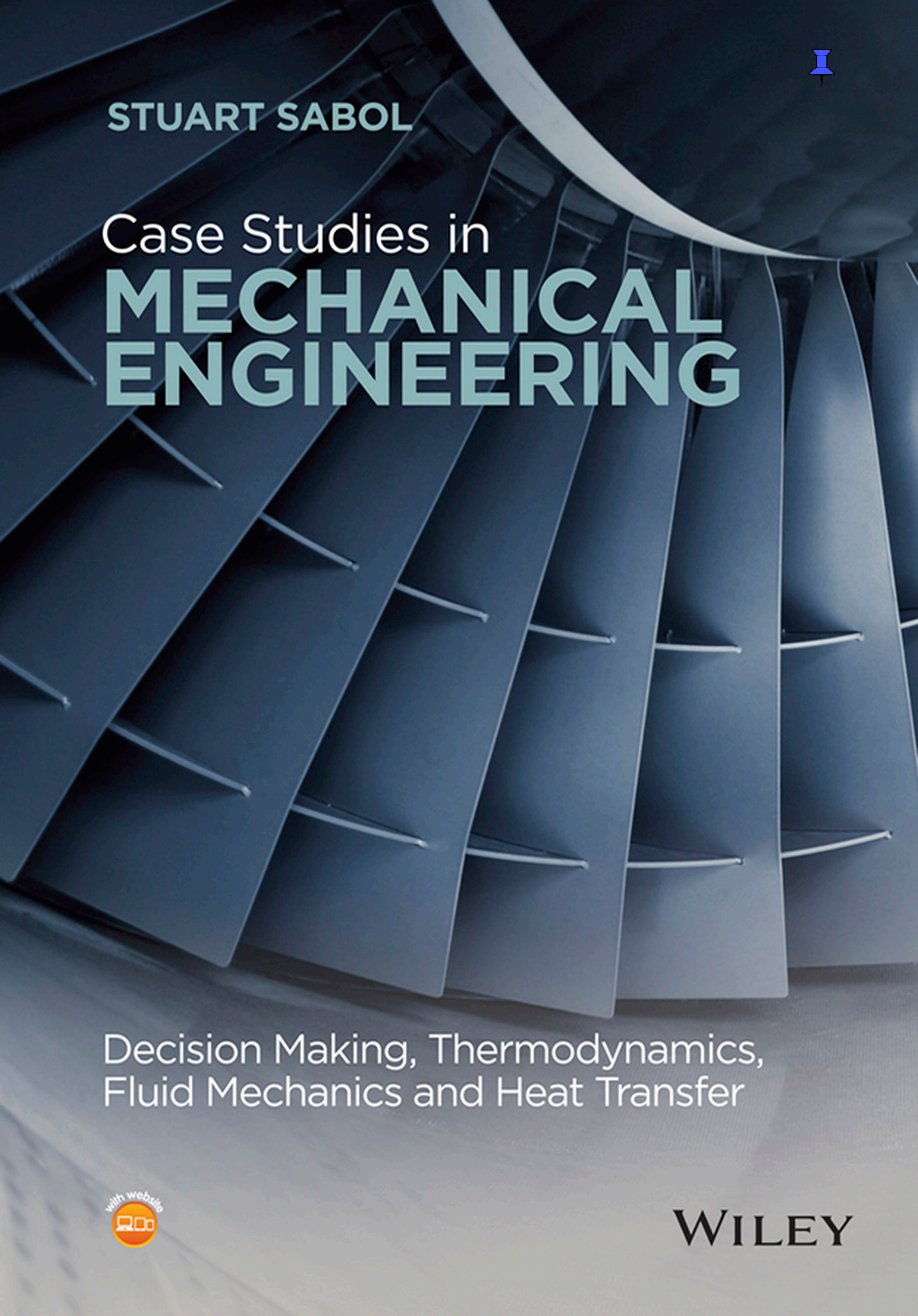

STUART SABOL

Case Studies in MECHANICAL ENGINEERING

Decision Making, Thermodynamics, Fluid Mechanics and Heat Transfer

with website

WILEY

CASE STUDIES IN MECHANICAL ENGINEERING

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This book is dedicated to my wife. She is my companion, my support, greatest believer, and my best friend.

