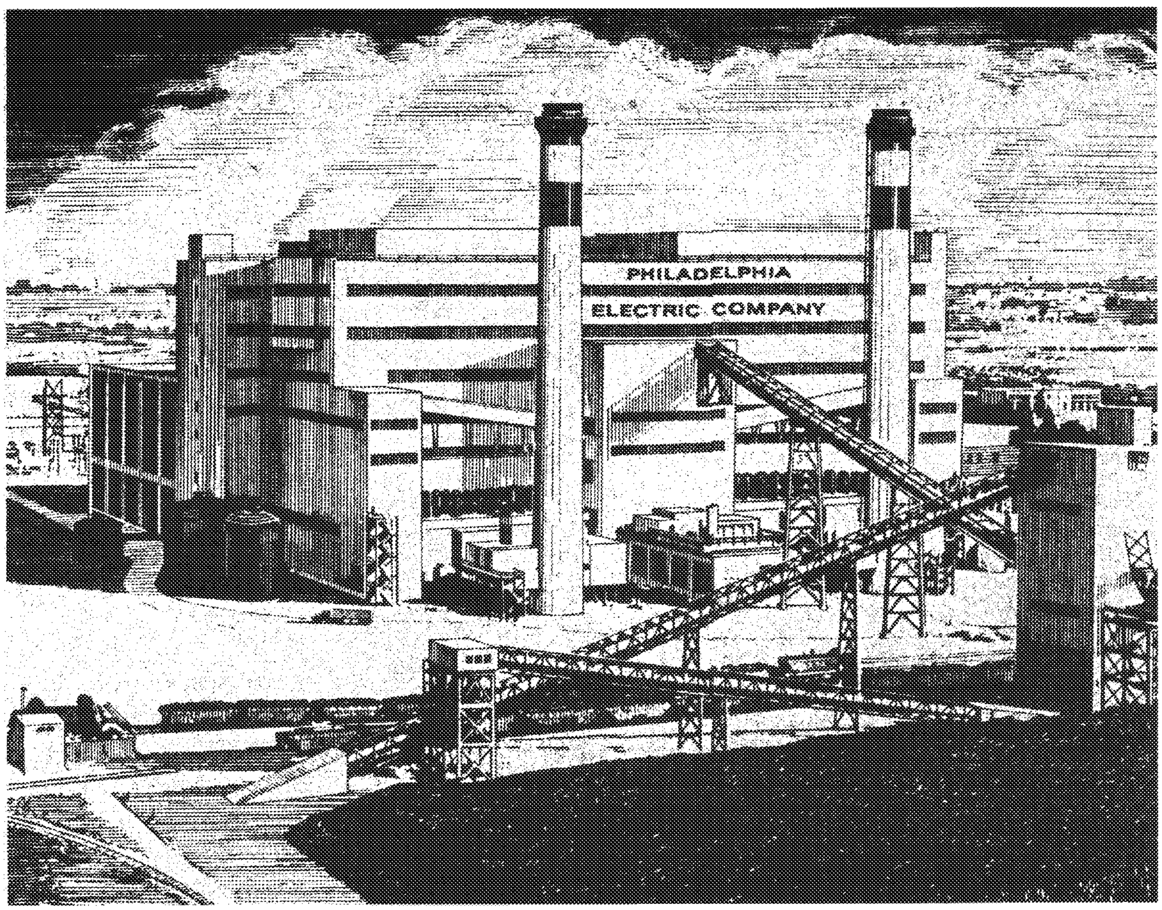
EDDYSTONE STATION, 325 MW GENERATING UNIT 1



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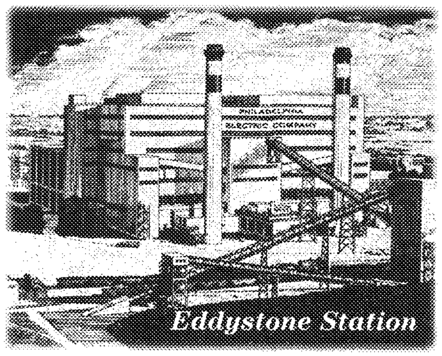
EDDYSTONE STATION, 325 MW GENERATING UNIT 1
A Brief History

by George J. Silvestri, Jr.

Introduction*

In the latter part of 1954, an agreement was reached among Combustion Engineering, Inc. (later known as ABB Combustion Engineering, now Alstom); Westinghouse Electric Corporation Steam Divisions (now Siemens Westinghouse Power Corporation of Orlando, Florida); and Philadelphia Electric Company (later known as PECO, now Exelon) to co-operate in the building of a (as initially designed) coal-fired, 3600 rpm, tandem compound, supercritical-pressure unit of 275 megawatt (MW) capacity (using 25 inch last row blades) with throttle steam conditions of 5000 lbf per square inch absolute (psia) and 1150°F and with two reheats to 1050°F [(1)] In rapid order other suppliers of equipment requiring greatly advanced technology were added. They were: (1) Ingersoll Rand (now Ingersoll-Dresser Pumps) for the boiler feed pumps;(2) Leeds and Northrup for the combustion controls; (3) M.W. Kellogg (now Kellogg Brown and Root, a division of Halliburton Co.) for the high-pressure piping; and (4) Graver Water Conditioning Company (now Graver Technologies) for the water treatment equipment and demineralizers.



The designated steam electric unit was Eddystone 1 and is located on the Delaware River at Darby Creek in Delaware County, approximately one mile from the City of Chester, PA. A drawing of the completed station is shown on Figure 1. The cover of the brochure contains a photograph of the completed station.

While it was recognized that materials in use at that time had been limited to about 1100°F in power-plant service, it was the opinion, based on previous experience, that suitable materials were available which would permit a 1200°F design in the critical highly stressed zones of the superheater and turbine rotor, and there was ASME code material which could be used for piping, control valve bodies, and in-line boiler stop valves.

* Non-technical readers are referred to the appendix for explanation of basic concepts and several key terms.

Overview

In the succeeding paragraphs a description is given of the design of the plant equipment and systems, followed by the operating experience in an attempt to give perspective to the prudent risk and judgment of the owner/operators of Eddystone 1 and the major suppliers of equipment and services. Considerable experimental work was undertaken to narrow the knowledge gaps in the materials properties data, much of which was shared with the broader engineering and industrial community.

New and innovative ideas were implemented along with widespread application of proven concepts in the feedwater train for example but to a greater extent than had been applied before. The steam generator and steam turbine were first time designs, and considering the advanced/pioneering steam conditions, Eddystone 1 rating was comparable to the larger conventional subcritical units that were being contemplated at that time.

Under the circumstances, operational difficulties, deficiencies, and unforeseen problems were to be expected, but the owner/operator and its suppliers cooperatively, diligently, and persistently confronted them as they occured. For the most part they were able to resolve the situations satisfactorily. While it became necessary to reduce the main steam temperature, it was the aggresive superheater and reheater corrosive attack on the fireside of the steam generator that led to this reduction.

The more conventional portions of the unit are not described herein and relate to the air handling system, the fuel delivery and combustion system, the electrical system, the heat rejection system and the stack gas cleanup system. These systems are an integral part of the unit operation. They are, however, standardized designs which are adapted to the specific application.

Did Eddystone fulfill its promise? From a 40 year retrospective view of a generating unit that is still a mainstay of the Exelon system, we believe that it did and we lay the following facts before you, our readers and those attending this dedication.

Design of Equipment and Systems

Selection of Unit Rating, Steam Conditions, and Cycle Configuration

A review of the Philadelphia Electric Co. system and its interconnection, as well as a thermal performance review, indicated that a 3600/1800 rpm cross compound turbine design with a size of about 325,000 kW would be appropriate and was cost effective. Moreover, substantially better thermal performance, about 150 Btu/kWh, was expected with the higher rating, from an increase in main steam temperature to 1200°F and the 3600/1800 rpm turbine configuration with 44 inch last row blades. All of these factors together led to the choice of a 325,000 kW cross-compound turbo generator and a steam generator with a design output of 2,000,000 Ibm of steam per hour.

The owner/operator characterized Eddystone 1 as a "Kilowatt-hour Mill." Eddystone 1, rated at 325,000 kW, was in the forefront of the largest conventional units being committed, 300 to 400 Megawatt electric (MWe) size range, at that time and which were designed exclusively for subcritical steam pressures (with throttle pressures in the 2000-2400 lbf per square inch gauge (psig) range).

A great deal of attention was directed to the various parts of the cycle in an attempt to minimize the plant heat rate (increase cycle efficiency). To this end, the pressure level of each feedwater heater, the use of drain cooler and heater desuperheater zones, the location of heater drains, and the disposition of pump and turbine shaft-seal drains, among many other items, were studied carefully. Also, a number of new and venturesome ideas were incorporated. Among these were arrangements for using lowest pressure turbine bleed steam to temper combustion air and for using a low-level economizer to heat condensate and thus lower the stack temperature to about 200°F.

The result of all of the design innovations and the increased main steam temperature as well as the higher rating and cross compound turbine configuration, was a final design heat rate of 8,320 Btu/net kWh with 1.0 inches of mercury absolute (in. HgA) backpressure at 325 MW gross generation, which included allowance for fuel used by the auxiliary boilers.[2] Eddystone 1 is still one of the most efficient steam generating units in the world.

Steam Turbine Arrangement

The 3600 rpm tandem compound turbine shaft consists of the SP (Superpressure) element and the combined VHP/HP (Very High Pressure/High Pressure) element and their associated electric generator system. The SP element received steam at 5000 psig, 1200°F and exhausted to the VHP section of the combined VHP/HP element at 2500 psia, 1000°F. Then the VHP section exhausted to the first reheater at 1133 psia and 790°F. Hot first reheat steam entered the HP section at 1043 psia and 1050°F and, after expanding, it exhausted to the second reheater at 283 psia and 705°F. A longitudinal view of the SP and combined VHP/HP elements is shown on Figure 2.

