, or arc-flame gouging. In some areas it is necessary to grind smooth the excavations before the repairs proceed. The normal method of weld repair is manual metal arc. It is also necessary to preheat the casting before repairs begin and to maintain the preheat temperature throughout the repair procedure. Preheat temperature is from 150 to

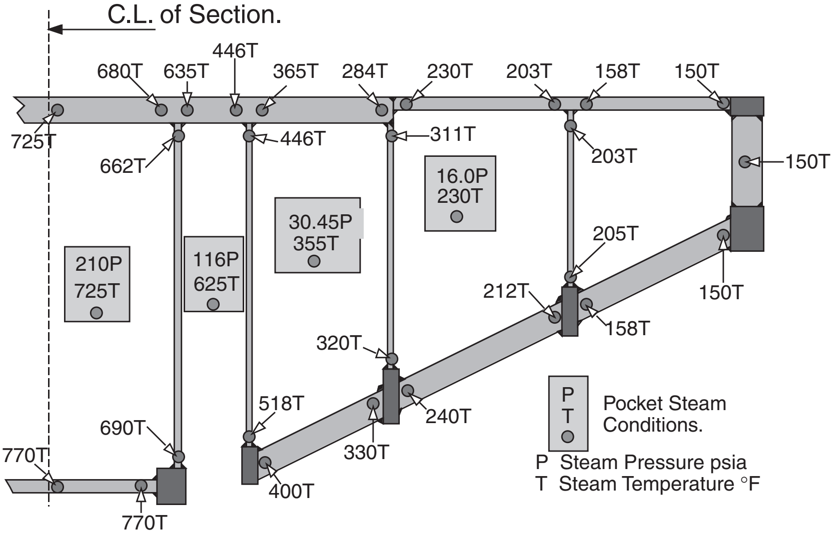

Fig. 5–22 Temperatures at Various Locations in a Fabricated Low-Pressure Casing

HIGH-PRESSURE TURBINE SHELL MATERIALS

Advancing steam conditions and increases in diameter, particularly for half-speed machines, have required a continual improvement in both the composition and mechanical properties of the material and the manufacturing techniques used to produce steam turbine casing shells. This is particularly important when applied to high-temperature, high-pressure units. Casings are produced from alloy steels, and the castings are carefully controlled both to ensure mechanical strength and freedom from casting defects which have the capability to compromise the integrity of the shell.

In defining weld requirements it must be recognized that over-welding can be as serious a fault as under-welding, because over-welding can induce residual stress capable of causing casing distortion. This can be difficult to correct. In selecting the weld for any location within the unit, the following three considerations need to be addressed.

1. If the weld is to provide a path for the transfer of forces, a welded design is justified, and the calculations necessary to determine stress levels and suitable weld sizes and geometries are mandatory.
2. If the weld is simply to locate or hold parts together, full-length welds are invariably wasteful and a few intermittent connecting welds will prove both more efficient and economical.
3. If the plates being joined are to provide a pressure barrier—the steam pressure on the two sides are different—then the welds must be constructed to produce isolation from side to side.

In selecting the weld, it is necessary for the designer to address certain considerations concerning the most appropriate form as follows.

- Are fillet welds acceptable and what size fillet is required? Will a single fillet be sufficient, and is there access for a double fillet? If not, will a partial or intermittent weld on one side be sufficient and acceptable?
- Are the stresses that will be developed at the weld shear, tensile, or compressive? The stresses will dictate the type of weld and to some extent the sequence of welding.
- Are the stresses cyclic and is their magnitude sufficient to make fatigue a consideration at the local operating temperatures? Is there a possibility of inducing low-cycle fatigue into any of the joints?

diameter and distance between hole centers, that stress levels in the casing flange do not become excessive.

Many older designs employed grooves produced on the face of the horizontal joint, which is designed to pass high-temperature steam between the bolt holes so the studs are able to achieve operating temperature at a faster rate in response to major temperature changes in the steam.

The shrink ring joint

A second design joining the casing halves is that employing shrink rings. With this design there is a combination of studs and shrink rings used to make the joint. While the studs do make some contribution to the total joint strength, their major function is to hold the two halves in their correct position while the shrink rings are heated and assembled over the casing halves.

Shown as Figure 5–46 is the section through a high-pressure unit in which the inner casing is held together by a series of nine shrink rings placed along the axial length of the casing halves. Eight of these rings are on the downstream side of the nozzle box and one is placed on the upstream side and above the balance piston.

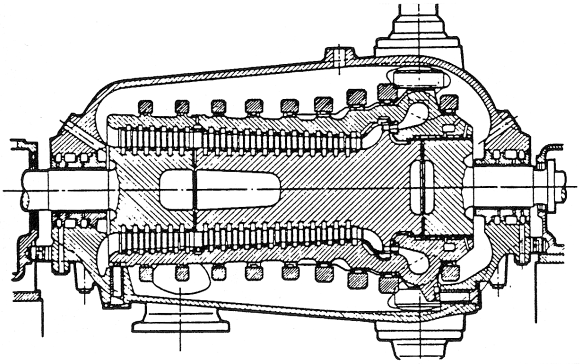

Fig. 5–46 An Inner Casing with Shrink Rings