Contents

Foreword

Professors teaching engineering and corporate managers teaching entry level engineers will find this book an invaluable resource not found in any university curriculum. The author, Mr. Stuart Sabol, has drawn from his many years in engineering in industry and has enthusiastically written this book in an attempt to complement the engineering knowledge gained from a university curriculum with real complex system engineering problems that were actually encountered in the real world and that impacted both his career and the bottom line of the companies involved.

Stuart Sabol is an engineering expert who was not only intimately involved in but was pivotal to the solutions of some of the most critical and complex problems in large-scale system engineering. In most university engineering courses students are given the problems to solve with only the data required to solve them. This unrealistically hints at the correct solution. In the real world, however, an abundance of information is available or can be determined and thus good engineering judgement is required to determine what information is crucial. The author presents, through his many industry case studies, an abundance of information for each in terms of data, background, photos, and drawings from which a student may draw to determine the best course of action. Mr. Sabol has organized the case studies with a number of special exercises for students or for student teams to perform. The actual resolution for each practical case study is also given for discussion.

I think that the author can be confident that there will be many grateful professors, students and engineering managers who will have gained a broader necessary perspective of real world engineering and the associated multidiscipline approach required to solve the large scale problems frequently encountered in industry.

Dr. William C. Schneider*
Endowed Professor of Engineering
Texas A&M University
and (retired) Senior Engineer, NASA Johnson Space Center

* Dr. William C. Schneider is presently an Endowed Professor of Engineering, teaching courses in engineering mechanics and engineering design to graduate and undergraduate students at Texas A& M University. He has a wealth of practical experience gained from 38 years performing critical analysis and design at the NASA Johnson Space Center. Some of his spacecraft components are still on the moon; he has 14 US patents and numerous NASA medals for his achievements. He had sign-off authority for the US space-shuttle flights.

Preface

Being an engineer, husband and father rank highly among my endeavors. I have had great mentors throughout my professional and personal life; and have tried to be a good mentor to those I worked with, and to those close to me. This book is perhaps a completion of that attempt to mentor others to become better engineers.

When I ask someone, "How do you solve a problem?" they look at me and ask anything ranging from "Don't you know?" to "What problem?" I don't know the answer either. What I do know is that the more problems I solve the better I am at solving problems. Thus, experience is a valuable teacher. The trouble is, experience takes time.

Reducing the time to gain experience in real-world problem solving is therefore a goal of this work. I have taken from my career the most memorable projects. They are memorable because they were difficult. Memorable because I learned something from each one. Although they may seem difficult, there are paths through the data and seemingly unconnected points that reside in our engineering education. My hope is that these scenarios open doors to problem solving and life beyond the university that will pay dividends in the reader's career as a mechanical engineer.

The cases in this book are experiences, altered to avoid identification with any owner. Names are excluded. Locations are not mentioned and in many cases transposed across oceans to disguise the original project. It is not my intent to identify anyone but to present a situation that provides a learning opportunity. I anticipate that each chapter, including the problems and outside readings, can be completed in one week as part of a supplement to course studies.

There are people and institutions that have made this book possible, and I would like to acknowledge a few of them. To the contributors of artwork, Mitsubishi-Hitachi Power Systems Americas, EPRI, Doosan, ERCOT, ThermoFlow, Fram, Nooter/Eriksen, Atco, General Electric, Siemens, ASME, Crane, DeWalt, Dresser, Alstom, Triad Instruments, and owners that permitted the use of photographs, I am deeply grateful. Being able to show size, scale, and details of equipment characteristics is a valuable contribution. Thank you.

My engineering and professional mentors are too numerous to recall; however, a few deserve a mention. Charles, it was great to work with you and create a first of its kind. Keith, you directed a mentor/mentee relationship that changed the company, and protected it in a

unique project that resulted in a considerable new opportunity. Who says Fortran is dead? Reid, "you can have only one first priority," "everyone has a contribution to make," and "there are only two decisions you make in your life" are valuable life lessons that will stay with me. Mike taught me how to appreciate everyone's opinion, to seek them out, and incorporate everyone's knowledge. George helped me understand that there is no greater joy than to enjoy what you do. Jo showed me how to progress the work and how to motivate people.