The second hot reheat steam, at 251 psia and 1050°F, entered the double flow 1800 rpm IP (Intermediate Pressure) element and expanded to 55.4 psia and 667°F, after which it entered the two single flow 1800 rpm LP (Low Pressure) sections with 44 inch last stage blades mounted on an 88 inch diameter disc.[3] These 3 elements drove the 1800 rpm generator system. An elevation view of the IP element and the two LP elements is shown on Figure 3. All of the steam turbine elements were

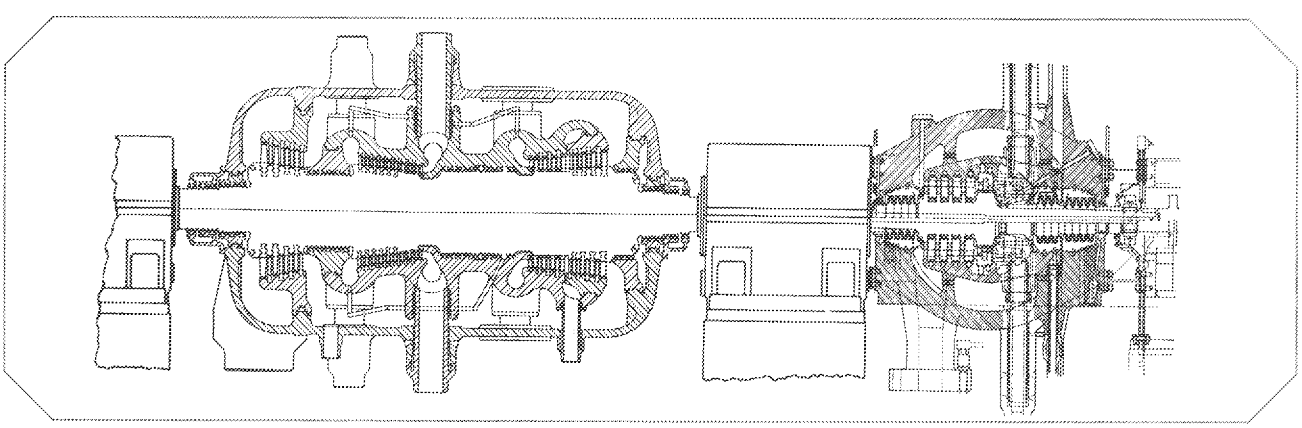


Figure 2: Cross-section of 3600 rpm turbines

new designs, specifically intended for the Eddystone 1 unit. In addition, the control, governor, and emergency valves had special functions on the Eddystone unit, which were necessitated by the once-through steam generator. At startup, it was necessary to maintain a minimum of 30% of design flow through the steam generator fluid circuits at a minimum throttle pressure of 3.500 psig. Consequently, it was necessary to bypass the turbine elements until the steam temperatures were compatible with reliable start-up operation of the steam turbine elements. Until these temperature levels were achieved, all of the flow was bypassed around the turbine elements to the condenser. When acceptable steam temperatures were achieved, the control valves were operated in a modulating mode, being partially open.

The bypass steam entered a special section of the condenser (injection cooler section) where it was desuperheated and its pressure dissipated prior to entering the main section of the condenser to protect the condenser from high pressure and high temperature steam. Bypass steam then entered the main section of the condenser, which it left as liquid water. From there the water returned to the feedwater train to begin a new circuit through the steam generator.[3]

The term "steam generator" is more accurate than the more familiar term "boiler." There is no fluid boiling when the substance is above its critical pressure, which is 3208.2 psia for water. Above the critical pressure the water changes from a liquid like substance to a vapor like substance, depending upon the pressure level and a so-called “transition temperature.” The differences in the state of the steam between a subcritical 2400 psi cycle and a 5000 psi supercritical cycle are illustrated on Figure 4. Note the absence of the constant temperature boiling that occurs in the subcritical steam during its passage through the steam generator. In contrast the steam temperature continually increases in the supercritical cycle as energy (enthalpy) is added to the steam.
On prior applications the interceptor and reheat stop valves (emergency valves) at the hot reheat inlets to the turbine elements were either fully open or fully closed. When satisfactory steam temperatures were achieved on Eddystone 1, the turbine control valves and the emergency valves admitted more and more of the 30% design flow until all of this flow was supplied to the turbine elements. This occurred in conjunction with an increase in generator excitation to increase electrical output. Steam flow was then increased until the turbine governing valves were wide open at 260 MW and a throttle pressure of 3500 psig.

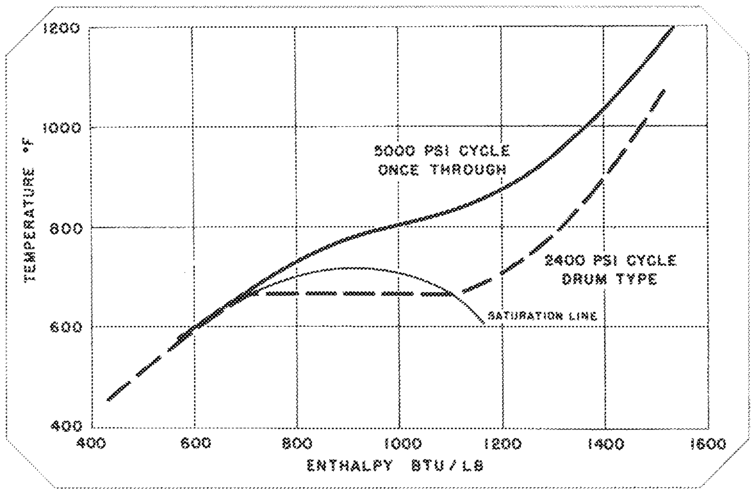


Figure 4: Temperature-enthalpy diagram 5000 psig cycle vs. 2400 psig cycle

Further increases in turbine load were achieved by ramping throttle pressure from 3500 psig up to 5000 psig and is known as sliding or variable pressure operation. This enabled the SP element to pass more steam flow. Use of sliding throttle pressure rather than operating at 5000 psig over the entire range of operation, reduced the pumping power and eliminated the throttling on the governing valves, thereby improving heat rate.[4][5]

The SP element had an austenitic stainless steel (Cr content of 12 to 18%) inner shell or casing and a ferritic steel outer casing. Its outer shell had a shape that approached that of a sphere whose material composition was conven-

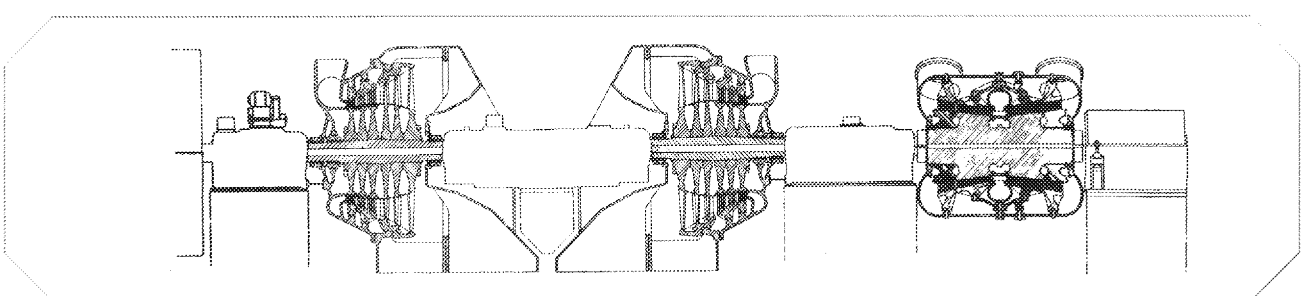


Figure 3: Cross-section of 1800 rpm turbines

tional 2-Cr, 1 Mo-V. The inner shell was made of Type 316 steel, as were the four 90-deg cast nozzle chambers and the valve bodies for the governing and stop valves. The outer shell is shown in light brown in Figure 5 while the inner shell is shown in gray. The semispherical outer shell of the SP element has the long inlet snouts attached to the base and cover halves and the exhaust pipe with an integral flange in the base half. The inner shell, next major structure as we move inside the SP element, contains the steam during its expansion from 5000 psig and 1200°F to 2500 psia , 1000°F. View (a) is a transverse view of the SP element. Type 316 discharge pipes from the governing and stop valves bodies were joined to the long inlet snouts of the ferritic outer cylinder by means of welded transition pieces as shown on the longitudinal and transverse views of Figure 5.

The transition pieces and their welds joining Type 347 austenitic piping and ferritic steels had an initial history of weld cracking during fabrication and while in service. Although these problems were brought under control, the much lesser sensitivity to cracking of transition pieces between Type 316 steel and ferritic steels was a factor in its selection. The operating experience has validated that choice.

The rotor forging for the SP element pushed the envelope for use of Discaloy (a Westinghouse aviation gas turbine alloy) because of the size of the rotor. As a consequence of initial uncertainty regarding success in obtaining a suitable forging, a backup investigation was initiated which involved the development of a suitable forging with high temperature properties similar to Discaloy and two backup rotor materials with limited life.[6] A major concern related to precipitation of the alloying elements at the crystal boundaries and segregation (freckling) of the alloying elements. A successful Discaloy forging was produced by Bethlehem Steel Co. and was, in part, a success because of a unique shaft seal design that shortened the length of the shaft ends. The unique shaft seal design is shown on View b of Figure 5.

The first turbine stage of the SP element was a fixed-arc admission design in that all of the nozzle chambers and their governing valves were activated together. Partial-arc admission would enable steam to be admitted independently to each of the nozzle chambers so that some chambers would be receiving steam while others would not. While this would improve part load efficiency, the partial-arc admission forces would result in excessive deflection of the relatively light Eddystone SP rotor, and blade shock loading was high enough to be of some concern.

Today, supercritical pressure turbines with more modest steam conditions (3500 psig throttle pressure and steam temperatures in the 1000°F to 1050°F range) routinely operate successfully with partial-arc admission.

