HADDAM NECK NUCLEAR POWER PLANT, TURBINE BUILDING (Connecticut Yankee Nuclear Power Plant, Turbine Building)
362 Injun Hollow Road
Haddam
Middlesex County
Connecticut

HAER CT-185-C
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WRITTEN HISTORICAL AND DESCRIPTIVE DATA

REDUCED COPIES OF MEASURED DRAWINGS

FIELD RECORDS

HISTORIC AMERICAN ENGINEERING RECORD
National Park Service
U.S. Department of the Interior
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Washington, DC 20240-0001

HISTORIC AMERICAN ENGINEERING RECORD

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(Connecticut Yankee Nuclear Power Plant, Turbine Building)
HAER NO. CT-185-C

Note: This documentation encompasses the Terry Turbine Building, HAER No. CT-185-E

Location:	362 Injun Hollow Road, Haddam, Middlesex County, Connecticut U.S. Geological Survey Haddam & Deep River Quadrangles UTM Coordinates 18.708748.4595057
Dates of Construction:	1964-1966 Major modifications c 1978 (concrete sumps in Auxiliary Bay), 1979-1982 (waste treatment facilities), 1986-1987 (low-pressure turbine replacement).
Engineers:	Westinghouse Electric Company (turbines, generator, related equipment), Stone & Webster Engineering Corporation (foundations and superstructure), Utility Power Corporation and Kraftwerk Union AG (replacement low-pressure turbine rotors)
Present Owners:	Connecticut Yankee Atomic Power Company (CYAPCO) 362 Injun Hollow Road, Haddam Neck CT 06424-3022
Significance:	The Haddam Neck Nuclear Power Plant was one of the earliest commercial scale nuclear power stations in the United States, and was eligible for the National Register of Historic Places. Its function was to generate electricity using steam generated in the reactor. Equipment design was typical of contemporary choices in nuclear-fueled turbines and generators, and had turbine and condenser problems common to plants of this vintage.
Project Information:	CYAPCO ceased electrical generation at the Haddam Neck plant in 1996 and initiated decommissioning operations in 1997, subject to authority of the Nuclear Regulatory Commission (NRC). NRC authority brought the project under the purview of federal acts and regulation protecting significant cultural resources from adverse project effects.[1] This documentation was requested by the Connecticut State Historic Preservation Office to mitigate the effects of demolishing a historic power generating facility.

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[1] National Historic Preservation Act of 1966 (PL 89-655), the National Environmental Policy Act of 1969 (PL 91-190), the Archaeological and Historical Preservation Act (PL 93-291), Executive Order 11593, Procedures for the Protection of Historic and Cultural Properties (36 CFR Part 800).

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Building Description

Like most structures at the Haddam Neck Nuclear Power Plant, the Turbine Building was oriented on a northwest-southeast axis with the northwest end "called north" on plant drawings. Framed in welded and bolted steel with columns forming 20 and 25-foot-wide bays, the building was structurally continuous with the Service Building and Control Room and housed the turbines and generator which rested on a reinforced concrete pedestal. There were two Turbine Building sections, each with metal roofs; the gable-end 122-foot-high, 106-by-268-foot main building, and a flat-roofed, 38-foot high, 27-foot wide auxiliary bay running along the southeast side of the main building. The auxiliary bay was 240 feet long on the ground floor and 268 feet long above (Figure 1).[1]

Enameled fluted aluminum siding sheathed all auxiliary bay exterior walls, and most of the north, east, and west walls of the main building. Except at the main building north end, where expansion for a second nuclear unit was originally planned, the exterior siding and metal roof panels were insulated using (in many places) Galbestos, the original asbestos insulated zinc coated steel panel[2].[a] The publicly-visible west and south sides presented more finished appearances. A 94-foot-high facade of glazed brown brick covered the south wall to the roof line and wrapped around the west facade almost to the first column line, with the same brick continuing along the rest of the west and north sides as a 4.5-foot-high base. North of the high brick face on the west side, paired 2.5-foot-wide vertical plastic strips flanked insulated aluminum panels on alternating exterior columns, providing natural interior light and dividing most of the west facade into five exterior bays. The northernmost of these bays was hidden by the west facade of the adjacent Administration Building and was blank except for a personnel door. The remaining four bays, 45 or 50 feet wide, were each distinguished by an 8-foot-high, 30.5- or 35-foot-wide arched louvered aluminum panels, which mirrored the two, somewhat larger arched sections on the west side of the Administration Building. As discussed below, the second and third arched panels from the south were removable to allow for condenser tube replacement, and a 20-by-9.5-foot area of removable wall panels above the southernmost of the removable arched sections allowed for withdrawal of certain feed water heater tubes.

Additional natural light was admitted by strips of bronze colored-plastic windows along the wall/roof junctions of the east and west sides, by vertical plastic panels in the pediments under the gable ends, and by a 107 -foot-long strip of 4.5-foot-high aluminum-sash windows along the east side of the operating floor. The east, north, and south exterior walls were otherwise almost blank, penetrated by one man door each at the north and south ground

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[a] Profiled metal sheeting with asbestos felt on both sides coated with either bitumen or polyester resin

levels, a rolling steel garage door on the south side, and a man door on the east side of the operating floor which accessed the roof of the auxiliary bay. Eleven transverse gravity roof ventilators at 25-foot-centers topped the main Turbine Building exterior.

Substructure and turbine-generator pedestal components were completed in 1964, during the earliest phases of plant construction (Historic aerial view 1965-Figure 12). Beneath the condensers described below as part of the plant heat cycle, steel and concrete circulating water intakes and discharges were installed to depths reaching elevation -6 feet. The ground floor concrete slab over these features was poured at the typical plant ground elevation of 21.5 feet, and supported steel superstructure columns. The reinforced-concrete pedestal had footings below the ground floor and extended to the operating floor elevation of 59.5 feet. The pedestal consisted of large columns and 10-foot-deep beams, with open construction allowing for placement of condensers and auxiliary equipment within the pedestal. Bottle-shaped in plan, the pedestal was widest under the low-pressure turbines (Figure 2, [Historic photo 1967-002.jpg]).[3] The operating floor elevation was presumably dictated by approximate 31-foot height of the condenser tops above the circulating water pipe entries.[4] Four openings in the operating floor level allowed for the insetting of the three turbine casings and generator.

