GE Power Systems

Structured Steam Turbines for the Combined-Cycle Market

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Contents

Abstract . . . 1
Introduction . . . 1
Cycle Optimization . . . 2
IP Admission and Reheat Pressure . . . 2
LP Admission Pressure . . . 3
Structured D-11 Design Features . . . 3
Opposed Flow HP/IP Section . . . 3
Steam Path Design . . . 4
Low-Pressure Section . . . 5
Application Rules for the Structured D-11 Steam Turbine . . . 6
LSB Selection . . . 8
Other Features . . . 8
Heat Balance Requirements . . . 9
Bypass System Information . . . 10
Advantages of Structured D-11 Steam Turbine . . . 11
Delivery Cycle . . . 11
Customer Drawing Availability . . . 11
Common Spare Parts . . . 11
Installation Time . . . 11
Future Structured Applications . . . 11
DX2 . . . 11
A-10 . . . 11
DX4/GX1 Designs . . . 11
Conclusion . . . 12
References . . . 12
List of Figures . . . 13
List of Tables . . . 13

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Abstract

GE's variety of robust steam turbine products has proven to be a valuable choice in today's highly competitive, combined-cycle marketplace. A discussion of the GE steam turbine offering for 2-on-1, "F" technology, gas turbine, combined-cycle plants is the main focus of this paper, with emphasis placed on the structured D-11 product – the customer's choice for delivery cycle, performance, reliability, and availability.

Introduction

To date, GE has built over 40 steam turbines used in "F" technology, gas turbine, combined-cycle applications, totaling over 6000 MW in steam turbine-generator output. In a GE Steam And Gas (STAG) application, the steam turbine is matched with one or more gas turbines, utilizing the exhaust energy from the combustion turbine(s) to produce steam through a heat recovery steam generator (HRSG). A typical GE configuration uses a three-pressure HRSG for the plant, where steam is supplied from high-pressure (HP), intermediate-pressure (IP), and low-pressure (LP) drums to the corresponding section of the steam turbine.

In the past, GE's design philosophy dictated standardization of some of the major turbine components, but customization of the steam path for each application. In 1997, in response to customers' continual demands for shorter delivery cycles and higher efficiency, GE recognized the need to take a more proactive approach to meet the demands of a competitive and growing marketplace.

To be competitive in this market, GE needed a steam turbine product that was both efficient at baseload conditions and robust enough to be used in a variety of climates, configurations, and operating modes. While only a custom-designed unit could operate at peak efficiency in any given situation, the design and production of such a unit would result in a prohibitively high price and an excessively long delivery cycle. This was not an option for a domestic U.S. market that was beginning to add significant capacity for the first time in many years. Based on an analysis of market activity, GE focused its standardization effort on steam turbines for 207FA and 209FA combined-cycle plants. GE's product for these particular applications is the D-11 turbine, a design consisting of a combined, opposed-flow, HP/IP section with single-shell construction, and a two-flow LP section (*Figure 1*).

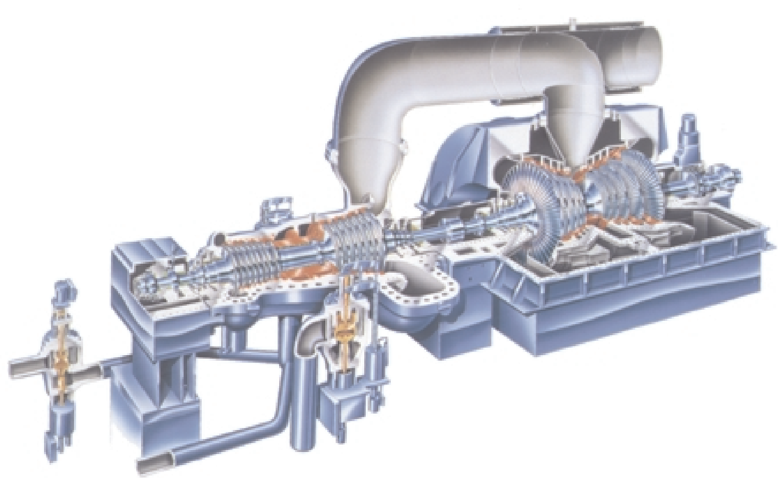

Figure 1. GE's D-11 steam turbine

The results of this design standardization yielded five basic D-11 structured configurations, which are listed in *Table 1*. For the 60-Hertz (Hz) market, three standard LP sections have been designed with last-stage bucket (LSB) lengths of 30 in. (76.2 cm), 33.5 in. (85.1 cm), and 40 in. (101.6 cm). For the 50 Hz market there are two standard LP sections, based on LSB lengths of 33.5 in. (85.1 cm) and 42 in. (106.7 cm).