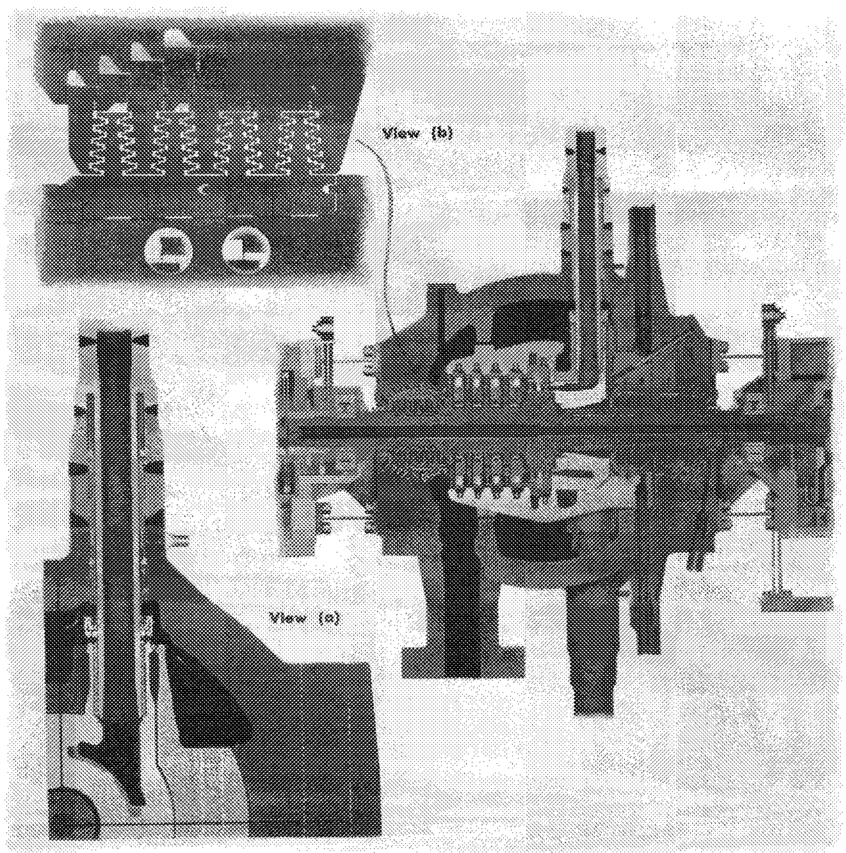


Figure 5: Longitudinal section – SP turbine element

Steam Generator Control System/Control Valve Development, and Water Purity

One of the most essential items was a steam turbine/steam generator control system which could be integrated carefully with the design of the steam generating equipment. An intensive series of reviews indicated that the principles employed by Sulzer Brothers of Switzerland were best suited to the steam generator needs. In addition, a broad research program was conducted relating to the problems associated with water purification and metallurgy for high-temperature, high-pressure steam.

The twin furnace steam generator design was adopted to enable independent temperature control of each reheater, which avoided the necessity fox spray desuperheating, thereby maximizing cycle efficiency and, at the same time, providing constant reheat temperature over a wide range of load levels. A vertical cross section of the steam generator, which is almost 200 feet in height, is shown on Figure 6 .

In the supercritical-pressure cycle using the once-through principle, the boiler and turbine must be closely integrated as a unit. A combustion control method was developed by Leeds and Northrup to accomplish this. The turbine-bypass system provided adequate cooling of all steam generator heating surfaces during cold and hot starts and permitted the development of proper characteristics of the steam before it was admitted to the turbine.[7]

The entire turbine-bypass system was initially designed to permit operation of the steam generator at 30% of its design capacity with full primary pressure and temperature with the turbine bypassed completely. As power is generated by the turbine and the power output is increased above the 30% flow capacity, the turbine governor valves at the throttle and the hot reheat inlets introduced an increasing fraction of the steam flow into the turbine elements until all of the steam was utilized by the turbine. This required a high degree of complex integration of the turbine, steam generator and bypass system controls. A simplified flow diagram of the steam system, Figure 7 on page 5 reveals the complexity of the controls and start-up system and the interfacing equipment. Later, the startup procedure was revised so that the pressure at the turbine inlet was maintained at 3500 psig until the governor valves were wide open.

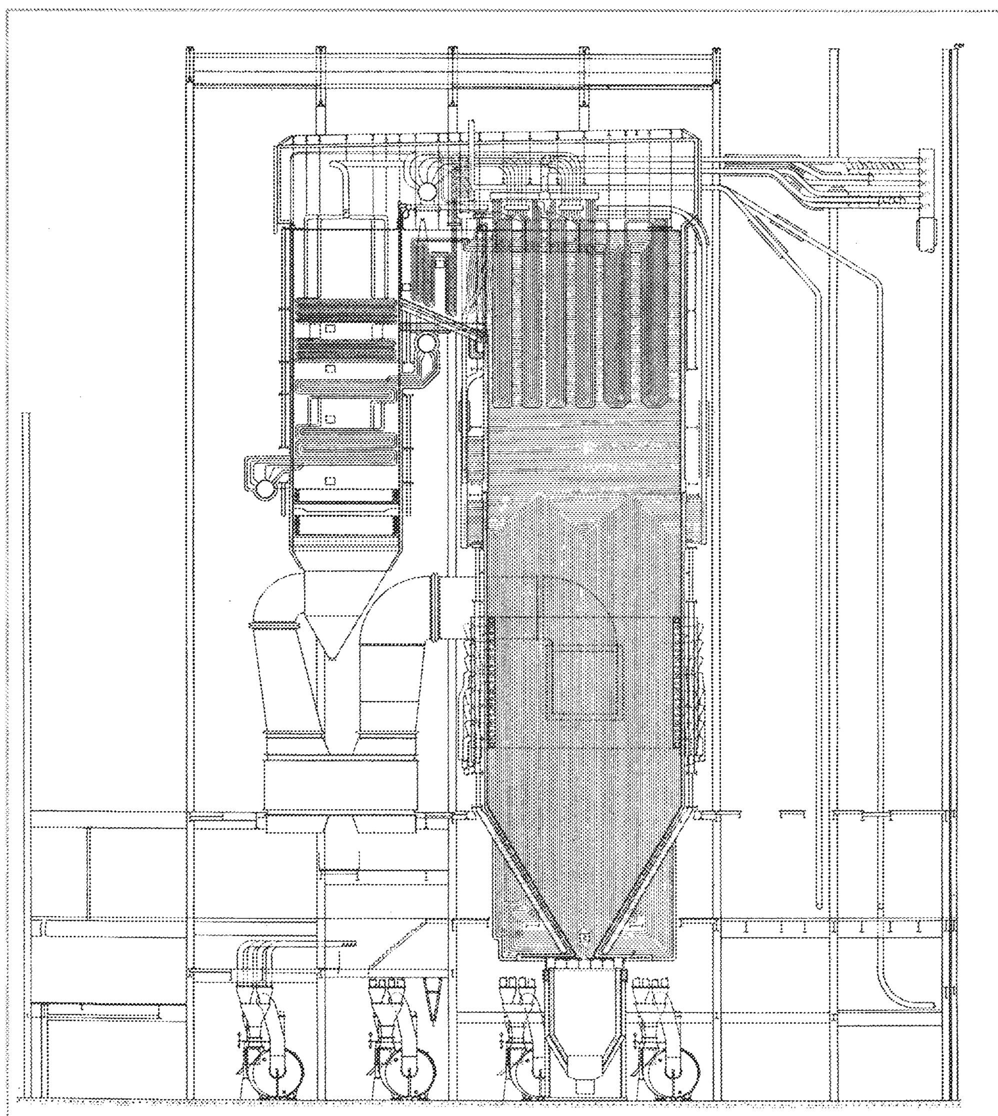


Figure 6: Supercritical pressure steam generator- side elevation

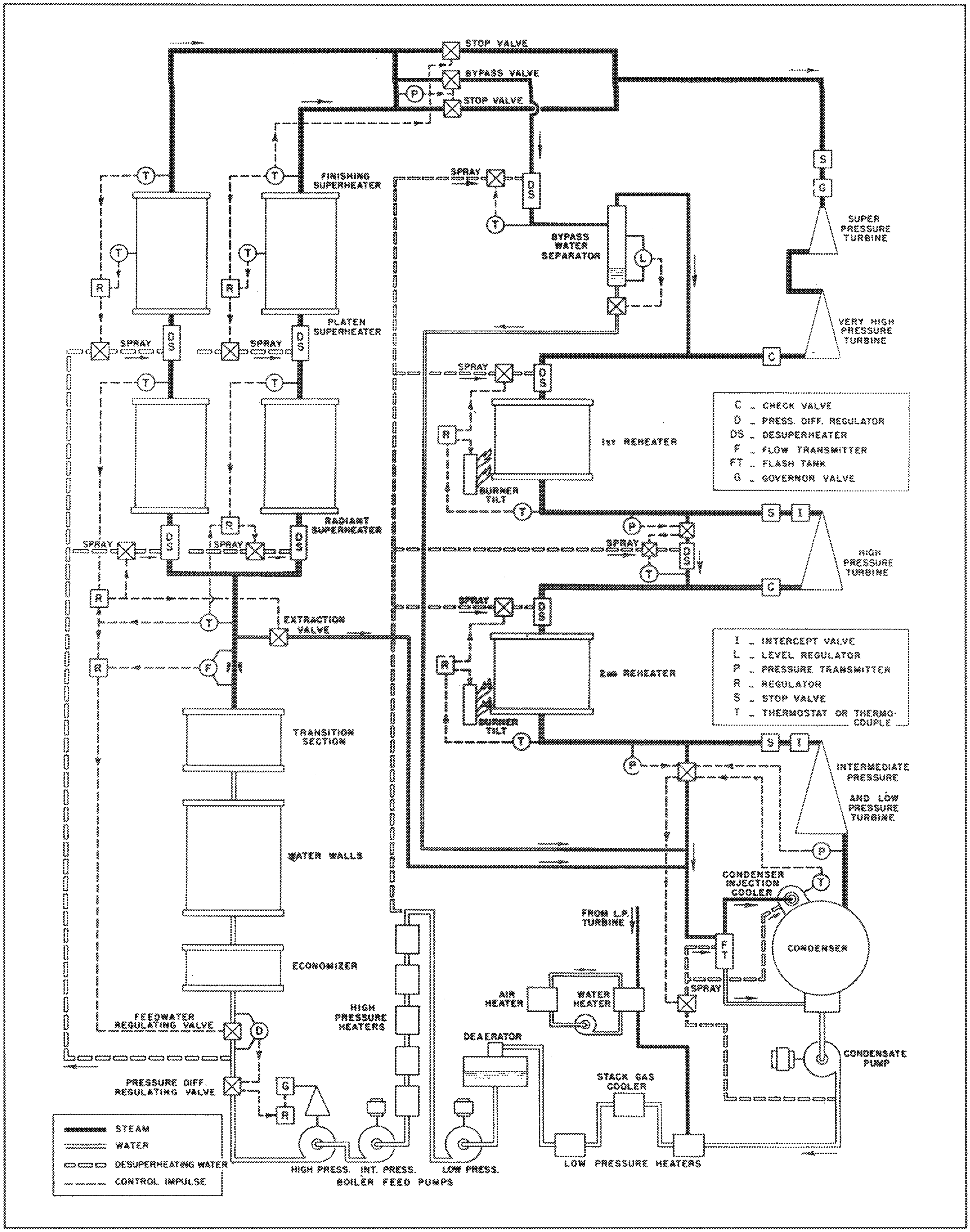


Figure 7: Simplified flow diagram, showing controls and startup-system

For steam generator components that exceeded the 1150°F maximum temperature for Type 316 steel steam generator tubes and where the expected tube-metal temperature was 1300-1350°F an investigation led to the selection of 17-14 CuMo steel, an alloy developed by the Armco Steel Co. during World War II. On the basis of the existing data and completion of a test program, this steel was selected as the most suitable alloy available for the finishing superheater at the time of the Eddystone application.[8]

Because Type 316 steel would result in excessive wall thickness of the Sulzer valve bodies for the Sulzer control valves, a non-ASME-Code material of higher strength, G-18B, developed by William Jessop Co. of England, was selected for investigation. The material test program, both fabrication and heat treatment, revealed that this material met the design criteria.[8]

Correct pressure drop calculations were especially important for the Eddystone 1 steam generator design because of the unique waterwall panel design, adapted from European practice. Tubes leaving the waterwall inlet header made eight up and down passes of more than 80 feet each to reach the outlet header. This vertical "ribbon panel" arrangement was new in the US and presented unusual problems of support as each vertical pass was hotter than the preceding one. Expectations were that the concepts used in designing the support system were sound.