The perimeter columns of the main Turbine Building superstructure were largest up to the 94.8-foot elevation and formed a shelf to support bridge crane rails. Smaller-section columns were attached to the outer portions of the perimeter columns to support the upper wall section and roof girders (Photograph Figure 9) Surrounding the turbine-generator pedestal, but structurally independent from it, were the steel-framed mezzanine (el. 37.5 feet) and re-heater (el. 47.5 feet) levels, which contained most of the auxiliary equipment systems dedicated to turbine operation. The mezzanine level continued across the auxiliary bay.[5] An electrically-powered Manning, Maxwell and Moore Company bridge crane traversed the entire length of the main building, supported on crane rails reaching an elevation of 98.25 feet. The main hook capacity was 125 tons. There was also an auxiliary 20-ton hook. Components could be brought up to the various levels by the crane through a large hoist way opening through the floors at the southwest corner.[6] Trolley beams mounted on the steel framing of the mezzanine and re-heater levels facilitated withdrawal of moisture separator re-heater, condenser, and feed water heater tubes for repairs. The main ventilation system comprised natural and forced-air flow from the louvers along the base of the west wall and out through vents in the roof.[7] The natural flow relied on the stack effect of rising warm air.[8] Fans also supplied forced air flow. For heating, air warmed by radiation from equipment was collected by fans and directed down to lower levels.

The major equipment in the Turbine Building served two main functions; conversion of steam to electrical energy, and condensation of steam for feed water return to the steam generators in Reactor Containment., These operations were controlled to maintain the overall plant heat balance as well as to supply power to the grid and the rest of the plant. Most equipment critical to the heat balance was located in the Turbine Building. A variety of secondary systems supplied and regulated water and air for these functions, often controlled by a wide range of control valves. Housed on the ground floor primarily in the Auxiliary Bay, secondary systems included the compressors, receivers, filters, and driers of the Control Air System, the intake filters, compressors, moisture separators, and receiver for the Service Air System, and components of the Water Treatment System.

The flow of steam, gases, and water through the turbine building was controlled by on/off and volume control (throttling) valves. These valve types, operated by threaded spindles, were in use before the Industrial Revolution.[9] For simple shut-off service, gate valves blocked the flow with a sliding wedge. For volume control, globe valves with circular discs pressing on circular seats were preferred. To insure flow in the correct direction, non-return valves were used, also a very old design. Pressure-reducing valves enabled low pressure devices to take steam from the main supply without damage.[10]

There were three main systems actuating plant valves: air, electric, and oil. The choice of actuation was based on the type of valve, the medium being controlled, and the requirements for safety backup redundancy. Many valves were actuated by the 100-psig[b] Control Air System, which ran through the plant and had backup receivers to provide emergency activation power even if the system failed.[11] The admission of air to the activation mechanism was made by solenoids operated from the control room with several backup electrical systems.[12] The air-operated valves were often designed so that if they failed, they would automatically go to the safe position.[13] Valves for isolating portions of the systems were generally electric-motor operated with both actuation signals and power coming from un-interruptible supplies which would continue to operated even in an emergency.[14] Both classes of valves could be set to operate automatically when signaled by an unsafe condition in the plant.[15] In most cases they also had manual overrides and hand wheels for local control. A third type of valve operated by oil pressure was used on the main turbine. These were powered by oil from the bearing-lube system and were actuated by electric solenoids. Redundancy was insured by backup pumps, backup electrical supply to the solenoids and fail-to-safe-position construction.[16]

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[b] Steam pressure was stated as pounds per square inch gage (psig) which was the pressure over the nominal atmospheric pressure at sea level of 14.7 pounds per square inch (psi). Pressure over true 0 was known as pounds per square inch absolute (psia).

Four 24-inch-diameter main steam lines (one from each steam generator) entered the auxiliary bay through the east wall at the 47.5-foot elevation, in line with the main building's re-heater level. The steam lines were constructed of nearly l-inch-thick carbon steel pipe, and hung from ceiling steelwork to allow movement during thermal expansion and contraction.[17] As it entered the turbine building the steam was measured by flow detectors on each line. Pressure differential devices automatically regulated the feed flow into the generators based on the steam flow out and signaled the control room. If the steam flow exceeded the feed flow by more than 20 percent the detectors sent a trip signal to the reactor to protect the steam generators from low water.[18] The main steam lines were welded [19] into the south side of the 36-inch-diameter, 1.33-inch-thick manifold suspended from the ceiling on an east/west axis.[20] The manifold served as a header from which steam could be taken to run various systems discussed below. In addition to the two turbine supply lines, auxiliary steam pipes went to the re-heater sections of the four moisture separator re-heaters, steam jet air and priming ejectors, turbine gland seal valve, and steam heating system.[21] The High-Pressure Steam Dump System came out of the header with two 12-inch-diameter steam lines. They could send steam directly to the condensers in the event of a turbine trip without reactor trip.[22] Two valve stations in the turbine building consisting of five valves on each line gave reliability to the critical steam dump function, and provided security against an accidental dump.[23] The main steam pipes were insulated with asbestos and covered with stainless steel casings. The insulation minimized the heat losses that inevitably occur when bringing steam to different locations. The design basis of this system was for 985 psig steam pressure at 650°F.[24]

Two 30-inch-diameter, 1.23-inch-thick main steam pipes were welded to the north side of the manifold and made a large diameter arc west into the turbine building at the 50-foot elevation, from which point they then made another large diameter arc south and formed S bends to rise up through the operating floor.[25] The steam pipes terminated at two main stop valves anchored to the floor at the high-pressure end of the turbine. The total steam flow was between 7.341 and 7.670 million pounds per hour. By the time the steam had reached the stop valves, it had lost pressure and heat.