STAG plant	207FA	209FA
Casings	2	2
HP Stages	11	10
IP Stages	7	8
LP Stages (per flow)	5	5
RPM	3600	3000
LSBs	30 in.	33.5 in.
	33.5 in.	42 in.
	40 in.	

Table 1. Structured D-11 configurations

Cycle Optimization

The starting point for designing the structured D-11 product is the highly efficient and reliable, three-pressure HRSG design, with nominal 1800 psia/1050°F (124 bar/566°C) throttle conditions and 1050°F reheat temperature. Given that the basic bottoming cycle parameters were already determined, efforts were centered on determining the optimum IP and LP admission pressures in terms of overall cycle and steam turbine efficiency.

IP Admission and Reheat Pressure

As shown in *Figure 2*, variation in hot reheat pressure does not have a significant effect on steam turbine generator output over the range considered. The reheat pressure will ultimately set the IP admission level since the IP admission is into the cold reheat line. The hot repeat pressure impacts the volume flow of the reheat system, and therefore, has a major influence on the design of both the HRSG and the steam turbine. Hot reheat pressure for the cycle is set by the flow passing area of the first IP turbine nozzle. For GE's structured D-11 product, the hot reheat pressure for the baseload condition was set at 333 psia (23 bar) for the 207FA configuration and 366 psia (25.2 bar) for the 209FA configuration. Since these results are very close to the combined cycle optimum level, GE's designs for the HRSG and steam turbine are both cost effective and mechanically conservative.

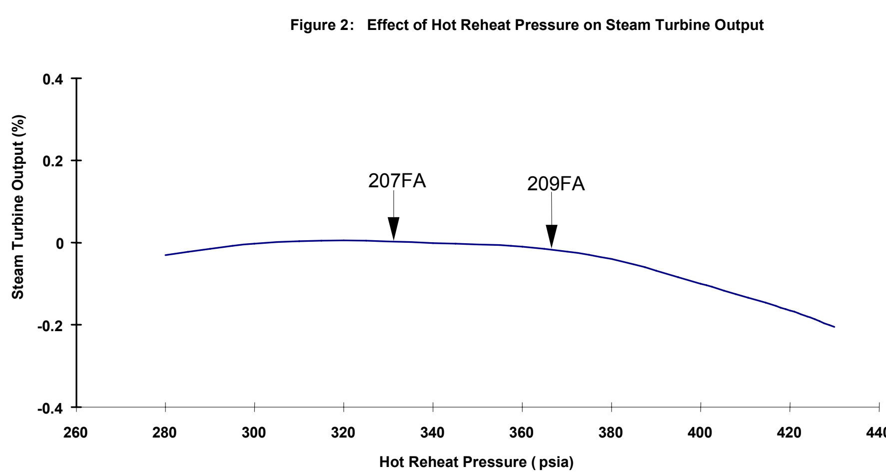

Figure 2. Effect of hot reheat on pressure steam turbine output

LP Admission Pressure

The second parameter that GE investigated for optimization was the LP admission pressure level, including the place within the steam turbine flow path to locate this admission. The effect of steam turbine output based on the variation of LP admission preassure is shown in *Figure 3*. This optimization considered steam turbine output effects, HRSG surface area effects and stack exit temperature, volume flow criteria, and location of admission interface with the steam turbine. As a result of the analysis of the parameters mentioned above, the low-pressure admission was located in the IP exhaust region of the steam turbine. Because the IP exhaust passes directly into the low-pressure turbine crossover pipe, the pressure in the crossover pipe is directly set by the HRSG LP drum pressure level.

As a result of extensive cycle and steam turbine efficiency optimizations as well as the careful selection and design of the IP and LP steam paths, GE was able to establish a common LP admission pressure and effective flow passing area (AeN). Because of this work on the standardization of the crossover pressure, it was now possible to design, for a given class of turbine (207FA or 209FA), a single IP section that was compatible with a variety of standardized low - pressure sections. The optimized LP Bowl pressures were set at 55 psia (3.8 bar) for the 207FA configuration and 66 psia (4.5 bar) for the 209FA machine.

Steam turbine condensing pressure has a large influence on steam turbine output and varies depending on the available condensing medium. Knowing the optimum required LP admission/LP crossover pressure made it possible for GE to match the fixed IP turbine with a newly designed series of standardized low-pressure turbine sections with different last-stage buckets and annulus areas for different condensing pressures. These LP modules can be interchanged without impact to the HP/IP turbine design.