Because of the once-through steam generator design, the permissible measured quantities of water contaminant concentration were extremely low in terms of past practice. Some maximum contaminant levels had to be in the order of 20 ppb (parts per billion) level while the typical operating levels were as low as 2 ppb, e.g., silica, SiO_2. In addition, the solid matter in the system had to be minimized to prevent objectionable deposits in the steam generator and the turbine. Maximum levels for the total dissolved solids in the steam were 50 ppb with typical levels of 20 ppb. Measures undertaken to prevent the deposits were (1) a condenser design in which leakage was controlled and isolated; (2) metal pickup from corrosion was controlled by limiting dissolved oxygen and maintaining pH levels; (3) makeup water was demineralized to achieve extremely high water purity; and (4) control of the presence of organic resins in the demineralizers.[9]

To validate the behavior of pure water and possible contaminants, two test steam generator installations were placed in operation to conduct a series of experimental investigations. The first installation was in the laboratory of Sulzer Brothers in Winterthur, Switzerland, and confirmed that if deposits were to be avoided, solids must be eliminated from the feedwater. The second experimental supercritical pressure steam generator, installed at the Combustion Engineering Kreisinger Laboratory in Chattanooga, Tennessee, as a joint project with Philadelphia Electric Company, supplied steam to a simulated turbine rig to study deposit formation as steam expands.

Feedwater Train Design and Configuration

The feedwater train, with 9 stages of feedwater heating, produced a water temperature of about 560°F leaving the top heater at rated load, which was considerably higher than predecessor units and has not been surpassed by any plant since then in the United States. The heat exchangers and pumps comprising the feedwater train, as well as the water temperature at various points in the feedwater train, are illustrated in Figure 8. In addition to the condensate pump in the feedwater train, there were three boiler feed pumps: low, intermediate and high pressure. The suction and discharge pressures and temperatures of the various pumps are shown on Figure 9. The low and intermediate feed pumps were driven by constant speed motors while the high pressure boiler feed pump (BFP)

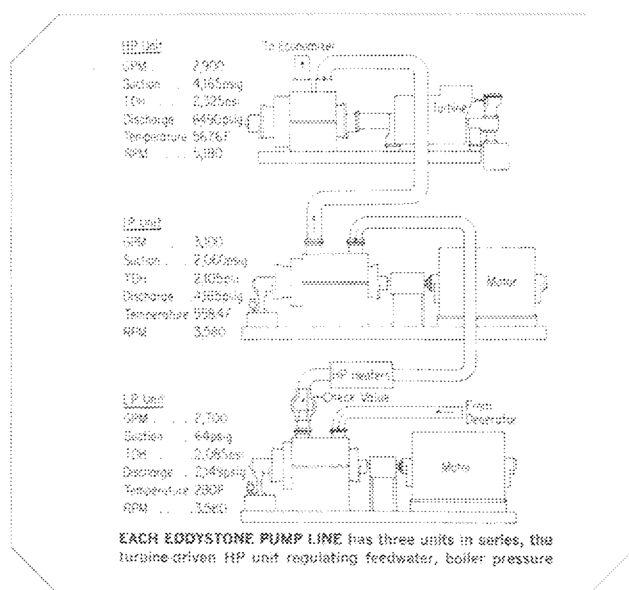


Figure 9: Eddystone feedwater pump arrangement

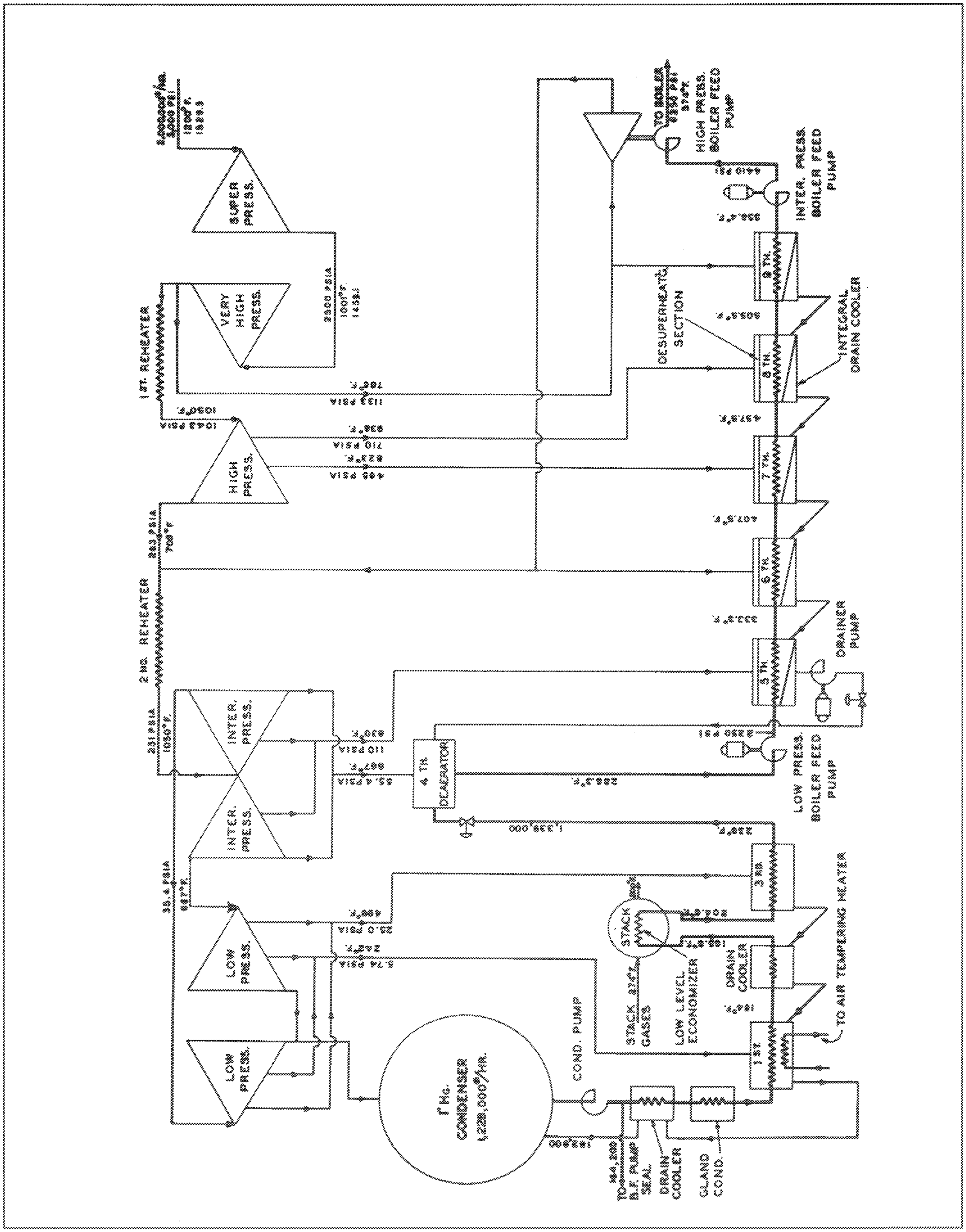


Figure 8: Single - line arrangement of feedwater heaters and pumps

configuration was novel and featured a variable speed steam turbine as the high pressure boiler feed pump drive (BFPT). The non-condensing BFPT was an integral part of the feedwater train and its exhaust supplied steam to one of the stages of feedwater heating See Figure 8. This non-condensing arrangement, carried to its ultimate conclusion on later plants, supplied steam to as many as 3 stages of feedwater heating. The low level economizer (stack gas cooler) provided the heat for the second stage of feedwater heating. This innovation was later discontinued because of fly-ash deposits and corrosion of this heat exchanger.

Main Steam Piping

A comprehensive study by the M. W. Kellogg Co. of various high temperature stainless-steels and super strength-alloy compositions covered not only the available mechanical and physical properties of each, but also their equally relevant manufacturing, fabrication, and service histories. This led to the selection of Type 316 steel for the Eddystone 1 main steam piping.[10][11]

An intensive test program was conducted regarding the weldability stability (mechanical and structural), and heat treatment of the Type 316 materials and other candidate steels. The outer diameter of the 2500 feet of main-steam-pipe was more than twice as large as the pipe internal diameter on all 4 pipe sizes fabricared for the plant.[10] Three of the pipe sizes had an inner diameter (ID) of 4.0 inches with a wall thickness of 2.345 to 2.525 in. The fourth size piping had an ID of 4.938 inches and a wall thickness of 2.860 in. The walls of the pipe were so thick that a typical cross section, shown in Figure 10, resembles the gun barrels of a battleship. The wall thickness of the junction header near the steam generator, Figure 11 on page 9, also attests to the requirements of the main steam elevated pressure and temperature in the plant The proven reliability of the main-steam-piping is a tribute to the thoroughness of the investigations conducted prior to its installation.