A special thanks to Steve Turns at Penn State. Your feedback was a breakthrough for this book. Also a special thanks to my publisher. Paul, thanks for believing in the book as much as I did, and in my ability to create it.

Stuart Sabol PE, PMP

Introduction

This volume of *Case Studies in Mechanical Engineering* strives to bring real-life experiences to students, recent graduates, and those seeking to continue their education either formally or on their own. These particular cases depart from traditional engineering case studies in that they are not evaluations of failures, and do not try to explore the field of engineering ethics. Instead, the author has drawn from his years of engineering to present those cases that affected his career and brought about new understandings in the field and practice of mechanical engineering. All deal with engineering's impact on a company's earnings and profit.

Each case is a study based on actual problems solved by engineers in industry. The names of the facilities and participants in the cases are absent, and the facts have been altered, but the lessons remain intact. Some of the case studies have been assembled from different projects or events that took place over several years. Most have been shortened or simplified to present a set of cases, each of which can be completed in a reasonable amount of time. The case studies thus provide a glimpse of how real-world engineering differs from traditional textbook problems and how engineering can impact management and the corporate bottom line.

Cases 1 through 3 are introductory. The first case study provides details of steam turbines, their design, and their operating characteristics. It provides a lesson in thermodynamic analysis, and its relevance to actual hardware. The second case study links commercial and engineering disciplines with the added dimension of time pressure and decision making. The third introduces manufacturer corrections from test to standard conditions for gas turbines combined with normal wear and tear, paradigm shifts, capital improvements and management decision-making processes.

Cases 4 and 5 explore aspects of detailed design. Case 4 studies the details of ASME flow elements in liquid and two-phase applications, thermodynamics, uncertainty evaluations, and computer programming. Case 5 dives deeper into applications of two-phase flashing flow with the problem of setting equipment elevations, pump characteristics, and detailed hydraulic calculations.

Case 6 develops a tool to analyze system availability and reliability.

Cases 7 and 8 deal with environmental subjects and an engineer's role in society and higher level decision making. Case 7 requires balancing of combustion calculations, and decision making. Case 8 explores fundamental market behavior and how a company's decisions can be impacted by taxes and governmental intervention.

Cases 9 and 10 deal with the application of engineering fundamentals combined with more abstract concepts. Case 9 combines knowledge of heat-transfer characteristics and detailed fluid system design, with quality-assurance requirements for engineers, and owners, and corporate responsibility. Case 10 develops a maintenance strategy for large equipment and complex systems, expanding the current state of the art in maintenance planning.

Case 11 explores the roles and responsibilities of an engineer responsible for a design team. The case illustrates developments, leadership and management tools that can be applied to a generic project engineering assignment.

Case 12 is a short study of engineering in daily life: how advancements are possible even in trades that have evolved over millennia, highlighting the necessity of using creativity and improving accuracy and quality.

In these studies, career decisions, standard practices, and engineering improvements are combined with decision-making and presentation skills to advance the traditional textbook approach to engineering beyond the classroom.

Each case study contains several exercises that can be used as in-class or homework activities. The cases may be approached as team activities. Solutions to the exercises, and detailed discussion, are included in each chapter.

Case 1

Steam Turbine Performance Degradation

A private investor-owned power company owns 15 GW of capacity including conventional fossil-fired generation and natural-gas fired combined cycle gas turbine power plants spread throughout the United States. The company competes in several unregulated power markets and takes seriously its ability to provide safe, reliable, low-cost power compared to its competitors while meeting all environmental permit requirements. Quarterly senior management reviews include reports on worker and contractor safety performance, the reliability and efficiency of the facilities, as well as any exceedances of environmental permits. The company spent time and resources establishing guidelines and procedures for regular performance monitoring at its generating facilities, including results analysis. These guidelines are routinely reinforced at every level of the organization with training for new recruits and refresher courses for midlevel management.