Structured D-11 Design Features

The optimized 207FA and 209FA thermal cycles have enabled the development of a standardized family of steam turbines. A cross-sectional drawing is shown in *Figure 4*.

Opposed Flow HP/IP Section

The structured D-11 steam turbine evolved from the opposed-flow, HP/IP turbine with a double-flow LP section, a design that has been

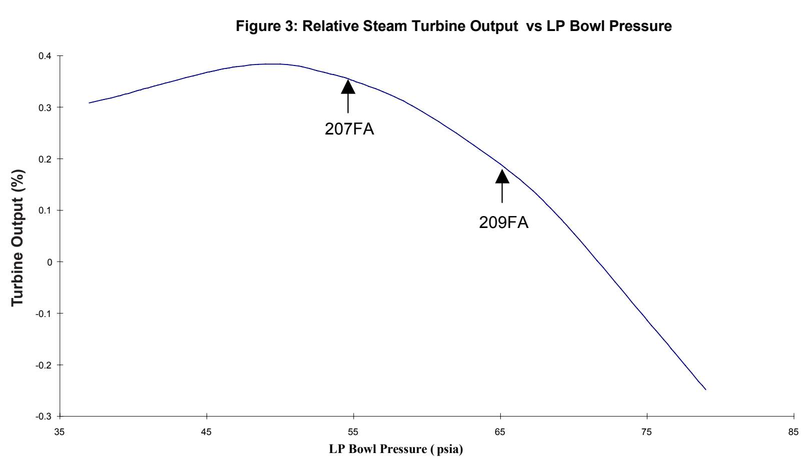

Figure 3. Relative steam turbine output vs. LP admission pressure

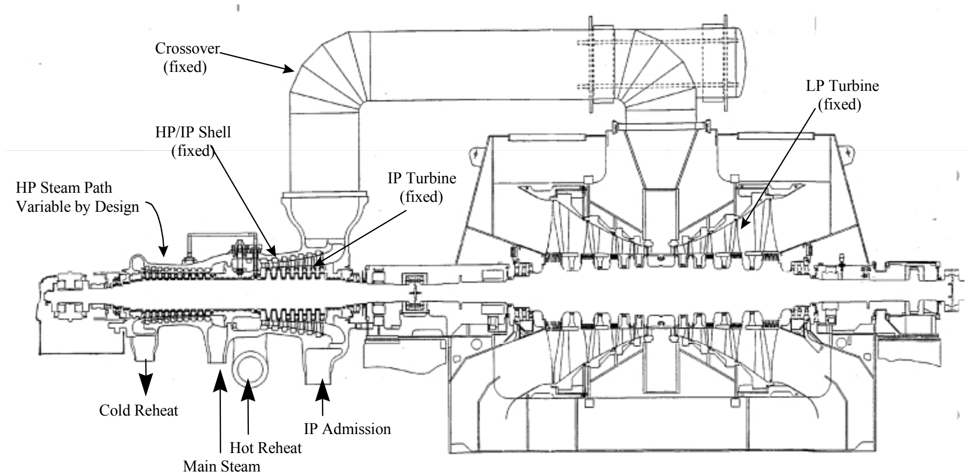

Figure 4. Cross-section of the structured D-11 turbine

applied in fossil and combined-cycle applications for many years. Main steam enters the turbine at the bottom of the high pressure shell via two separate stop and control valves. The flow of HP steam continues to the left in *Figure 4* and exits the section via the cold reheat line where it returns to the HRSG. The reheated, intermediate pressure steam enters the center of the casing via the hot reheat piping and flows through the IP section in the direction opposite that of the HP section. This design results in an even temperature gradient from the center of the casing to the ends, as the highest temperature steam in the system enters at the center of the shell and then gradually reduces its temperature as it flows outward toward the end packings and bearings.

The combined HP/IP section utilizes single shell construction that has been proven by successful operating experience at a maximum operating pressure of 1950 psia at an operating temperature of 1050°F. There are two HP/IP shell designs, one for 207FA, 60 Hz applications and one for 209FA, 50 Hz applications. Each shell design is standard, with the interstage diaphragm grooving and supports already designed into the shell (*Figure 5*). Variability in the steam path design is limited to the high pressure section, with the HP staging customized for each application.