Connecticut Yankee documents show the pressure at the valves at around 640 psig, 50 pounds less than that issued by the steam generators; steam temperature at the stop valves was about 490°F, about 11 degrees less than that at the steam generator outlets.[26] The steam was described as dry and saturated, meaning it had moisture content under 0.25 percent and a temperature that was the same as that of the water from which it was liberated.[27]

The thermal energy to rotating energy conversion device was a Westinghouse/KWU three-casing, tandem compound turbine direct-connected to a Westinghouse generator. The turbine included one high-pressure and two low-pressure units, which was typical of many large power plants from the early 20th century. The nominal turbine output was 619,328 KW with a maximum output of 648,527 KW or almost 1,000,000 hp.[28] At that load, the turbine was taking 7.463 million pounds of steam per hour. The casings of the Connecticut Yankee unit were all on a single shaft with a high-pressure element exhausting into twin low-pressure units. This design was known as a tandem- compound arrangement to distinguish it from cross-compound types which had two or three separate turbine shafts.[29] Turbines were also typed according to the directional flow of steam through the casing. The Connecticut Yankee units were double-axial flow types, in which the steam entered the center of the casing and flowed outward to each end.[30] One advantage of this design was that the thrust on the blades was well balanced which simplified the design of the support bearings.[31] The Connecticut Yankee turbines were also categorized by their exhaust arrangements. The steam exhausted each casing from two ports at each end, called quadruple exhaust. The splitting of the exhaust path allowed a greater flow without greatly increasing the size of the casing ends. This was an additional benefit of the double-flow design.[32] The steam flow volume dictated the size of the exhaust ports, which in turn dictated the length of the last row of blades in each stage. Blade size is a critical factor in turbines because of centrifugal forces acting to pull the blades out by the roots. (See Appendix A) Blade length and thus casing size had to be increased as steam pressure dropped and steam volume increased during the flow of steam through the turbine.[33] The constraint of relatively poor steam conditions from the pressurized water reactor generators on exhaust-port design and blade-tip speed required larger-diameter blading in the last stages than were found in fossil-fuel power stations. This limited the rotor speed to 1800 rpm.[34]

The steam entered the turbine through the two hydraulic, on/off, swinging clapper type stop valves.[35] Their main purpose was to provide emergency shut off to prevent turbine over-speed.[36] The valves had a built-in safety feature: they were held open by oil pressure but closed by a spring and steam flow, thus defaulting to shutdown (trip) in the event of a power supply loss.[37] Other malfunction scenarios such as over speed, low condenser vacuum or low bearing oil would shut off the steam flow.[38] They would also close by solenoid signal if the reactor scrammed.[39] The stop valves were sized so that one valve could supply enough steam for 2/3 output with the other valve closed for testing or repair.[40] Steam flowed through the stop valves and into four hydraulic plug type governor valves which were welded in pairs to each stop-valve body.[41] They were actuated by servomotors linked to the turbine-governing devices as the main method of speed control and emergency shutoff during turbine run.[42] Generally the plant ran with three of the valves fully open with governor actuation on the fourth valve.[43] High-pressure hydraulic oil for shutoff and governing valves was provided by the main oil pump though the Turbine Control Oil System (TCOS).[44] Since the main oil pump was driven directly by the rotor, an AC electric motor pump supplied the system during startup and shutdown.[45] The TCOS also supplied low-pressure oil to the governor control block, located in the governor pedestal, which detected speed variations via an oil line pressurized by an impeller on the turbine shaft.[46] The variations could be caused by changes in the steam supply and/or the electrical load. The control block magnified variations enough to operate the governor valve-control servomotors.[47] Changes in speed or malfunction scenarios generally caused a differential of oil pressure on one side of a relay piston allowing springs to activate the valve servomotors controlling the oil actuators of the valves. In the case of the control valves, as the electrical load on the generator rose and fell, the governor raised or lowered the oil pressure to open and close the fourth valve in small increments, modifying the steam flow to keep the speed at 1800 rpm.[48] Once connected to the grid, the grid maintains 60 cycles and changes to governor valve position increase or decrease the load on the governor. The control block also contained an auxiliary governor and malfunction trip devices. For critical over speed protection, a centrifugal weight device on the shaft automatically contacted a trip relay if the speed increased by more than 45 rpm, shutting all the valves.[49] The stop and governor valves were also remotely controlled by personnel in the control room to admit and throttle steam admission during startup, synchronizing, and shutdown.[50]

The casing for the high-pressure turbine was a fabricated weldment of carbon steel, consisting of upper and lower shells bolted together at machined mating surfaces.[51] These surfaces were so precisely finished that no gasketing material was needed; only boiled linseed oil was used as a seal.[52] The lower outer casing was attached to the concrete foundation by lugs and keys to allow movement with expansion and contraction. The stationary blade rings were doweled into the inside surfaces of the casings.[53] The casing was insulated with asbestos and clad with sheet metal for a neat appearance.[54] A separate sheet metal enclosure covered the stop valves, governor and control valves.

Steam leaving each governor valve was sent through a pipe to a sector of the first rows of stationary blades or vanes.[55] Two pipes were in the upper casing and two in the lower, serving as nozzles for steam admission to the moving element. The rotative motion was caused by a flow of steam passing alternate rows of stationary blades mounted on the inner casing and rotating rows attached to a spindle. In the 1884 Parsons design, the pressure drop in the steam flow path was equal between the fixed and moving blades. The fixed blades served as nozzles in which the steam expanded and reached the speed of the moving blades. The steam continued to expand in the moving blades, changing its momentum and producing a rotative force via reaction.[56] Each blade row utilized an additional expansion of the steam and the rows got larger in diameter as the steam flowed through the turbine.[57] Rateau in France and General Electric in the United States brought out a competing design around 1905 using differently-shaped impulse blades: In impulse turbines, steam issuing from the stationary nozzle blades was reduced in pressure and increased the velocity. The high velocity steam impinged on the moving blades causing rotation by impulsive force.[58] By 1907 Westinghouse designers realized that an efficient turbine combined elements of both types.[59] An impulse turbine needs fewer rows of blades for the same power output.[60] That advantage was somewhat negated by the difficulties of sealing the ends of the blades against steam leakage. Impulse blading also facilitated steam throttling, and allowed for turbine designs which were more efficient at partial loads.[61]Thus the Connecticut Yankee high-pressure (hp) element had Rateau type impulse blading on the first stage meeting the steam, and seven reaction stages following on each half of the rotor.[62]

The rotor for the high-pressure turbine section was of solid-forged construction.[63] A stub extension shaft was bolted to the governor end to carry the main oil pump, governor impeller and over speed trip weight.[64] The forging was made large enough so that the blade mounting discs were created by machining away the surrounding metal. The airfoil-shaped blades were rooted into the discs. The rotating blades resisted ejection from centrifugal force with inverted serrated "Christmas-tree" roots in the impulse section and inverted "T" roots in the reaction section.[65] The stationary nozzles and blades were doweled or keyed into the casing to ensure correct position relative to the moving blades. Both moving and stationary elements had shroud or seal strips to limit steam leakage past the ends and provide rigidity.[66]