Material and Fluid Properties

The mechanical properties of the materials used in the fabrication of the equipment were researched and verified intensively by the various supplier organizations. We begin with the understanding that all measurements have errors. Data on material properties have a level of uncertainty reflecting the variability of various batches of the materials, deviations in the processing of the materials, the inherent error in the measurement devices and the reproducibility of the data obtained from the equipment used to evaluate the properties. This uncertainty has a bias component and a random or precision component. Bias is the systematic error that is constant for the duration of the material evaluation, while precision errors are observed in repeated measurements that do not, and are not expected to, agree exactly because of numerous error sources.

Scatter in the data is a reflection of the uncertainty. Which data points to include or exclude is a matter of engineering and scientific judgment. Procedures for conducting tests of materials and the allowable stress levels are reflected in the ASME Codes and Standards, the methodology of ASTM (American Society for Testing and Materials) and ANSI (American National Standards Institute)

In many instances the manufacturers used proprietary data in the design of their equipment, which were not available in the public domain because of competitive concerns. In the case of Eddystone the results of the extensive research program for the verification of the main steam piping selection were shared with the industry and reported in ASME publications, permission being granted by the Philadelphia Electric Co.[10]

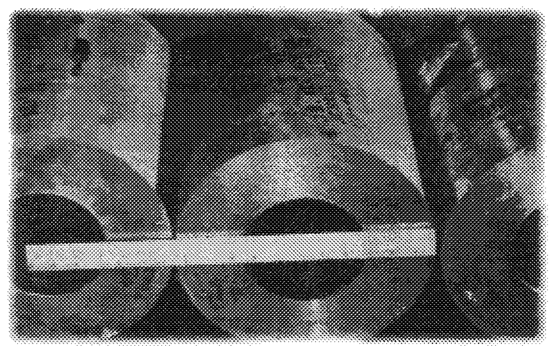


Figure 10: Pipe sections showing massive thickness. Ruler is 18 inches long.

steam properties were also of concern as supercritical plants like Eddystone and, to a lesser extent, the highest pressure, subcritical pressure units operated at steam conditions that were beyond the temperature and pressure range of the experimental data that were the basis of the existing steam tables. The data for these out-of-range steam conditions were based on the extrapolation of the correlating equations developed for the range where valid and authoritative experimental data were available. Over some portion of the tabulated data in the existing steam tables, graphical techniques were employed to obtain best guess values, where the correlating equations results were Suspect.[12]

Concern over the adequacy of the data in Reference 12 led to the formation of an ASME Subcommittee to develop an interim steam table using existing data. The ongoing

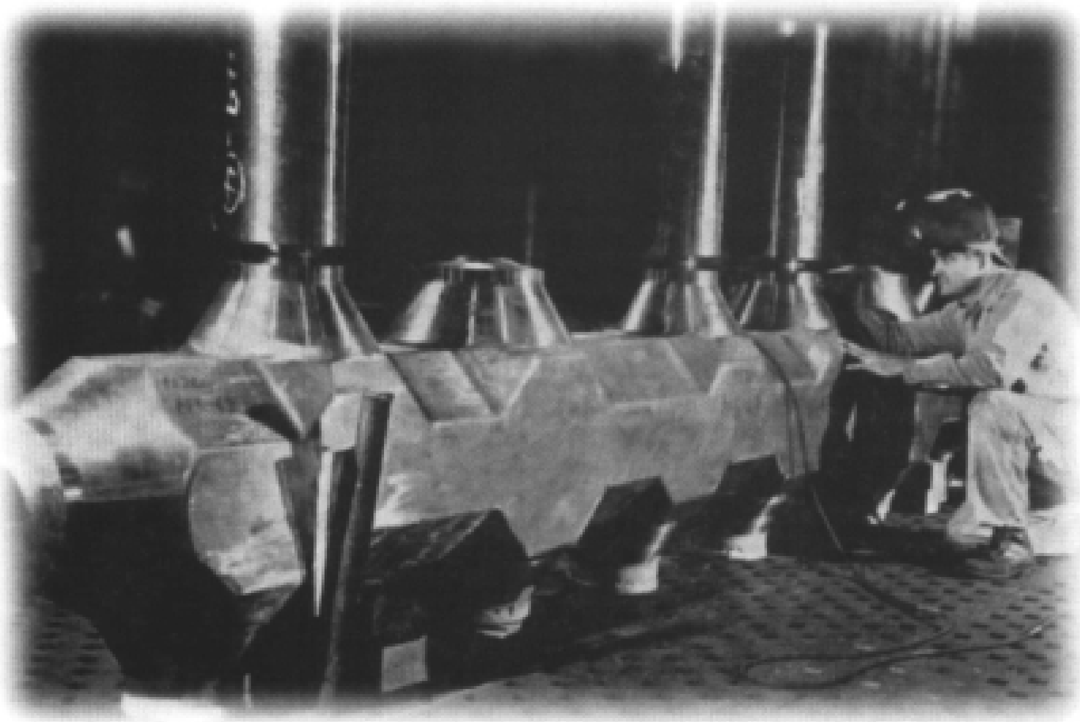


Figure 11: Weld pass between junction header and four stub ends

international effort to develop new steam properties data was estimated to require 4 to 6 years to complete the experimental work leading to an authoritative steam table to 1500°F and 15,000 psia. Thus, development of an interim steam table was mandated by the ASME Subcommittee late in 1955.

To facilitate the development of the interim steam table, the following program was initiated. To the Westinghouse Electric Corp. fell the task of determining the specific volumes of the fluid. The General Electric Co. calculated the thermodynamic properties, enthalpy and entropy, from the specific volumes by numerical methods using a high-speed main frame electronic computer. Because of some inconsistencies in the body of data available to develop the specific volumes, there were several iterations between the computer results and the specific volume data to eliminate the anomalies in the base data and produce more thermodynamically consistent results. [13][14][15] Allis Chalmers Manufacturing Company checked the reliability of the data by determining specific volumes, enthalpies and entropies using different methods from those employed by the Westinghouse and General Electric engineers.

The use of electronic computers in engineering work was quite limited at the time Eddystone was committed by the Philadelphia Electric Co. (PECO).

Computer programs for mechanical design and analysis were initially applied for the less complex structures and utilized the simplified models used for manual calculations. As time progressed, a major step forward occurred with the use of finite difference numerical methods, which allowed the analysis of more complex structures. In more recent years, this approach has been replaced by a more powerful tool; finite elements. Also with the increased size and speed of computers, modeling the total irrotational flow field of entire turbine blade paths became commonplace.

For thermodynamic evaluation of equipment performance, a fundamental basis had to be codified, the thermodynamic properties of steam. Two ASME papers presented the means for determining fluid properties with electronic computers.[36][37] The time frame, when these computer programs were available, greatly limited the use of computers for the thermodynamic design and evaluation of Eddystone 1. Consequently, the manual use of the tables and graphs (temperature-entropy diagram, enthalpy-entropy diagram, and pressure-volume product plotted versus enthalpy for example) was a major tool in the design and performance predictions for the steam turbine, steam generator and other equipment that used steam as a working fluid.

Data on air and combustion gases, used in steam generator design and handling of these fluids, were more tractable as those gases were more readily correlated because of the weak pressure dependence of the thermodynamic properties. Such is not the case for steam properties because of their sizeable pressure dependence. In some cases judicious selection of the correlating parameters greatly simplified the charts needed for manual calculations.

Computerization of steam turbine cycle thermal performance required the development of calculational elements that represented such mundane processes as pressure drops, heat addition and heat rejection, and simplified models for the heat exchangers and pumps in the feedwater train. The development of simplified models for the turbine (blading and sealing systems) followed after Eddystone was built and operating. Eddystone was truly a great engineering achievement.

Uncertainties in the application of the Keenan and Keyes Steam Tables were evaluated when the *1967 ASME Steam Tables* were available, the culmination of several years of steam properties research [12][18] The calculated performance of the steam turbine and its cycle was about the same regardless of which steam table was used.[19]

The situation was different when the evaluation of test data was considered. The calculated heat rate with each steam properties table differed by about 0.2% for throttle steam conditions of 3500 psig, 1000° F with the heat rate being lower with the *1967 ASME Steam Tables.*[19]

In addition to the thermodynamic properties, the data for what are known as the "transport properties" of steam, viscosity and thermal conductivity, covered only a limited portion of the pressures and temperatures that needed investigation and verification. Viscosity is used in the determination of pressure losses in conduits (pipes, tubing and ducts) and the calculation of heat transfer rates. Thermal conductivity, as the name implies, is used to determine heat transfer. The calculated results from the correlating equations in the Keenan and Keyes Steam Tables, Reference 12, were inadequate. As a result of the extensive international steam properties research program following World war II, the International Association on the Properties of Steam issued a “Supplemental Release on Transport Properties" in November 1964. The release had correlating equations that covered most of the range needed. In addition, some of the data points had significantly large uncertainties (tolerances), which were outside the acceptable limits of the correlating equations.

To increase the usefulness of *The 1967 ASME Steam Tables*, Reference 18, a set of computer algorithms (subroutines and functions), which included direct, indirect, and derived steam properties relationships, was presented in a paper at the ASME-IEEE Joint Power Generation Conference in September 1967. This paper was later published in an ASME booklet.[21] An update was presented at the ASME Winter Annual Meeting in 1969,[21]

Since the correlating equations for the transport properties did not cover the entire region of interest, the authors of Reference 21 used graphical techniques and tabular interpolation for the region not represented by the correlating equations. The rationale was that data with greater uncertainty than desired was better than no data at all. Moreover, this approach yielded better results than the correlating equations presented in the Keenan and Keyes Steam Tables.

Plant Operational History

Plant Thermal Performance

Eddystone went into commercial operation on February 5, 1960. Eddystone 1's record performance of 8,743 Btu/(net)kWh in 1961 and the 8,534 Btu/(net)kWh in 1962 was due in part to the low level economizer in the feedwater train. Operation of this heat exchanger was satisfactory during the 1961-1962 time frame,[22] Included in the 1962 heat rate is 50 Btu/kWh for auxiliary-boiler steam for soot blowing and miscellaneous uses. Unit availability was 82.6% and its average load was 331 MW in 1962 vs. the 325 MW rated load [23] At 2,000,000 Ibm/hr steam generator flow, the design heat rate was 8,230 Btu/kWh, however the best measured heat rate was approximately 8,530 Btu/kWh. A diagram known as a heat balance, Figure 12, reveals the operating conditions of the plant equipment (pressures, temperatures and flows) at maximum generator output.