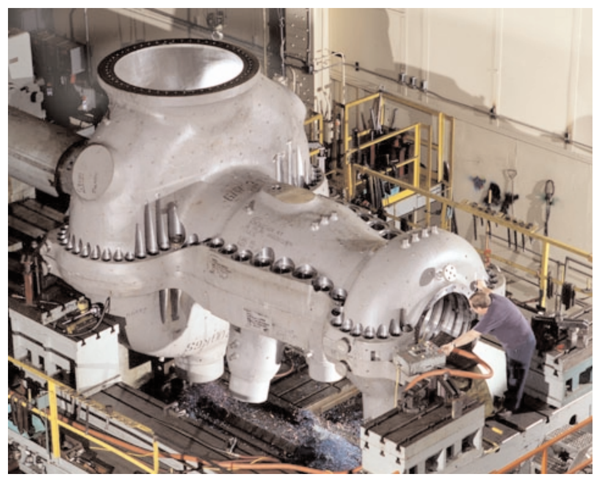

Figure 5. Machining of HP/IP casing

Steam Path Design

Staging within the HP and IP sections is based on low reaction design theory, which leads to the use of wheel-and-diaphragm construction (*Figure 6*). Rows of rotating blades, or buckets, are machined from blocks of 12Cr steel, utilizing a pinetree dovetail design, as shown in *Figure 7*. These buckets are assembled tangentially on a rotor wheel and locked into place by the use of several specially designed closure buckets and by bands or covers, which are fastened or "peened" over several buckets at a time. Stationary blades, or nozzles, are also machined from 12Cr steel and are assembled in the outer ring and inner web portions of the diaphragm (*Figure 8*). The diaphragm sections are then affixed in grooves in the upper and lower halves of the shell.

Figure 6. Assembled HP/IP rotor

The HP section was designed to accommodate up to 45% additional throttle mass flow based on the site-specific requirements for supplementary firing. Because of the fixed IP steam path and the variable range of reheater pressure drop, the cold reheat pressure varies within a certain range. Hence, this pressure variation requires some customization of HP staging for each application. Since two 7FA or 9FA gas turbines provide a predetermined amount of exhaust energy, and the HRSG surface areas are somewhat standardized by the constraints discussed earlier, it was possible to optimize HP turbine thermal performance, and to fix the number of high pressure stages at 11 for the 207FA turbine and 10 for the 209FA turbine. With the fixed staging of the IP section, it became possible to closely control the HP/IP rotor design in terms of forging size and bearing span. Rotor dynamic criteria have been thoroughly analyzed so that the relatively small steam path variations allowed in the high-pressure section do not require re-analysis of the design for each application.

Figure 7. Tangential entry "Pinetree" dovetail bucket

Figure 8. Diaphragm section

Low-Pressure Section

The low-pressure section designs are based on GE's established, highly reliable and efficient family of last stage buckets (LSBs), shown in *Figure 9*. These buckets are of the continuously

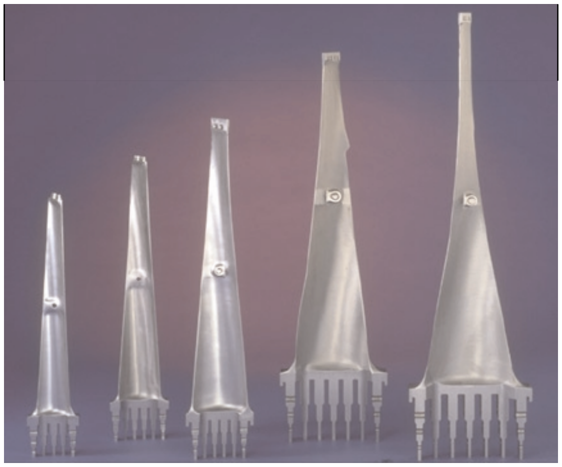

Figure 9. Last stage bucket family

coupled design, with attachments at both the vane tip and mid-vane to provide a high degree of rigidity, model suppression, and damping.

Through use of computer modeling of the LP section, GE found that this section could be optimized with a 5-stage design. In addition, maximization of the steam turbine output required redesigning the upstream LP stages, utilizing the most advanced, three-dimensional blade design technology. This redesign effort resulted in an integrated and interchangeable set of low-pressure turbines, specifically designed for combined-cycle applications.

In previous designs, provisions for feedwater heating extractions from the low-pressure turbine were included only if required by the specific application of any low-pressure section. Extraction provisions for feedwater heating are now included on all structured D-11 LP turbine sections.