At various stages in the steam flow, steam was extracted or bled to supply auxiliaries described below. In addition, steam exiting the high-pressure turbine was diverted down to the re-heater floor below for reheating and drying before being sent to the low pressure turbines. Shaft penetrations at either end of the casing were leak points.[67] Two sets of gland seals attached to the casings and closely surrounding the shaft prevented air from entering the turbine or steam from exiting. These consisted of labyrinth packing in which steam and air moving along the spinning shafts were forced to travel in a zigzag pattern between grooves cut in the shaft and surrounding soft seal rings. At each change in direction there was a loss in velocity.[68] Expansion chambers in the glands provided a space for the leaking steam to loose energy.[69] High pressure steam from the auxiliary steam header was admitted to a portion of the gland to provide an additional screen against air leakage in during low power operation.[70] Once pressure rose in the casing this was not needed. Leakage and sealing steam were drawn from the glands by blowers and condensed in adjacent gland seal condensers.[71] A separate Cylinder Heating Steam system supplied steam to the glands to prevent leaks from uneven thermal expansion.[72]

The entire weight of the rotor was literally floated on a film of oil in two split-shell, spherical babbitted bearings at each end outside of the casings of each low pressure and high pressure turbine. In this design, going back to the earliest days of power machinery, a cast-steel pedestal held a split cylindrical shell around the shaft. Babbitt antifriction metal, a lead and tin alloy patented in 1839, was poured into the shell and finished to very close tolerance with the shaft journals.[73] The bottom of the shell rested in a spherical bored seat which allowed the bearing to move and align itself with the shaft.[74] The main oil pump forced oil into the bearing, forming a fluid wedge between the metal surfaces. While the double-row flow arrangement provided well balanced loads, a Kingsbury-type thrust bearing was also provided. This design originally pioneered by Westinghouse for supporting the weight of hydraulic turbines, had a collar around the shaft with oil-immersed babbitted pads on either side maintaining very precise shaft position.[75] A complex system maintained pressure and flow in the bearings and then cooled and filtered the used oil.[76] During turbine start up an auxiliary electric pump pressurized the supply lines until sufficient speed was reached for a rotor shaft mounted centrifugal pump to take over. Separate oil lift pumps on each low pressure turbine bearing lifted the rotor before the turning gear was started.[77] Because loss of oil pressure could lead to a destructive failure, there was an additional electric emergency pump run from the plant's station batteries. Clearance space between the shaft and bearing resulted in continuous flow of oil. Used oil was cooled in shell and tube coolers. Impurities such as water and entrained bearing metal were removed in filters and centrifugal purifiers.[78] New and processed circulating oil was stored in two 12,500 gallon tanks in the free-standing oil storage room on the ground floor at the north end of the turbine building.[79] The 10,000 gallon main reservoir was at the same level north of the condensers.

All the attachment points between high-temperature elements and ambient temperature parts had to allow for relative movement. The very close tolerance between the moving and stationary blades required monitoring. Differential expansion probes measured the relative movement between the rotor and the casing.[80] Vibration monitors mounted at each bearing facilitated balancing of the rotors at low speeds. They also indicated problems during run. At the rear end of the high pressure turbine shaft a bolted coupling attached to the mating coupling on the first low-pressure rotor. Steam leaving the high-pressure turbine[81] could be diverted directly to the condenser by the Low-Pressure Steam Dump System. This would prevent over-speeding of the turbine during trip scenarios by reducing the low-pressure turbines' input. The safe limit of this over-speed protection function was set at 128 percent of 1800 rpm.

Towards the end of reciprocating steam engine development in the late 19th century, builders experimented with reheating.[82] By adding more heat to the steam (superheating) between expansion stages they hoped to improve efficiency. Turbine builders first applied reheat cycles to American power stations in the mid 1920s, but the practice remained uncommon until after World War II.[83] Steam conditions at the high-pressure end of the Connecticut Yankee turbine were generally adequate for reliability, but once the steam left the high pressure unit, it was severely degraded. The drop in pressure through the unit from 640 to 195 psig, and in temperature from 490 to 371°F, resulted in partial condensation of the steam.[84] When entrained in the steam flow, the resulting 9-10 percent moisture could cause erosion of the low-pressure turbine blades and stress corrosion cracking of rotor parts.[85] To reduce this problem, the steam was dried and reheated after leaving the high-pressure turbine.[86] The "crossover" exhaust steam[87] was directed from the four high-pressure exhaust ports through 29-inch lines to four moisture separator re-heaters (MSRs) mounted on the mezzanine floor adjacent to each side of the low-pressure turbines.[88] These were 9-foot-diameter, 41-foot-long tubular pressure vessels. Upon entering the MSRs, the exhaust steam passed through demisting screens which trapped the entrained water and drained it away, leaving the steam essentially dry.[89] Approximately 265 tons of water was removed every hour and drained to the feed water heating system.[90] After passing through the screens, exhaust steam flowed over a tube bundle charged with 690° F steam tapped directly from the steam manifold in the auxiliary bay. Baffles caused the exhaust steam to separate and pass through four groups of tubes.[91] The high pressure steam gave up heat to the exhaust adding 90-100° F of superheat and brought the steam temperature back up to 461°F, This process consumed 5% of the steam generator flow.[92] Plant engineers acknowledged that while, in theory, the thermal benefits were uncertain, the moisture reduction function made them worth their cost and maintenance.[93] The reheated dried steam left the MSR units by four pipes which went through the operating floor, to meet over and enter the center of the adjacent low-pressure turbine casings (two pipes/casing).[94] The condensed heating steam was collected and sent to the feed heating system and helped to maintain system heat balance.[95] The MSR's were laid out with clearance for their tubes to be pulled south for repair, using trolley beams mounted from steel building framing.[96]

The two low-pressure turbines were numbered 1A and 1 B to distinguish them from those in the projected #2 unit. They had separate casings and rotors. Each was split horizontally like the high-pressure unit, and in addition had separate outer and inner sections.[97] The outer casing formed the exhaust hood which directed the exhaust steam to the condensers. The shape of the hoods was critical to the free flow of the exhaust from the casing.[98] During low-steam conditions the rotating blades could act as fans, overheating the exhaust hoods (outer casings).[99] This was controlled with condensate spray manifolds in the hoods. The casings formed the supports for the rotor bearings, which were of similar construction to the high-pressure unit.[100] The inner casings were supported by the outer casings and held the stationary blades.