The performance-monitoring procedures and guidelines include techniques to analyze the test data based on industry guidelines, particularly ASME PTC Committee (2010) and technical papers from noted industry experts such as Cotton and Schofield (1970). For the company's steam turbines, the condition of the various stages is related to changes in stage pressures at standard conditions knowing how the throttle flow to the machine has changed. The methods are based on the fact that, for a large multistage condensing turbine, all stages, except the first and last, operate with a constant pressure ratio (p_2/p_1.) This allows the general flow equation for flow through a converging-diverging nozzle for stages beyond the first stage to be simplified to equation (1.1)

$$\dot{m} = \Phi \cdot \sqrt{\frac{P}{\upsilon}} \tag{1.1}$$

Case Studies in Mechanical Engineering: Decision Making, Thermodynamics, Fluid Mechanics and Heat Transfer, First Edition. Stuart Sabol.

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where

$\dot{m}$, P and υ are the flow rate, absolute pressure and specific volume to the following stage;

Φ is a constant flow function (area).

The flow function Φ includes unit conversions, constants of proportionality, the area of flow, and the coefficient of discharge for the nozzle and blade path. Except for unit conversions it has units of area.

A production engineer at one of the company's coal-fired power plants with three 600 MW subcritical single reheat units has been monitoring the units' performance according to company procedures. In just over 7 months since the last major overhaul one unit has lost 3.4% of its output, and the cycle heat rate has increased 0.6%. Using the guidelines, most of degradation in performance can be explained by changes in the flow-passing capability of the steam turbine and losses in the high-pressure (HP) turbine efficiency.

However, there are changes to characteristics that are not discussed in the corporate standards or the technical papers available in the office. In particular, the intermediate pressure (IP) turbine's extraction temperature has risen noticeably from the expected value. Efforts to explain the symptoms as instrumentation issues have failed. Rather than dismiss or ignore the findings, you, the engineer, are determined to find the cause, its economic value, and to recommend a course of action to address the issue.

1.1 Steam Turbine Types

The variety and application of steam turbines is enormous. It includes the utility tandem compound unit pictured in Figure 1.1, mechanical drives for onshore or marine applications, combined-cycle and single Rankine-cycle units, super critical, single or double reheat units, and nuclear power-plant applications. One way to categorize the various models is by size. Very basically, smaller installations typically serve as variable speed mechanical drives for pumps and compressors. These may be as large as 50 to 75 MW and have inlet conditions up to 750 psi (5.2 MPa) and 700 °F (644 K). Many are located within chemical processing plants or refineries and exhaust into a lower pressure steam header that provides steam for heating, or to drive smaller steam turbines that may exhaust into a surface condenser. The larger varieties will be multistage units with an axial flow exhaust.

Up to about 150 MW, steam turbines typically have an axial flow exhaust with throttle conditions as high as 1500 psi (10 MPa) and 900 °F to 1000 °F (755 K to 810 K). Figure 1.2 shows a drawing of a Siemens axial flow machine. Such turbines may be used in a chemical process plant and have a controlled extraction for process heat or other uses. This size is also common in combined cycle power plants with uncontrolled expansion to the condenser. Occasionally, an axial flow machine will have single reheat as part of the cycle. If it is a condensing cycle, the condenser can be placed on the same elevation as the turbine. Combined cycle units utilize waste heat from a gas turbine to generate steam; thus, steam-turbine extractions for regenerative heating are not employed in a combined cycle. A single Rankine cycle would employ uncontrolled extractions for feedwater heating.

Above approximately 150 MW, the last stage blade (L-0) becomes too long to manufacture and operate reliably. The low pressure (LP) turbine becomes a dual flow design with steam entering the center section and steam traveling in opposing directions to exhaust downward

Figure 1.1 Alstom steam turbine. *Source*: Reproduced by permission of Alstom.