Application Rules for the Structured D-11 Steam Turbine

The structured D-11 steam turbine is designed for an 1800 psia inlet pressure at nominal flow conditions. Like most combined-cycle steam turbines, normal operation is with valves wide open in boiler-following mode. Once the guarantee point inlet pressure is established, the corresponding HP turbine flow passing area (otherwise known as AeN) becomes fixed, at which point inlet pressure will vary directly with inlet flow. *Table 2* summarizes the key design parameters for the structured D-11 turbine. When supplementary firing is applied, the maximum inlet pressure for the fired case is allowed to float higher than the unfired case. This is permissible, given that the additional flow generated by supplementary firing causes a greater pressure drop across the inlet valves and piping, so that the same pressure will be seen at the high pressure bowl. If the intent is to apply a significant level of supplementary firing only during periods of peak energy demand, it is necessary to set the unfired inlet pressure at a much lower value. For instance, if up to 20% supplemental firing is anticipated on an intermittent basis, then the unfired pressure should be set at 1910 psia/ 1.2 = 1592 psia. (*See Figure 10.*)

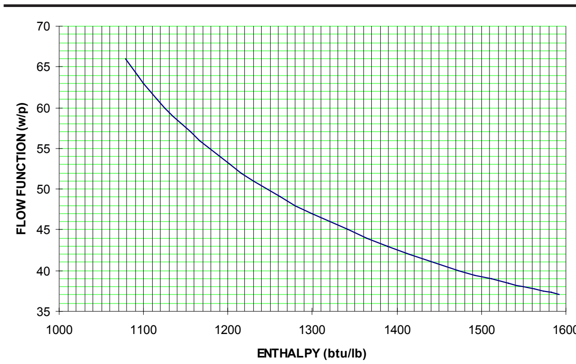

Figure 10. Flow function vs. enthalpy

Note that in *Table 2*, the inlet AeNs of both the IP turbine and LP turbine are already fixed because, unlike the HP turbine, the designs of both the IP and LP sections of the steam path are based on the optimizations mentioned in the "Cycle Optimization" section of this paper. These inlet AeNs remain fixed, regardless of the

STAG Configuration		207FA	207FA	209FA	209FA
Machine Speed (RPM)		3600	3600	3000	3000
Supplementary Duct Firing		UNFIRED	MAX FIRED	UNFIRED	MAX FIRED
Machine rating	MW	180	265	283	400
Throttle pressure limit	psia	1890	1910	1890	1910
Throttle temperature limit	F	1050		1050	
HP AeN	Sq-in	11.75	17.27	17.56	25.73
Cold reheat pressure at turbine flange, based on 12% reheat pressure drop	psia	379	509	416	548
Cold reheat pressure at turbine flange, based on 6% reheat pressure drop	psia	355	476	390	513
RHT pressure drop (Min.)	%	6		6	
RHT pressure drop (Nominal)	%	10		10	
RHT pressure drop (Max.)	%	12		12	
Hot reheat pressure	psia	333	448	366	482
Hot reheat temperature	F	1050		1050	
IP/Reheat bowl pressure (Nominal)	psia	330	443	362	477
IP/Reheat bowl AeN	Sq-in	74.38		101.78	
IP exhaust pressure (Nominal)	psia	56	71	69	87
LP admission pressure at valve	psia	58	73	71	89
LP bowl AeN	Sq-in	421		513	

Table 2 Thermal Application Data

amount of supplemental firing. Hence, for given mass flows, the pressures at the inlets of the IP and LP sections can be established. If the cycle is fired, then the additional flow will result in higher pressures at these points.

AeN, or the pressure that results from establishing the AeN, may be reasonably estimated from the equation:

AeN* = *F/ (w/p) x P ; or

P* = *F/ AeN x (w/p),

where:

F* = *Flow in lb/hr

AeN* = *Flow passing area in sq. in.

(w/p)* = *Flow function, determined from the graph in Figure 10, once enthalpy is known

P* = *Initial pressure, in psia

Close attention must be paid to the pressure vs. AeN equation to ensure that the turbine and HRSG are properly matched. *Table 2* shows AeNs for the IP and LP inlets, and the nominal pressures associated with each of these points if the thermal cycle is configured around these parameters.

It is important to note that under all steady state operating conditions, both the main steam inlet and reheat steam inlet are designed to accommodate a maximum temperature of 1050°F.

It can be seen from *Table 2* that two sets of cold reheat pressure values are given. The first assumes a total of 6% pressure drop through the reheat section of the HRSG including cold and hot reheat piping, while the second assumes a total of 12% pressure drop. By using these pressure drops, the cold reheat values may be predicted knowing that the reheat turbine inlet AeN is set at 74.38 in^2 (479.87 cm^2) for the 60 Hz turbine and 101.78 in^2 (656.64 cm^2) for the 50 Hz turbine. This flow restriction controls the pressure in the reheat section of the HRSG and therefore, the pressure at the turbine high-pressure section exhaust.