As described below, steam was also extracted between stages of the low pressure turbines to heat feed water sent back to the steam generators in Reactor Containment (HAER No. CT - 185-B). Steam extraction from the three turbines reduced steam flow to approximately 4.40 million pounds per hour passing into the condensers.[101] The low-pressure turbines contributed about 70 percent of the output to the condensers.[102] Unlike the high-pressure unit, the low-pressure casings were not insulated.[103] Steam entered the units at around 174 psi. Because the steam had increased in volume by hundreds of cubic feet after leaving the high pressure turbine, the low-pressure units were much larger to accommodate that expansion.[104] The larger casings required rotors of a size that exceeded forging capacity, so they were of built-up design. Steel alloy blade mounting discs were expanded, pressed, and shrunk on to the spindle and locked with keys to prevent rotation.[105]

As originally constructed, there were ten reaction stages on each half of the rotors.[106] As the steam flowed through the low-pressure blades it continued to gain in volume so even with four exhaust paths, the last stage of blades had to be 44 inches long to cover the passages. With the increase in volume there was also an increase in steam velocity to over 600 ft. per second.[107] Coupled with the increase in moisture content as the temperature dropped, these steam conditions put the last three rows of blades at risk. The ends of their leading edges were protected with strips of Stellite, a hard cobalt based alloy.[108] The long blades in the last stages were highly twisted in shape, and subject to torsional and resonance vibrations.[109] Metal wedges between the blades helped to stabilize them. "Christmas-tree"-style blade roots were used, similar to those in the high-pressure reaction stages.[110] To control moisture, the last blade rows had slots to allow steam to flow directly to the condensers pulling out entrained water. As in the high-pressure turbine, steam was extracted between blade rows to heat feed water. The extraction points at the bottom of the casings were an additional source of moisture removal.[111] Each low-pressure casing was mounted directly over and exhausted into a surface condenser described below.

Entry points of the rotor shafts were sealed with glands similar to those used on the high-pressure turbine. On the low-pressure units, where there was a vacuum at the ends of the casings, the main problem was keeping the exterior air from rushing in.[112] Steam was continuously injected into these seals to maintain equilibrium.[113] The rotors were each about 60 feet long and weighed over 118 tons. The long span between bearings and the weight of the rotors made it imperative that the unit never be stopped for any length of time, or sagging would occur. To avoid this problem when the units were not operating, a motorized turning gear was mounted alongside the 1B turbine (closest to the generator). The gear automatically began rotating the shaft at 1.5 rpm as soon as coast-down was completed.[114] During long shutdowns, after the rotors had cooled to ambient temperature, the unit was manually engaged to turn the rotor daily. [115]

Design and construction of the original Westinghouse low-pressure units had flaws causing reliability problems. These led to refurbishments and reconstructions, and finally to their replacement during the 1987 refueling outage.[116] The new low pressure rotors were supplied by the Utility Power Corporation, a subsidiary of the German firm Kraftwerk Union AG (KWU). Their engineers measured the units and utilized original drawings to design the replacements, which were made to metric specifications and required metric tools for maintenance.[117] The new units were generally similar to the originals but with impulse blading in the first rows, and eight reaction stages following making nine stages at each end, one less than in the original units.[118] The last-stage blade length was the same in as the

Westinghouse units, but the last three rows were made free standing. Root designs were changed to "T" slots for the first six rows.[119] Though also of built-up construction, the new rotors had advanced engineering, metallurgy and manufacturing making them reliable. The disc bore keyways, an area prone to stress corrosion cracking, were of improved design.[120] Mean hours between inspections went up from 60,000 to 100,000.[121] The new blade configuration of the rotors required completely new upper and lower inner casings.[122] In spite of having one less blade row, the new rotors used the same extraction points as the originals.[123] The casings had "crash rings" (strengthened sections) for improved protection against ejected rotor or blade parts due to over speed failure.[124] The new inner casings were designed to fit into the original Westinghouse outer casings, avoiding modifications to the turbine-generator pedestal. The hood sprays were improved with outside casing accessibility.[125] The heavier replacement rotors made it necessary to increase the capacity of the bearing oil lift system. Improved vibration and differential expansion monitoring probes were installed, and exhaust pressure monitoring probes were added for the first time. [126]The two rotors were attached to each other by bolted coupling flanges. As the original bolts had proven to be hard to install and remove, new quick connect types were used on the replacement units.[127]

The new components were barged up the Connecticut River and then up the discharge canal. Multi-wheeled Halliwell conveyors moved the units across the underground condensing water discharge structure and to the southwest end of the turbine building.[128] Parts were then hoisted by the traveling crane through the access opening running through the floors. New calculations were done for the loads on the ground and for staging on the main floor as the units were somewhat heavier than the originals.[129] This documentation has not determined how the original components were disposed of, or whether any warranty action was taken on Westinghouse. Generally, the life span of fossil-fuel turbine-generator sets was taken to be a minimum of 20 years.[130] The original low-pressure elements of the Connecticut Yankee turbine/generator just reached that milestone.

After the steam finished its work in the turbines, it was condensed back to water and recycled. Two surface condensers (nos. lA and 1B) stood directly below the low-pressure turbines. The condensers were of shell and-tube construction in which cooling water and exhaust steam were not mixed, a standard design evolved from mid-19th -century steamships which needed fresh water for feeding high pressure boilers.[131] In principal the Connecticut Yankee condensers simply reversed the heat exchange of the steam generators. Water flowing through tubes cooled and condensed the surrounding steam. At full load, 93,000 gallons per minute (gym) of water was required for condensation.[132]

Each condenser was a welded steel tank mounted rigidly on the ground floor and connected to the bottom of its respective low-pressure turbine by a rubber expansion joint. Mounted in each condenser neck, just under the turbine connection were two feed water heater shells. Below them was the condenser tube section containing over 13,000 50-foot-long, 1-inch-diameter tubes.[133] The total tube surface area was 350,000 square feet, about three times more than that of the steam generators.[134] The tubes, mounted horizontally, went from one end of the shell to the other, and were attached to the sides by tube plates. Intermediate supports along the tube runs kept them from sagging. The ends of the tubes came through drilled holes in the plates and were sealed there. There were two separate tube plates at the inlet end and two at the outlet end of each condenser. Surrounding the exterior of each tube plate and bolted onto the shell was a water box, consisting of a steel semi-cylindrical casing, which channeled the cooling water flow into and out of the tubes. The water boxes, tube plates and sealed tube ends formed a contained pathway for the cooling water to travel through the condenser shell insuring that it did not mix with the steam. The twin set of water flow paths (divided water boxes) allowed one set to be closed for servicing while the other functioned at reduced turbine output.