Steam Turbine

Once the initial shakedown problems were corrected, the unit ran very well with 1150°F main steam temperature. ASME field economy tests demonstrated that the steam turbine met its performance guarantees. The tests, conducted in the summer of 1961 and during operation at 5000 psi and 1150°F, substantially bettered the expected performance. These and additional tests showed all turbine elements were performing in line with expectations at both 1150°F and 1200°F [23] A photograph of the turbine room, Figure 13, illustrates the

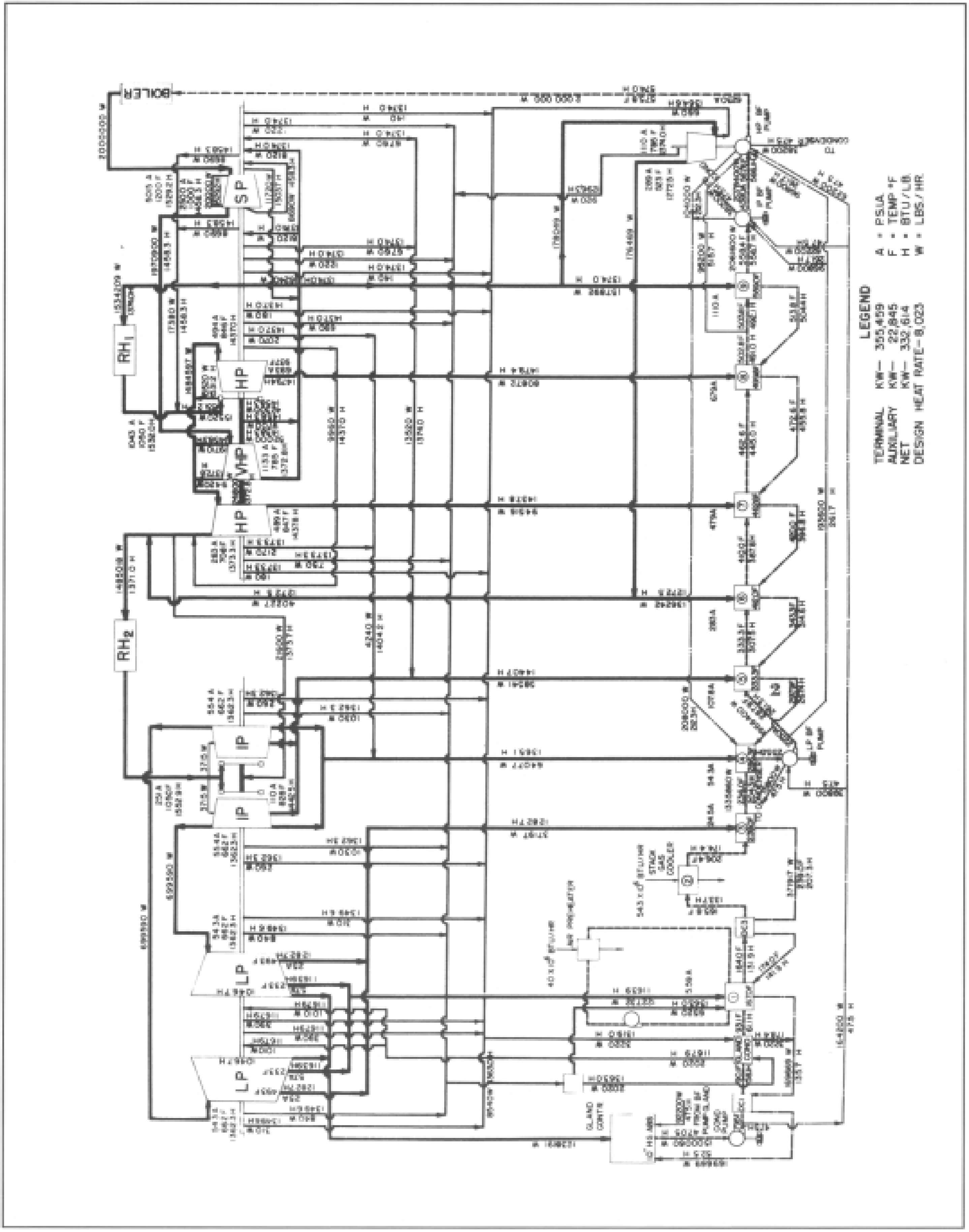


Figure 12: Heat balance diagram - Unit No. 1

size of the equipment. The man is standing ahead of the SP element in the foreground while the 1800 rpm elements are shown in the background.

Up to and including December 31, 1962, the SP Discaloy rotor had performed very well through many load cycles and as of this same date had accumulated approximately 19,000 hours of operation, of which 9,000 hours were with 1200°F at the main steam inlet.(2) Main steam temperatures had been held at 1150°F for about a year after attaining full-load commercial operation to obtain experience at this temperature prior to steady operation at 1200°F.(2)

The nozzle block of the first stage of the SP element exhibited more serious erosion than any other units on the Philadelphia Electric system.(2) A replacement nozzle block was installed in 1963, some time after the publishing of "The Eddystone Story" in *Electrical World magazine.*

In the mid 1960s several instances of SP turbine rotor vibration (due to seal rubbing) and instability resulted in damage to the nested seals at the shaft ends (view b of Figure 5). As a consequence, steam blew out of the shaft ends, necessitating a unit shutdown. Each shutdown required disassembly of the SP element, removal of the rotor, disassembly of the nested seals, replacement of the damaged seals, reassembly of the nested seals, installation of the rotor and reassembly of the inner and outer cylinders or shells.

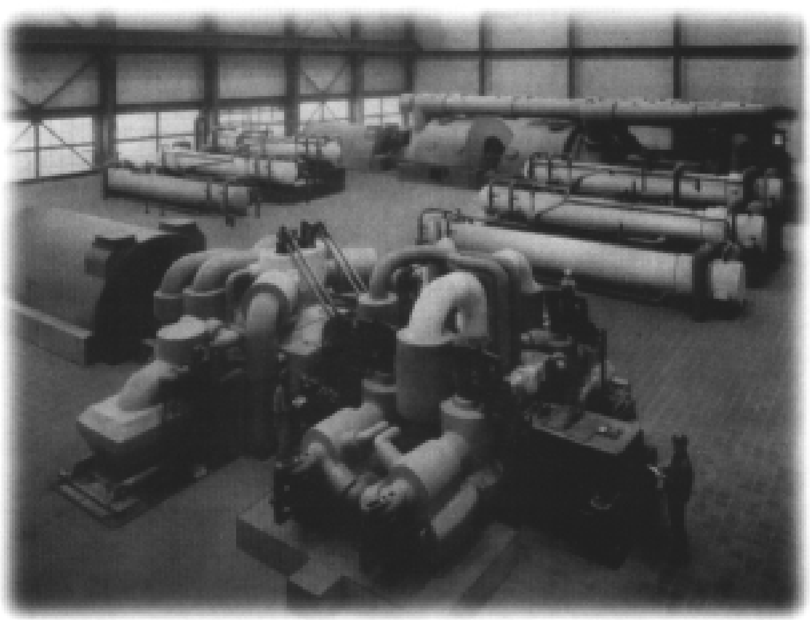


Figure 13: Turbine room at Unit No.1

Inspection of the SP austenitic inner shell, light brown portion of Figure 5, revealed distortion of this part. Austenitic steels have low thermal conductivity and a high thermal expansion coefficient as compared to ferritic steels, making them susceptible to distortion when local heating or chilling occurs. In addition, the rigid nature of the nested seals and their susceptibility to friction or seal whirl could cause the vibration. Moreover, the power to weight ratio of the SP rotor was suspect as an unfavorable condition in preventing rotor whirl.

Two corrective actions were adopted. One approach involved the design and manufacture of a new austenitic inner cylinder, which reduced the possibility of local heating or chilling and thereby reduced the susceptibility to distortion and, in turn, could result in shaft rubs. The combination of high thermal expansion and low thermal conductivity, which increases the susceptibility to distortion, presents a major challenge in the design of austenitic pressure vessels. The new inner cylinder used an advanced shell design computer program that was a major improvement in Westinghouse pressure vessel design.

The other approach involved the removal of the nested seals and their replacement with conventional spring backed labyrinth seals. This resulted in fewer effective shaft seals and consequently higher shaft leakage. A heat rate penalty of about 35 Btu/kWh was expected. Considering the degradation in plant annual heat rate that resulted from each startup and shutdown, there would be little or no increase in plant annual heat rate, if that number of forced outages were reduced. It was estimated that a cold start on Eddystone 1 results in an economic loss of 345 tons of coal.(4) Therefore, reducing the number of forced outages has a beneficial effect on plant annual heat rate.

Both corrective actions were implemented, and subsequent operation verified the absence of the vibration and instability that was present prior to the modifications. The question remains: Which of the modifications eliminated the problem? Was it a combination of both? Or was the most probable root cause related to neither of the corrective actions? It was evident that operation at 1150" F was more reliabIe than operation at 1200°E [2,22,23] Moreover, rotor vibration and instability were experienced following operation at 1200°F. However, it is not possible to conclusively identify the actual root cause of the vibration and instability. There are ardent supporters of one or the other turbine modifications as being the solution.

When both modifications were made to the SP element, the decision was made to reduce main steam temperature to 1130°F because of fireside corrosion of the superheater and reheater surfaces. If the temperature reduction eliminated the most probable cause, the other corrective actions would still be beneficial if an increase in main steam temperature to 1150°F were implemented. This will be discussed in greater detail in the section on steam generator operation.

Copper deposits, found on the turbine blades in the SP element and the initial stages of the VHP turbine, were an unanticipated development. The distribution of the deposits and their composition is illustrated on Figure 14. Copper buildup reduced the blade passage flow areas, resulting in a reduction of flow capability of about 7% prior to the disassembly of the SP and VHP/HP elements in the spring of 1962. There was only a slight reduction in VHP efficiency accompanying the presence of the copper deposits. Consequently, the heat rate increase was very small. [2,23] In addition, it was found that the copper deposits flaked off and increased turbine capcity when the turbine was cooled and restarted.[22]

Throughout the 1960's, Eddystone 1 provided the best annual heat rates in the nation. However, as a result of add-on environmental control equipment and diminished coal quality, plant heat rates were less than exceptional during the 1970’s and 1980’s. In the early 1990’s, a major modernization program was undertaken, and in 1995 a replacement SP rotor was installed. To eliminate the alloying element segregation, a potential problem with superalloys like Discaloy, a rotor material composition that represented the best characteristics of A286 and Discaloy was selected. Discaloy had much greater high temperature capability than was needed for 1200°F.