Similarly, the LP bowl AeN is set at 421 in^2 (2716 cm^2) for the 60 Hz turbine and 513 in^2

($3310\ cm^2$) for the 50 Hz turbine. This parameter controls the pressure in the turbine crossover and therefore, the IP turbine exhaust, which is also the LP steam admission point. There is normally a total of about 2-psi pressure drop across the LP admission strainer, LP butterfly control valve and LP butterfly stop valve, admission pipe and turbine inlet flange. This is shown in *Table 2* as the pressure difference between IP nominal exhaust pressure and LP admission pressure.

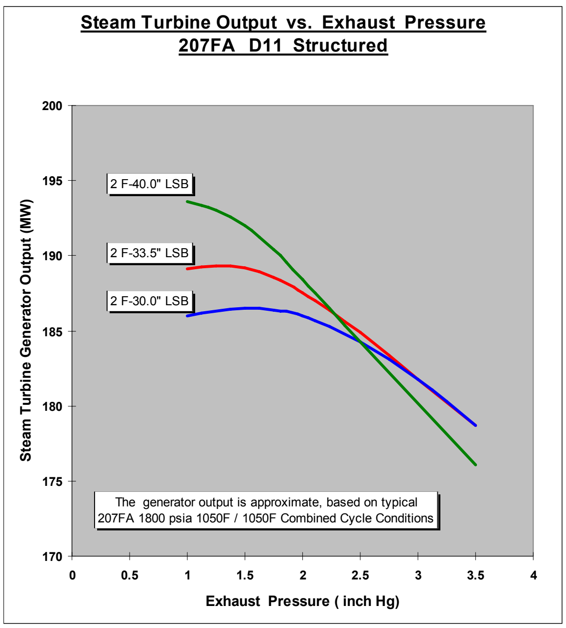

Figure 11a. Output vs. exhaust pressure – 60 Hz

LSB Selection

When configuring any steam turbine, it is very important to choose the proper annulus area for the anticipated exhaust flow and condenser pressure. *Figures 11a and 11b* show potential choices of last stage buckets for 60 Hz and 50 Hz applications, respectively. Given the design point of the turbine and the range of condensing pressures, the optimum LSB can be selected, and from there, the associated annulus area may be calculated. Economic factors come into play when selecting low-pressure turbine sections, but the use of *Figure 11* together with the LP turbine data shown in *Table 3* provides the proper selection for most applications, where LP exhaust loss is minimized for a particular condenser pressure.

Other Features

Structured D-11 steam turbines have additional flexibility because of the following thermal cycle variations that were taken into account as part of the conceptual design process:

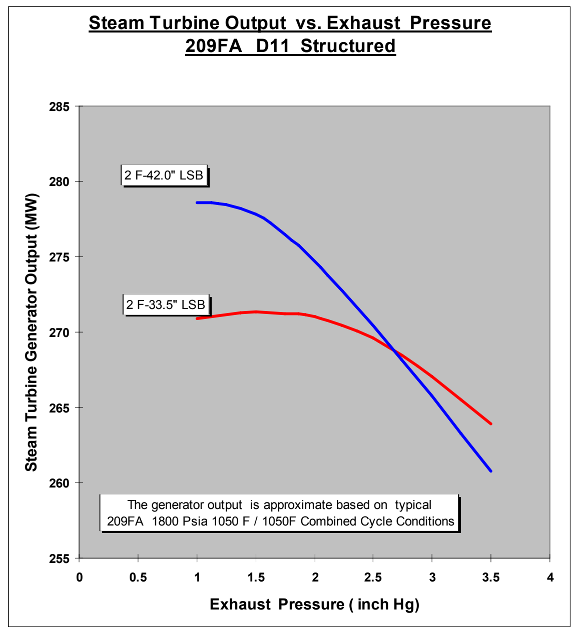

Figure 11b. Output vs. exhaust pressure – 50 Hz

1. Two-pressure reheat cycle (no LP admission). If fuel oil (containing sulfur) is the primary or secondary fuel, the thermal cycle will not support the third level of steam generation in the HRSG. A structured D-11 turbine applied to such a cycle should be configured without the LP admission port.
2. Process extraction from HP or IP exhaust piping, as shown schematically in *Figure 12*. The shell connections and

Note: All pressures are approximate

		207FA	207FA	207FA		209FA	209FA
LP LSB Length	inch	**40**	**33.5**	**30**		**42**	**33.5**
Back pressure range w/o firing	inch Hg	1.0 - 2.3	2.3 - 2.8	2.8 - 3.5		1.0 - 2.5	2.5 - 3.5
Back pressure range with firing	inch Hg	1.2 - 2.9	2.9 - 3.5	3.5 - 4.5		1.2 - 3.0	3.0 - 4.5
LP bowl pressure w/o firing	psia	55	55	55		66	66
LP bowl AeN	sq-in	**421**	**421**	**421**		**513**	**513**
LP extraction stage for DA	-	L-4	L-4	L-4		L-4	L-3
LP extraction size for DA	inch	2x14	2x14	2x14		2x16	2x16
LP extraction flow % of LP bowl	%	10	10	10		10	10

Table 3. LP turbine data for structured D-11 steam turbines

IP staging are designed to withstand the additional loads caused by process extraction flows.