The cooling water flowed through the tubes in a single pass, a design which required much more cooling water flow than the more common two-pass type.[135] Steam from the turbine exhausts flowed down past the feed water heater shells and into baffling that prevented damage to the tubes from direct steam impingement. After leaving the baffling at reduced velocity, the steam flowed around the outside of the water-cooled tubes. Contact with the tubes condensed the steam forming water droplets that fell to the bottom of the shells. The collection point in each condenser was a hot well from which the Condensate and Feed water systems drew their supply. Condenser tubes inevitably needed replacement due to wear and corrosion. During tube renewal the old tubes were withdrawn and new tubes inserted though the removable arched panels in the west outer wall adjacent to the units.[136] In the original installation most of the tubes were Admiralty Brass, an alloy of brass, zinc and tin.[137] There were also some stainless steel tubes in areas where there was a risk of damage from steam impingement and ammonia attack. Maintenance costs of the brass tubes were high due to stress corrosion cracking and the first tube replacement occurred in 1977.[138] By 1986 all the tubes were again replaced in a series of repair episodes with a stainless steel alloy called Trent Sea-Cure.[139] Though the new tubes had enhanced resistance to biofouling, they proved vulnerable to vibration cracking which required additional supports.[140]

Circulating water to condense the exhaust steam was pumped from the river and arrived at the west side of the Turbine Building at the 12-foot elevation via four 66-inch-diameter carbon-steel pipes.[141] Two pipes rose up through the floor slab adjacent to each condenser.[142] Each pipe supplied one half of the condenser by a flexible connection to a water box.[143] The circulating water pumps in the Screenwell House (HAER No. CT-185 A) could not pump water all the way from the river intake level of -15 ft to the tops of the condenser tubes at 35.5 ft when starting up.[144] They were augmented by a vacuum priming system including two vacuum priming pumps on the Turbine Building ground floor and vacuum priming tanks attached to each of the four water boxes.[145] Once the condensers were filled and the flow started, the priming pumps were not needed for that purpose. After exiting the condenser tubes and outlet water box, cooling water was piped out in four carbon-steel pipes of similar construction to those connected to the inlet water boxes.[146] The pipes carried the water about 23 feet to a concrete discharge tunnel running next to the east wall of the turbine building, directly under the auxiliary bay.[147] The tunnel was 12 feet wide by 15 feet high; an even larger tunnel was built next to it with a shared wall to accommodate the discharge requirements of the never-built second reactor.[148]

In addition to allowing the condensed steam to be recycled as feed water, the condensers provided the important benefit of vacuum. When condensed in a closed space, steam rapidly loses volume producing a vacuum. This allowed the steam flowing through the low-pressure turbines to do work considerably below 14.7 1bs atmospheric pressure.[149] The Connecticut Yankee condensers produced a vacuum of up to 1.9 in. Hg absolute (28.1 inches of mercury).* The additional use of steam below 14.7 psig in the turbines provided a large portion of their total output.[150] While the vacuum-forming process was naturally the result of condensation, air build-up would have negated the level of vacuum in a short time. Two priming and two main two-stage air ejector units on the second level mezzanine were the primary units used to start and maintain the vacuum.[151] Steam from the main steam manifold was piped into the ejectors and flowed through velocity-increasing venturi nozzles in communication with the condensers. The high speed steam flow in effect, "dragged" the air out of the condensers.[152] The discharged condenser air was sent to the atmosphere by the primary vent stack located northwest of Reactor Containment. A radiation monitor was located in the stack to detect air contaminated by radioactive steam resulting from a steam generator tube leak.[153] The air ejectors could also aid in reactor decay heat removal by blowing steam into the atmosphere if the high pressure steam dump system was not available.[154] In addition to its job of topping off the condensers, the vacuum priming system also removed air from supply piping, water boxes, and tubes before startup. The system remained on during turbine run to remove collected air in the tubes and water boxes.[155] Condenser vacuum control was critical to plant efficiency. The levels in each unit had to match closely or the turbines would be un-evenly loaded. A rise in back pressure to 24.5 in. would lead to an emergency shut down.[156]

The condensers provided an important safety function. In the event of a turbine trip and reactor trip, steam could be bypassed directly from the steam header to the condensers by the high pressure steam dump system.[157]

Condensate and Feed water Pumping

The condensed steam (condensate) was the main source of feed water for the steam generators. The collection points were the hot wells which constituted the lower two feet of the condenser shell, and normally held 33,000 gallons. Two condensate pumps on the Turbine Building ground floor removed water from the hot wells and started it on its route to Reactor Containment.[158] These were 6200-gpm, 1500-hp AC induction-motor-driven vertical pumps with suction and pressure stages.

They pulled at condenser vacuum and output at 350 psi. The feed water first passed through the condenser air ejectors to condense their exhaust.[159] It then flowed through two parallel trains of five low-pressure feed water heaters described below (heating steam taken from low-pressure turbines) to the steam generator feed pumps on the main floor of the auxiliary bay. Most exhaust steam used in the feed water system heaters drained into the main condenser, but there were still losses requiring replenishment. The "make-up feed" was drawn from two wells south of the plant.[160] and stored in the 100,000-gal. demineralized water tank near Reactor Containment (TK-25-1 A). This tank fed directly into the condenser hot wells in the event it received a low level signal.[161] The inside piping diameters in this system varied from 30 inches at the hot wells to 16 inches through the feed water heaters leading to 18-inch suctions for the feed pumps. Leaks from steam generator or condenser tubes could pollute the feed water leading to damage.[162] The original design included two demineralizers on the ground floor of the auxiliary bay that were used to treat well water prior to use in the plant systems. Later in the plant's operating history truck mounted units proved to be a better option. Provision for adding corrosion inhibitors to feed water also existed in the auxiliary bay. After leaving the condensate feed pumps, the condensate water flow was considered part of the feed water system.[163]