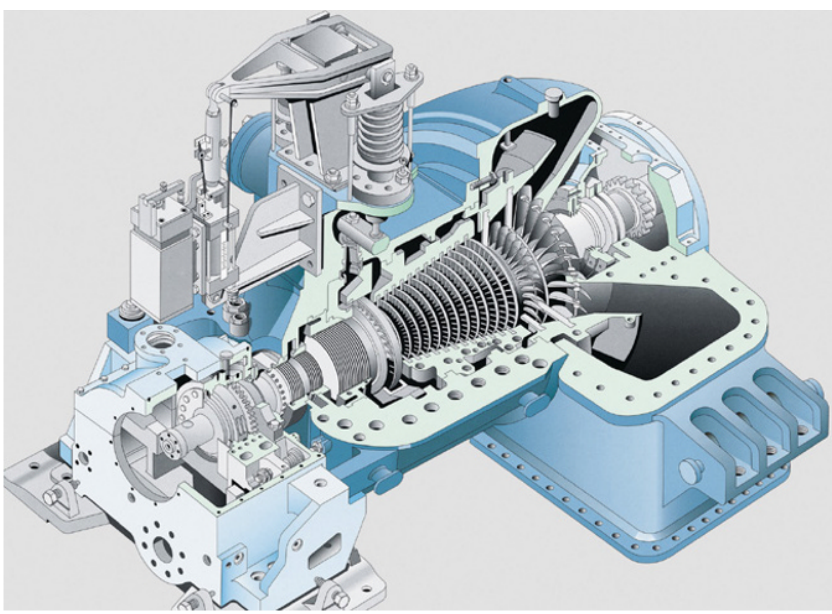

Figure 1.2 Typical axial flow exhaust steam turbine. *Source*: Reproduced by permission of Siemens Energy.

Figure 1.3 700 MW ST Hekinan Unit 3, Chubu Electric Power Co. *Source*: Reproduced by permission of Mitsubishi Hitachi Power Systems America, Inc.

into the condenser. For these machines, the steam turbine must be raised above the condenser, which increases construction costs to include foundations for an elevated turbine. Figure 1.3 is a photograph of the 700 MW ST Hekinan Unit 3, Chubu Electric Power Co. steam turbine. The tandem compound machine has dual flow HP and IP sections in the foreground with two dual-flow LP sections in the background.

Machines as large as 650 to 750 MW usually operate with subcritical steam pressures with a single reheat. Throttle conditions may be as high as 2800 psi (19 MPa) and 1050 °F (840 K) with the reheat temperature matching the throttle temperature. Units in this size range are generally uncontrolled expansion, condensing units used for power generation either in combined cycles or single Rankine cycle units with regenerative heating. The larger single Rankine-cycle units may have two or three dual-flow, down-exhaust LP sections. Combined-cycle steam turbines are limited in size by the gas turbine portion of the combined cycle. As a rule of thumb, the steam portion of the combined cycle plant is about one-third of the plant total electrical output. Most of the single Rankine-cycle units are fossil fired although some may be in nuclear facilities. Combined cycle and fossil-fired units operate at synchronous speed with a two-pole generator. Nuclear units typically have four-pole generators and operate at half synchronous speed.

Above about 650 MW, fossil-fired units begin using supercritical pressures and may include double reheat Rankine cycles with regenerative feedwater heating. Throttle conditions may be above 4000 psi (28 MPa) and 1150 °F (895 K). Reheat temperatures usually match the throttle conditions but cost optimizations may result in the reheat temperatures somewhat above the throttle. Nuclear steam cycle conditions generally do not change much with size. The largest steam turbine at the time of this writing was in the neighborhood of 1800 MW.

1.1.1 Steam Turbine Components

The active components of steam turbines are the rotating and stationary blades. Rotating blades are sometimes referred to as *buckets*, from their shape. Steam to the machine is controlled by multiple throttle valves. In large modern machines there are four hydraulically controlled valves that can close very quickly in the event of an upset. From the control valves, the steam is directed to the first control stage through sets of nozzles. Each set of nozzles accepts steam from one of the inlet throttle valves. The first control or governing stage has impulse or Curtis blading. Beyond the governing stage, the blades take on an increasing amount of reaction, as the pressure diminishes and the pressure ratio increases across each rotating stage.

The rotating blades are mounted on wheels or disks that are fixed to the shaft, or the shaft is machined with integral wheels to accept the blades – see Figure 1.4. The wheels provide increased torque on the shaft. The blades are secured in the wheel by a dovetail or fir tree shaped slot. Each blade is weighted and moment balanced, then ordered so that the assembled rotor is nearly balanced. During assembly of the rotor, the blades are slid into the dovetail slots until the ring is full. The blades are locked in place and the locking mechanism is frequently peened to ensure the security of the blades during operation.