3. Feedwater heating deaeration extraction from low-pressure turbine section. (Generally used for cycles where the gas turbine fuel has relatively high sulfur content)

4. Application of 1000°F/1000°F cycle temperatures in lieu of the standard 1050°F/1050°F, due to economic considerations, which allows the use of (less expensive) P22 main steam and hot reheat piping, rather than the more expensive P91 piping.

5. Application of two different GE generators at both 50 Hz and 60 Hz to accommodate the range of output, considering the steam turbine output difference between unfired and maximum supplementary fired cases.

Heat Balance Requirements

The information given above will allow a conceptual steam turbine design to be successfully incorporated into the thermodynamic design of the plant. It is necessary, however, to pay strict attention to the entire range of operating scenarios to which the plant will be subjected and to anticipate such occurrences in the design of the steam turbine, so that reliability and per-

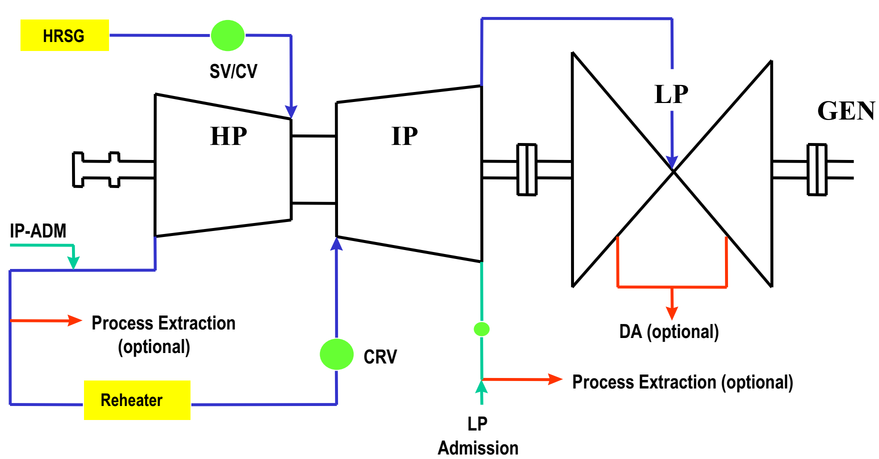

Figure 12. Schematic showing structured D-11 layout with possible extractions

formance targets are met. In addition to the guarantee point heat balance data, GE also requires the heat balance data at the maximum and minimum ambient conditions for which the plant will be designed. Simply put, cold air is denser than hot air, so that on a cold day the gas turbines will pass a greater mass flow and produce more power and exhaust energy. This in turn drives greater steam production from the HRSG, which results in greater flow to the HP turbine, and a corresponding higher throttle pressure. On a maximum ambient temperature day, the reverse scenario takes place, but the decreased steam production will result in potentially higher steam temperatures. Since the plant cannot operate safely at temperatures above 1050°F, excess heat must be handled by attemperation, or through features in the overall plant design. Therefore, at a minimum, the following three heat balances must be available:

1. Cold ambient day steam conditions.
2. Hot ambient day steam conditions.
3. Guarantee point steam conditions.

If these heat balances do not fully describe the operating envelope with respect to maximum throttle pressure and temperature, maximum and minimum IP and LP admission flows, and maximum and minimum process extraction flows, then additional heat balances will be required. This information is used to ensure that temperatures and pressures within the turbine steam path are accounted for in the design of the HP section, and evaluated against the pre-established design limits of the IP and LP sections.

Bypass System Information

Bypass system data is additional information necessary to successfully release any steam turbine for steam path design. Most modern combined-cycle power plants use the “Cascading” type of bypass system, for which the structured D-11 steam turbine may be configured as a standard option. Specific bypass system information required is:

1. Bypass configuration (i.e., cascading, or other configuration);
2. HP and LP bypass system capacities, expressed as a percentage of main steam flow; and
3. HRSG floor pressure (this parameter must be provided by the HRSG vendor).