The system had the important role of providing a contiguous heat sink (absorber) of reactor generator heat.[164] The two steam generator feed water pumps were horizontal 960-gallons per minute (gpm), 4500 hp induction- motor-driven centrifugal units. The feed water left the pumps at 1100 psi and went through a last high-pressure stage of heating noted below. The two lines fed an 18-inch header in the Turbine Building from which a separate 12-inch feed line was routed to each steam generator in Reactor Containment.[165] Each of condensate and feed water pump took half the station load. All had to be operated to pump the 7.6 million gallons per hour (gph) required under full load.[166]

Auxiliary Feed Water System-Terry Turbine Building

To ensure a continuous un-interruptible supply of feedwater if the main Feedwater system was not functional, Connecticut Yankee had an Auxiliary Feedwater System supplied from the Terry Turbine building. The facility was named after two Terry Turbine driven auxiliary feed pumps.[167] The Terry turbine was developed by the Terry Steam Turbine Company of Hartford, CT early in the 20th century, [168] and became a favored prime mover in the power industry for driving fans and boiler feed pumps due to its ruggedness, relatively high efficiency and high speed.[169] The single forged turbine wheel had multiple semi-circular "buckets" machined directly in the forging and reversing chambers in the surrounding casing. Steam was admitted directly into the buckets causing them to move from the impact. Steam was then turned 180 degrees and re-admitted to the blades several times until most of the energy was gone. The unit had very large clearances between the turbine wheel buckets and the reversing chambers for reliability and could even continue to operate if the steam supply turned to water.[170]

The pumps were 450-gpm multi-stage centrifugal types which supplied their own lubrication, shaft sealing, and cooling, independent of plant systems. The Terry turbines were the only rotative steam powered auxiliaries in the plant. Even if all plant electric power and backup diesel generators were lost, the Terry turbines could continue to provide pumping power from steam produced by decay heat from the reactor.

The atmospheric dump valves were located at the Terry Turbine enclosure. When a rapid shutdown of the unit was necessary, equipment operators would dash out the east door of the turbine hall, down the outside stairs, across the roof of the service building to the Terry Turbine enclosure to manually open the atmospheric dump valves to vent steam away from the turbine. [171]

An auxiliary feed water system, with two pumps operated by steam turbines, was located in the nearby Terry Turbine Building (Figures 1 and 8). These units were driven by steam from the steam generators and provided feed water to the steam governors removing heat from the reactor when main feed pumps were not functioning. Main feed water air-operated regulating valves controlled the flow of water to the steam generators and maintained their level.[172] The valves in the feed water system automatically opened on turbine trip to reduce reactor coolant temperatures.[173] If their control air failed they would close automatically to prevent overfeeding which could overfill steam generators, resulting in ineffective moisture removal and blade damage and missile ejection caused by excess water.[174]

It was well established by the middle of the 19th century that preheating the water going into a boiler with waste heat gases saved the amount of fuel required to raise steam.[175] The regenerative (extraction) system was developed cl915 in which steam was bled of the turbine between blade-row pressure stages to heat the feed water.[176] Although there was a net loss of steam for power production, overall system efficiency was increased, in part due to the reduction in steam entry into the condensers.[177] The combination of reheating between turbines and regenerative feed heating improved the overall station efficiency even more.

In the Connecticut Yankee regenerative system, there were six stages of heating.[178] This process was split between six pairs of feed water heaters in different locations in the main and auxiliary sections of the Turbine Building, forming two separate trains.[179] The feed water heaters were pressure vessels filled with a tube bundle. Feed water forced through the tubes was heated by condensing a flow of steam passing through the vessel.[180] All the feed heating steam was bled from six extraction points (stages) between the blade rows in the lower casings of the turbines. The heating process began at the condensers and continued in the direction of Reactor Containment. However, the heaters were numbered according to their steam extraction location (blade row) in the turbines which was in reverse order to the feed flow.[181] Heaters Nos. 6-2 were technically part of the condensate system flow path.[182]

Each heater train was designated 1A or 1B from its respective source of feed water, the 1A and 1B condenser hot wells.[183] The first portion of feed water heating (stage 6 and 5) occurred in four low-pressure units mounted two each in the necks of the condensers on a west/east axis. The reason for this location is undocumented but was apparently the-standard location in Westinghouse plants.[184] Two units (6A and 5A) received steam from the 6th-and 5th-stage extraction points on low-pressure turbine 1 A. The 6B and 5B units received steam from the same points on low-pressure turbine 1B.[185] The feed water emerged from the first group of heaters, flowed on either side of the turbine pedestal, and was piped up through the operating floor to the second group of low pressure heaters (4A and 3A, 4B and 3B), mounted on that floor along the east and west walls.[186] The A heaters were on the east side and the B heaters on the west. Each set received steam from the 4th- and 3rd stage extraction points of its respective low-pressure turbine. The last portion of low pressure heating occurred on the auxiliary bay mezzanine, where Heaters 2A and 2B were floor mounted under the main steam manifold. They received steam from the exhaust of the high pressure turbine.[187] At this point, the feed water was routed down to the steam generator feed pumps on the ground floor. These forced the water through the high-pressure, final stage of feed heating, in high-pressure heaters 1 A and 1 B also on the auxiliary bay mezzanine. These received steam from the first extraction stage of the high-pressure turbine.[188]

Since the feed water heaters 1 and 2 were downstream of the feed water pumps in the heat cycle, they were technically considered part of the feed water system. Feed water was kept from boiling by the high pressure in the line.[189] In total, as the feed water traveled from the hot well to the last heater outlet it had gained between 260-330°F of heating.[190] The water in an extraction feed heating system is a considerable reservoir of heat energy. If the turbine were to trip, there was a risk of high temperature water flowing back into the turbines and then turning to steam (flashing) as its pressure dropped, causing an over speed.[191] To prevent that, most of the heaters had balance-type check valves or electrically-activated non-return valves. The condensate produced by the heat exchange in the feed water heaters was collected by a drain system and returned to the feed flow.[192] Water from the high pressure heaters flowed through to the high pressure drain tank. This source provided about 30 percent of the feed flow to the steam generators.[193] The low pressure heaters drained back through the shells to the condenser hot wells.[194] The feed water heaters were originally piped with the same type of Admiralty Brass tubes as the condensers. Copper shedding into the feed flow led to the complete replacement with stainless tubes.[195] As in the moisture separator reheaters, plant builders had to provide clearance for the tubes to be withdrawn from one end of each shell for service. In the case of the condenser mounted heaters, removable panels in the west outer wall of the building were used to provide clearance for tube withdrawal from 1A heaters. The lB heater tubes were pulled into the auxiliary bay. [196]