A large steam-turbine generator in a reheat cycle will have a high pressure (HP) rotor, one or more intermediate pressure (IP) rotors, and one or several low pressure (LP) rotors. These may be mounted on a single shaft (tandem compound) or in a dual shaft arrangement with two

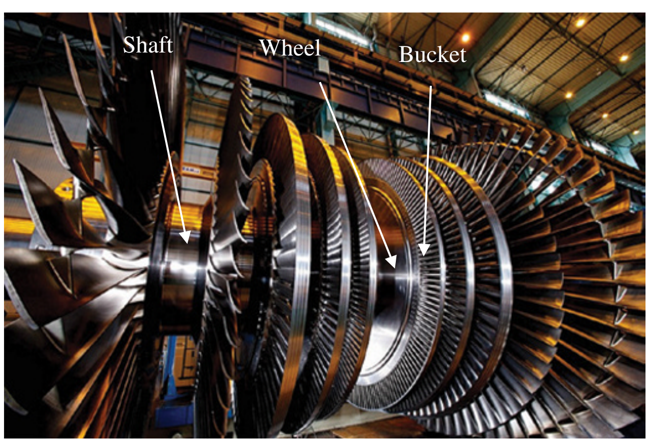

Figure 1.4 An LP section of a large nuclear steam turbine. *Source*: Reproduced by permission of Alstom.

generators (cross compound). Intercept valves are located in the hot reheat line immediately upstream of the IP turbine section. These valves do not control flow but are configured to close quickly in the event of an upset condition preventing the energy stored in the steam lines to and from the boiler reheater from overspeeding the rotor after the generator is disconnected from the electric grid. The pipeline to the boiler from the HP turbine exhaust is referred to as the “cold” reheat line. From the boiler to the IP turbine is the “hot” reheat line.

Once assembled, each rotor is balanced first at slow speed then at high speed. If a field repair requires replacement of worn or damaged blades, the rotor may be removed from the casing and field balanced prior to completing the repair. A trim balance may also be required once the machine is assembled and run at full speed for the first time.

Between rotating blades are stationary vanes, sometimes referred to as nozzles or diaphragms. The blades of the diaphragms are shop assembled in halves between inner and outer blade rings. One half will be fitted in the lower casing and the other half in the top half of the turbine casing. The stationary vanes turn and focus the steam from the exhaust of the upstream rotating blade and direct it to the downstream blade. Each expansion stage is a combination of one set of nozzles and one set of blades.

During assembly of the rotors and casings, sealing strips are mounted to the rotor between the wheels, and in the casing between diaphragms. Mating seal strips are placed on the blade tips, or are made as an integral part of the blade, to match with the casing seals. The inner rings of the diaphragms have seals that match with the rotors. Figure 1.5 shows blade tip seals from US Patent 6926495. The sharp edges are an inefficient flow path reducing leakage between the rotating and stationary components. The sealing components are adjusted during assembly so that there is proper clearance throughout the circumference to prevent the rotating seals from striking the stationary components in the cold and operating conditions.

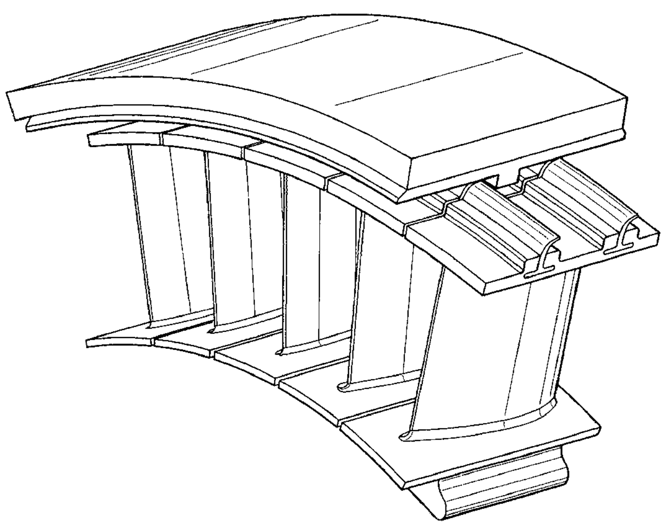

Figure 1.5 Blade tip-seals (US Patent 6926495 Ihor S. Diakunchak). *Source*: Ihor S. Diakunchak, Siemens Westinghouse Power Corporation.