This information enables the high pressure exhaust set point to be established, to enable bypass mode thermal modeling of the HP, IP, and LP turbines. This ensures that the low flow forward through the IP and LP turbines, and reverse flow through the HP turbine, do not cause overheating of any stages; a very important consideration in a machine already brought to 1050°F at the main steam and reheat steam inlets, and also continuing to rotate at rated speed. The floor pressure information is key to establishing:

1. Transfer point from reverse flow to forward flow in the HP section;
2. HP turbine exhaust temperature during the flow transfer operation; and
3. No excessive windage heating is occurring in the HP section during this low flow, high backpressure operating regime.

The bypass system flow information is then used to establish proper sizing for the HP reverse flow valving so that sufficient cooling steam will be available for all operating situations.

Advantages of Structured D-11 Steam Turbine

Delivery Cycle

Design standardization permits the structured D-11 steam turbine to be offered with 12 months ex-factory shipment from release date. Since the design of items which require long lead times will be essentially complete, GE will forecast reserve capacity and volume with experienced suppliers, resulting in shorter delivery cycles for rotor forgings, castings, and exhaust fabrications.

Customer Drawing Availability

Critical customer drawings will be available immediately after the customer gives GE notice to proceed. The product is specifically designed so that minor adjustments in the high pressure steam path to configure the turbine for the thermal cycle conditions of a particular application do not change the outline dimensions, component weights, sole plate layout or foundation loadings. This design consistency allows architect engineers and owners to get an early start on the turbine foundation design, overhead crane specification, auxiliary equipment placement, and design of piping and electrical systems.

Common Spare Parts

Spare parts inventory can be reduced from the levels required prior to standardization of the D-11's design. All possible variants of the structured D-11 steam turbine have common components throughout. Items such as valve stems, valve discs, journal bearings, thrust bearing, shaft end packing, interstage packing, spill strips, horizontal joint shell bolting, auxiliary system components and various gaskets will be common to all D-11 turbines.

Installation Time

Installation of the structured D-11 turbines has been simplified and will proceed more quickly than installation of non-structured turbines. When it is shipped from the factory, the HP/IP section of the turbine will be fully assembled with diaphragms and rotor installed and properly aligned, and with the horizontal joint shell bolts fully tightened. Delivering the HP/IP turbine pre-assembled saves about four weeks of field erection time.

Future Structured Applications

The structuring philosophy that was used to standardize the D-11 turbine is also being applied to other turbines being built by GE.

DX2

The DX2 is GE's new family of high-efficiency steam turbines, designed for both 207F and 209F applications. These new turbines feature separate casings for the HP and IP sections, while utilizing the LP sections that were developed in the structured D-11 design program.

A-10

The A-10 design consists of a single HP section and a combined IP/LP section and is used primarily in 107F and 109F multi-shaft applications. Although this design utilizes separate casings, it is compact, and has the additional feature of not requiring a crossover pipe.

DX4/GX1 Designs

GE is currently developing steam turbines for combined-cycle plants that are designed to operate with inlet conditions of 2400 psia (165 bar) and 1050°F (566°C). Although this increase in operating pressure requires use of more expensive balance of plant (BOP) components, the inherent benefit in overall cycle performance can outweigh the higher initial capital investment in certain operating environments.

As a result of the structuring process, GE's delivery cycle for these optimally designed steam turbines will be comparable to that of the structured D-11 line.

Conclusion

The structured D-11 steam turbine is a highly efficient, highly reliable, cost-effective steam turbine, configured specifically for 207FA or 209FA combined-cycles. Within the base design, there is allowance for significant variation on the basic three-pressure level reheat condensing cycle, while maintaining a 12-month ex-factory shipping commitment. The concept of product structuring has proven to be valuable on the D-11 turbine, and will be equally beneficial on future GE steam turbines.

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List of Figures

Figure 1.	GE's D-11 steam turbine
Figure 2.	Effect of hot reheat pressure on steam turbine output
Figure 3.	Relative steam turbine output vs. LP admission pressure
Figure 4.	Cross-section of the structured D-11 turbine
Figure 5.	Machining of HP/IP casing
Figure 6.	Assembled HP/IP rotor
Figure 7.	Tangential entry, “pinetree” dovetail bucket
Figure 8.	Diaphragm section
Figure 9.	Last stage bucket family
Figure 10.	Flow function vs. enthalpy
Figure 11a.	Output vs. exhaust pressure – 60 Hz
Figure 11b.	Output vs. exhaust pressure – 50 Hz
Figure 12.	Schematic showing structured D-11 layout with possible extractions

List of Tables

Table 1.	Structured D-11 configurations
Table 2.	Thermal application data
Table 3.	LP turbine data for structured D-11 steam turbines