During a startup in 1993, the VHP section of the combined VHP/HP rotor experienced windage overheating that caused some of the rotating blades to fail. Temporary repairs were made to the rotor, allowing operation at a reduced load of about 230 MW. A replacement rotor was manufactured and installed in 1995 during the same outage when the replacement SP rotor was installed.

Steam Generator Operation

Steam generator tests indicated the overall efficiency met its guarantee. This is an achievement considering the aggressive environment of the fireside of the steam generator and the uncertainty regarding the thermodynamic properties of steam. The behavior of ultra pure water also became a source of concern because of the leaching out of alloying elements from the internal surfaces of the structures involved with heat transfer.

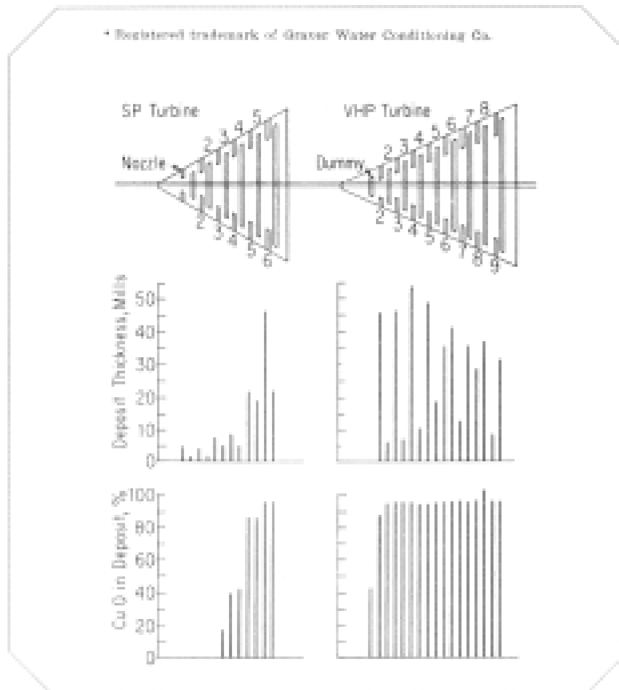


Figure 1.4: Metallic deposits in final stages of SP and all of VHP elements showing high copper content

Experience with the 17-14 Cu-Mo steel tubing for the platen and finishing superheaters was most satisfactory for the period covered by the reporting in the series of technical articles in “The Eddystone Story”, *Electrical World*, March 11, 1963.[2,22,23,24] This material continues to be satisfactory after more than 40 years of operation.

There were some initial steam generator problems with the finishing superheater during operation at 1200°F which were related to fabrication defects and welding procedures. Similar causative factors were identified as the culprits in some failures of Type 316 and type 321 steel boiler tubing. Actions were initiated that corrected the problems. [2] The conventional high pressure (HP) reheater was replaced. In the early to mid 1960's, it was observed that fire-side corrosion was occurring in the steam generator superheater and reheater surfaces. The fireside corrosion was brought under control by reducing the main steam temperature to 1130°F. Main steam pressure was reduced from 5000 psia to 4800 psia to keep steam flow to the SP turbine element constant. Cracking of the steam generator stop valves was eliminated by redesign with a new material.

Currently, the unit is operating with the main steam pressure in the 5000 to 5100 psia range and 1130° temperature. Although there has been talk of operation at 1150°F, where the unit had operated reliably for over 1 year (approximately 10,000 hours), there was evidence of tube wastage and pitting of the platen and pendant superheater sections in certain areas at 1150°E [25][26] Since the fireside corrosion occurs over a limited range of tube metal temperatures, the selection of 1130°F steam temperature reduces the possibility of severe attack.

There was some concern as to whether the physical and thermal properties of supercritical steam were known with sufficient accuracy to perform satisfactory design of the steam generator heating surfaces. Actual operation proved that the calculation of pressure drop and heat absorption drop had the necessary accuracy for this application. In contrast, a number of later coal fired plants had severe slagging problems because of overly optimistic heat transfer predictions and had to reduce the continuous operating output by as much as 15% from the output that was possible if slagging were not present. These plants had the benefit of the improved transport properties data from the *1967 ASME Steam Tables* and the published computer algorithms in References 20 and 21.

Welds

Inspections of the piping joints, both shop and field welds, were made during plant outages. At the time The Eddystone Story" was published in *Electrical World*, over 80 separate examinations had been made, revealing no cracking or other serious indications of deterioration in the weld between similar types of materials, e.g., austenitic steels to austenitic steels. The inspections consisted of visual and dye-penetrant examination.[27]

The only imperfections found were in 4 dissimilar welds that connected super pressure bypass ferritic piping to the austenitic main steam system at the junction header, Figure 11. Although dye-penetrant and radiographic techniques did not reveal any defects in the as-welded condition, dye. penetrant examination in March 1960 revealed the imperfections. A few additional imperfections were discovered and removed in The subsequenr period covered in “The Eddystone Story."[27]

Feedwater Train

The low level economizer experienced fouling of the muffs (cast iron fins to enhance heat transfer). Weekly water washing was employed to control fine ash deposits on the muffs. There was some corrosion of the muffs, which was initially moderate although the corrosion was more severe at the stack gas outlet from the low level economizer. After about 9 months of service, most of the coatings on the cast iron muffs had deteriorated so that they offered no corrosion protection. Subsequently, the low level economizer was removed from service because of the corrosion and plugging concerns.[28]

The injection cooler section of the condenser, a necessary part of the bypass system, proved inadequate as originally conceived and fabricated. The original horizontal, in-line, venturi-type desuperheater was replaced with one of vertical, multi-nozzle design with provisions for adequate water removal and operated satisfactorily.[29]

The source of the copper deposits in the turbine was attributed to copper alloy tubes in the feedwater heaters. The Monel-tubed HP feedwater heaters were replaced with carbon-steel tubed heaters. In addition, ion-exchange, resin-coatal filters were installed at the outlet of the LP feedwater heaters.[22] No forced outages were experienced because of feedwater pump troubles[30]. A change in The stuffing box design was implemented to eliminate the minor shaft-sleeve fretting that was experienced in the stuffing boxes. However, load was reduced occasionally when one of the twin pump lines required attention or experienced distress. This was one of the real advantages of having two feedwater trains operating in parallel. In addition, the HP pump shaft material was changed from 17-4 Cr Ni to AISI 410 steel[30].

Water Treatment

The feed water makeup and condensate scavenging system effectively removed dissolved and suspended solids from the makeup and condensate. Makeup is fresh water supplied to the unit to replace fluid losses from a number of causes. Deposits of copper oxide occurred on the turbine blades and were not anticipated during the design phase. Corrective actions included installation of an ion-exchange, resin-coated filter unit (condensate polisher) installed at the discharge of the low pressure, LP, heaters as well as changing out the Monel (copper alloy) tubed HP heaters with steel-tubed heaters.[2][22][24]

The copper deposits on the blades reduced the flow area, resulting in a reduction of steam flow and consequently a loss in power output. This loss in turbine capacity because of copper deposits occurred in many of the follow-on supercritical pressure units. This same copper deposition problem also began to occur in subcritical pressure units. Subsequent research revealed that feedwater oxygen levels were a major influence on copper pickup from the feedwater train.

A major advance in reducing the impact of copper deposition on turbine blades was the development of a procedure whereby copper was removed from the blade surfaces without disassembling the turbine. Successful use of this procedure was reported in at least two instances at technical conferences.

Life Extension

In the 1990s Exelon (successor to PECO) began a life extension program on Eddystone 1. The projected retirement date of Eddystone 1 is in the 2015 to 2025 time frame. At that time the unit would have seen at least 55 years of service. Quite an achievement!

Lessons Learned - Reflections Presented in "The Eddystone Story", Electrical World, March 11, 1963

Reference 2 noted that "One of the most satisfying facts that came out of this project...is that our estimates of modern technology and its abilities to correct deficiencies was validated...corrections were required in certain areas of equipment, material and design."[2] The observations of the contributors to "The Eddystone Story" were gleaned from over 3 years of commercial operation of Eddystone 1. The contributors to that "Special Report" in *Electrical World* identified areas where cost and complexity of future supercritical pressure units could be reduced and plant efficiency increased

Steam Conditions

The consensus was that future supercritical pressure plants would have more modest steam conditions and a revisiting of the Eddystone steam conditions would have to wait on future advancements of the technology. An additional 25 double reheat units were built in the U.S. with main steam pressures of 3500 psig and steam temperatures in the 1000°F to 1050°F range, for example, Eddystone 2. Over 100 supercritical 3500 psig single reheat units were built in the US and all but one had steam temperatures of 1000°F. An EPRI-sponsored study in the 1979-1981 time frame confirmed that Eddystone 1 design conditions remained a benchmark in pulverized coal plant design.[31][32]

While no supercritical pressure units have been built in the US for several years, such units are currently under consideration using on-shore and off-shore equipment suppliers. Pacific-rim (especially Japan, China and Korea) and European utilities and their equipment suppliers have been aggressively developing higher temperature designs, some of which will exceed those of Eddystone 1. The higher fuel costs in those countries make these advancements economically viable.

Bypass Systems

The Eddystone 1 bypass system, which is used during startup and load operation, dissipated as much a 100 MW of energy, was reevaluated. The steam generator supplier concluded that future units would utilize the concept of superimposing recirculation on once-through flow. This approach leads to a greatly simplified bypass system which handles smaller quantities of energy with considerably less cost to install and operate, as well as smaller performance penalties during bypass operation and low load. In addition, the number of steam leads could be reduced with accompanying reductions in the number of associated valves, 152 on Eddystone which could be reduced to 19. Other steam generator vendors reduced the startup losses recovering the heat of the bypass flow in the feedwater train.

Eventually, these steam generator startup system designs progressed to the point where variable or sliding pressure operation was implemented for either the superheater or for the entire steam generator circuitry.[35][36]

Steam Turbine

Follow-on turbine designs at 3500 psig throttle pressure resulted in the application of partial-arc admission first stages, following some initial field deficiencies which were soon corrected. In addition, variable or sliding throttle pressure was utilized where such operation was compatible with the steam generator design. This improved part load efficiency and resulted in a more benign environment during part load operation.

Steam Generator

The feasibility of variable pressure operation over the entire load range was accomplished by differing equipment concepts by the various steam generator suppliers in the U.S.[33][34][35][36] In many instances collaborative efforts with off-shore utilities and steam generator suppliers continued to advance the state of the art.

Reevaluation of the Eddystone 1 steam generator design verified that although the concepts used in designing supports for the vertical "ribbon panel" were sound and proven in operation, it was expected that future supercritical units probably would not use this vertical ribbon panel arrangement because of cost and the inherent high pressure drop. Each tube was over 700 feet long, and as unit size increased, the pressure drops involved with ribbon panels would probably make other arrangements more practical.[37]

Feedwater Train

Future feedwater train designs were expected to reduce the number of pumps after the deaerator from the three pump units employed at Eddystone.[30] Succeeding plants eventually placed the boiler feed pump at the deaerator discharge with the HP feedwater heaters being subjected to full steam generator inlet pressure.

Piping

Type 316 main steam piping was increasingly applied on both supercritical and sub critical pressure units.

The Pioneering Supercritical Generating Units

The first supercritical unit built in the US was Philo 6, American Electric Power Co. and its commitment was announced in June 1953. The 120,000 kW unit was in service between 1957 and 1975, when it was deactivated. An entirely different team of suppliers of equipment and systems participated in the design, building and operation of Philo 6 than the team involved in the Eddystone 1 venture. Philo 6 has also been designated as an ASME Historic Mechanical Engineering Landmark with its dedication planned for August 7,2003.

Eddystone 1, committed in the latter part of 1954; was comparable in size to the largest conventional subcritical units being committed at that time. Eddystone 1 is still operating and will continue to do so for several years. The steam conditions of Eddystone 1 were more advanced than those of Phi1o 6. Eddystone 1 represented a much greater level of technical and financial risk than Philo 6 because of the difference in rating and steam conditions.

Both Philo 6 and Eddystone 1 fulfilled the expectations of the organizations involved in their building and operation. While the design concepts of some major systems and equipment of the two units differed from each other, they created the technology base for the commercialization of supercritical steam power plants.

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Siemens Westinghouse Power Corporation

EXELON

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Appendix
Steam Power: A Primer and the Significance of the Eddystone 1 Steam-Electric Generator Plant

The body of this brochure contains an excellent description of the Eddystone Steam Electric Generating Plant written in the jargon of power engineers, and is perhaps difficult for some readers to understand. This foreword is offered as a way to reduce a complex subject to a simplified account.

Water and steam are familiar and found everywhere, but they have some amazing properties.

One of water's properties is latent heat. Latent or "hidden" heat is heat that must be added to or subtracted from water to make it change state from liquid to solid (ice) or liquid to vapor (steam). The heat is hidden because there is no change of temperature of the water until the water has changed to the new state. The release of latent heat of fusion is the reason that a cold drink stays cool until all the ice has melted, and the taking in of the latent heat of evaporation is the reason that the water in the pot on the stove gets to boiling temperature some time before steam appears.

Steam is made by adding heat energy to water, e.g. boiling a kettle on a stove. The steam therefore contains heat energy which, in a suitable machine, can be used to produce work (e.g. electric power). But steam is a vapor, which means that it contains molecules of the gaseous phase (so-called "dry" steam) in equilibrium with molecules of the liquid phases (tiny droplets of water). One of the characteristics of a vapor is that as heat is extracted from it, the amount of gaseous phase decreases the amount of liquid phase increases - for steam, the steam is said to become "wetter" but the temperature does not change because it is the latent heat in the gaseous phase that is being given up. In short, water/steam is a very good medium for transporting thermal energy, but the water droplets make for some problems in a machine that extracts that energy to produce work.

Primative steam engines appeared in the 18th century but were not very efficient. the builders were essentially practical who made steam boilers and engines that would produce work, but the theory behind the machines had not been developed. By the mid19th century, much more was understood about "heat engines" in general and steam power in particular. one of the major figures was a Frenchman Sadi Carnot who explained in theoretical terms how the most efficient heat engines could work in terms of their cycles. A heat engine "cycle" is the complete process of heating and extracting thermal energy from the working fluid. For a steam “machine”, the working fluid is water / steam and the cycle covers heating the water in a boiler to make steam, using that steam in a machine to produce work, then taking the exhaust fluid from the machine and passing it back into the boiler to be reheated. This in turn means that to produce a constant level of work, the mass flow rate (e.g. pounds/minute) of working fluid is constant throughout the cycle.

Efficiency is proportional to the amount of heat going into the system that is turned into work, and the efficiency is determined by both the type of working fluid and the conditions - temperature, pressure and so on - at which it is used. In electrical power generation, efficiency is often expressed as “heat rate” - the number of units of thermal energy required to produce a unit of electricity. Carnot’s work suggested that any "heat engine,” e.g. a steam machine, would become more efficient as the temperature of the working fluid going into the machine was increased and the temperature of the working fluid exhausted from the machine was made as low as possible. And so the race was on to test these conditions.

At sea level, water boils at approximately 100°C (212°F) and that is the temperature of the steam produced. To get higher temperature steam it is necessary to increase the pressure. Conversely, to get steam to pass through a machine and give up more of its heat to produce work, it is necessary to make the exit temperature as low as practical. This means making the exit pressure as low as practical where the steam has a large volume and contains many water droplets.

Steam machines were initially reciprocating engines, that is, a piston was moved inside a cylinder by the expansion of steam admitted into the cylinder at high temperature and pressure, and the piston turned a shaft to produce work. As the benefits of higher temperatures and pressures were recognized, steam engines began to have several cylinders. The first was a small cylinder to expand the high-pressure steam, the next was larger to use the lower pressure but higher volume steam exhausted from the steam, and a third would be larger still. This scheme of extracting energy from the steam in successively larger and lower pressure cylinders is called “compounding.” The low pressure at the exhaust is achieved by condensing the remaining wet steam back into water. Since water has a much smaller volume than steam, the condensation process produces a vacuum that pulls the steam through the steam machine. (Incidentally, the plumes of steam coming out of the cooling towers at an electric power station are not the exhaust from the steam machine - which is recycled back into the boiler - but water that has been used to cool the exhaust. This water normally comes from a nearby river.)

When steam is made at a temperature higher than is required to make it just dry at the operating pressure, the steam is said to be “superheated.” In addition, a peculiar property of water is that at a temperature of approximately 380°C (and a corresponding pressure), the latent heat of evaporation disappears and the water turns directly into dry steam without going through the “wet” vapor phase. This is called the critical point, and temperatures and corresponding pressures above this point are said to be “supercritical."

Steam turbines were invented in the late 19th century, and quickly made reciprocating engines obsolete for generating electricity. Turbines may be thought of as very specialized windmills (i.e., they have rows of rotating blades) inside a series of cylinders that contain and direct the expanding steam, and they run smoothly at high speeds and generate large amounts of power (or work). One feature is that each row of blades on the rotating shaft is followed by a row of stationary blades. Steam flowing through the machine first pushes on the rotating blades to turn the shaft on which they are mounted, and then, passes through the stationary blades which redirect the steam flow back into the next row of rotating blades, and so on. Each ring of rotating blades plus its associated ring of stationary blades is known as a "Stage.” The steam in the initial stages of the highest pressure cylinder is directed into the blades and expands through them. From the previous discussion, the highest-pressure cylinder sees the highest temperatures, and the lowest pressure cylinder becomes very large because of the large volume of the steam. In addition because of the water droplets in the low-pressure steam, the low-pressure blades are subjected to a high velocity stream of water droplets, which can erode them. In the case of Eddystone, the volume of steam becomes so large at the lower pressures that the turbine generator is constructed as two turbine-generators side-by-side, each having a large volume. This arrangement is known as “cross-compounding."

The engineers who designed the Eddystone plant pushed the technology of steam-electric generating plants. They knew that higher temperatures and pressures make a more efficient plant, and that larger machines are generally more efficient than smaller machines. They knew from European and American experience a few years before, that supercritical steam plants would work. But they pushed beyond the frontier to see if an even larger And more efficient plant could be built and operated. and they succeeded, but found in a few years that if the pressure and temperature conditions were reduced slightly, a more economically viable generating plant could be built. And that is how many supercritical plants are built today. In a sense Eddystone was for a few years the supersonic airliner that showed that the large subsonic airliner made more economic sense. This is Eddystone's legacy, and that the plant has continued commercial operation to this day is a tribute to the engineering that went into its design to make it truly on the cutting edge.

R. Michael Hunt, PE
ASME History and Heritage Committee
March 2003

The History And Heritage Program of ASME International

The History and Heritage Landmarks Program of ASME International (the American Society of Mechanical Engineers) began in 1971 to implement and achieve its goals, ASME formed a History and Heritage Committee initially composed of mechanical engineers historians of technology and the curator (now emeritus) of mechanical engineering at the Smithsonian Institution. Washington, D.C. The History Heritage Committee provides a public service by examining, noting recording and acknowledging mechanical engineering achievements of particular significance. This Committee is part of ASME's Council on Public Affairs and Board on Public Information. for further information, please contact Public Information at ASME International, Three Park Avenue, New York, NY 10016-5990,1-212-591-7740.

Designation

Since the History Heritage Program began in 1971, 221 landmarks have been designated as historic mechanical engineering landmarks heritage collections or heritage sites. Each represents a progressive step in the evolution of mechanical engineering and its significance to society in general. Site designations note an event or development of clear historic importance to mechanical engineers. Collections mark the contributions of a number of objects with special significance to the historical development of mechanical engineering.

The Landmarks Program illuminates our technological heritage and encourages the preservation of the physical remains of historically important works. It provides an annotated roster for engineers, students, educators, historians and travelers. It helps establish persistent reminders of where we have been and where we are going along the divergent paths of discovery.

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EDDYSTONE STATION, 325 MW GENERATING UNIT 1

1960

This was the second U.S. steam-electric generating unit. It pioneered significant increases in steam pressure, steam temperature, and unit size. It was built by a consortium of the Philadelphia Electric, Westinghouse Electric, and Combustion Engineering companies and, at this time, was the most efficient in the nation. The knowledge gainted from its successful operation made it the model for today's high-efficiency, steam-electric stations.

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