Electrical Generation

The south end of the 1B low-pressure turbine shaft was directly connected by coupling bolts to a 667 mega volt ampere (mva) synchronous alternator (generator).[c] It had a revolving-field design, which evolved in the late nineteenth century from the original revolving-armature dc generators.[197] The main elements were the armature (stationary windings) known as the stator and the field (rotating magnets) known as the rotor. In basic terms, electrical energy was produced in the armature windings when an interrupted magnetic field was passed through them by the rotating field.[198] As the rotor turned, the electro-magnets produced a moving field that extended out into the stator windings producing a voltage by electromagnetic induction. Since each magnet pole was of opposite polarity to its neighbor the induced voltage was intermittent.[199] The voltage produced in the stator windings rose and fell in a sine wave called an alternation. Since the rotor had four magnetic poles it produced two cycles (hertz) per revolution.[200] At 1800 rpm, it gave an alternating-current frequency off 60 cycles per second (cps). Synchronous machines are designed to operate in cyclic phase with all the generating equipment supplying the grid.[201] When operators in the control room connected the unit to the power grid, they used a synchroscope to ensure that the output was in phase with the rest of the system. Failure to do that could lead to explosive destruction of the generator, requiring automatic safety relays to protect from operator error.

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[c] Kilovolt amperes (kva) and megavolt amperes (mva) are ratings for electrical equipment based on potential capacity and are higher than the watts measurements used since the nineteenth century. Volt ampere ratings are affected by power factor, the electrical efficiency of a circuit expressed as the ratio of actual power to apparent power. When noted with the power factor figure they provide an accurate picture of the real capacity of the electrical equipment (Dawes 1928: 158).

The conductors for magnetizing the poles were laid in deep slots cut into the rotor spindle. This form was pioneered by C. L. Brown for high-speed turbine driven generators in the early twentieth century.[202] To resist the centrifugal force acting to throw out the windings, they were held in place by retainer rings. The rotor was supported in oil-pressure bearings of the same type as the turbines and was in the same oil supply loop.[203] The stator body was fabricated of individual punched-out rings of silicon steel. The silicon content gave the laminations high magnetic permeability, reduced reluctance (resistance)[204] and concentrated the field magnetic flux in the windings. Slots were formed in the inner circumference of the rings to receive the copper conductors. The laminations were individually insulated, then stacked and pressed forming a hollow core.[205] Insulated through-bolts running from end to end ensured structural integrity. The laminated form of construction in which each component was insulated from its neighbor reduced the production of eddy currents which caused electrical losses.[206] The core was mechanically locked into the stator inner frame with key bars set into dovetails on the outer surface of the core.[207] Working in the early twentieth century, B. G. Lamme, Chief Engineer of Westinghouse, made many of the improvements to the wiring form of turbine generators incorporated into the Connecticut Yankee armature.[208] There were three separate winding coils running the length of the stator giving three-phase power. They divided the stator circle equally giving 120 degree separation of their alternations.[209] There were two insulated copper bars laid in each longitudinal trough formed by the lined- up slots. Each bar was made up of a number of insulated copper conductors formed in a spiral pattern. Insulation of each component of the conductors from adjacent components was critical to prevent destructive Short circuits and electrical phenomena such as coronas.[210] The electrical discharge from coronas constituted an electrical loss and produced ozone which could attack the insulation.[211] The coils had Thermalastic mica and resin insulation, introduced by Westinghouse in 1949, which had good resistance to ozone attack.[212] In addition to the insulation requirements, the conductors had to withstand structural displacement. They were held in place by wedges and springs to resist the powerful electromotive forces at work. At the ends of the core, the bars were joined by connection rings which completed the coils and oriented them in their respective phases. By connecting the bars in each coil in series, the voltages induced in each added up.[213] The electrical power was taken off with a grounded wye (Y) connection[214] eliminating the need to take out six leads (two for each phase). Instead, one lead came off each phase, with a neutral attaching to all three.[215]

The current flow in the conductors produced heat which had to be drawn off to prevent a drop in output.[216] The generator utilized pressurized hydrogen gas at over 60 psi passing through the stator and rotor for cooling. This cooling method came into use in the mid 1930s.[217] Hydrogen gas was supplied from outdoor banks of cylinders. To ensure complete coverage by the gas, a blower fan was shaft mounted near the coupling at the turbine end. This forced the gas into four hydrogen coolers where the gas gave up its heat to a flow of water from the service water system. Hydrogen then flowed through the rotor and stator. Field windings in the rotor were ported to ensure gas flow. Vent plates between the stator laminations promoted even cooling. Heating of the generator leads, bushings and connectors was prevented by hydrogen streams.[218] Because the generator's outer housing was under gas pressure, special gland seals were needed at each end of the casing at the shaft penetrations using oil under pressure.[219]These prevented hydrogen from exiting and creating an explosive mixture with the air in the Turbine Building. Any hydrogen left in the casing when opened for repair could also combine with incoming air and cause an explosion. Carbon dioxide was used to purge the hydrogen before maintenance, and to purge air in the machine before hydrogen was introduced.[220]

Most direct-current generators produce their own field magnetizing current. Synchronous alternating -current machines must have an outside source of this DC excitation current. The 500-volt DC to excite the rotating field came from a separate AC/DC rotating rectifier exciter mounted on an extension shaft coupled to the south end of the generator shaft. Utilizing an AC exciter generator and rectifying the current to DC (instead of a direct DC exciter) allowed a simpler and more reliable unit without pickup brushes. The exciter conductors were ventilated by air which gave up its heat in an air cooler connected to the service water system.[221] The exciter received its excitation current from a small permanent magnet DC generator (pmg) on the end of the exciter shaft.[222] A bored hole in the rotor shaft provided a route for wires from the exciter to the field magnet conductors.[223] In addition to producing the magnetizing current, the exciter system controlled generator output voltage during start-up. The critical device for this purpose was the solid-state voltage regulator which controlled the output of the pmg.[224] Varying the current going into the rotor with the voltage regulator directly affected the voltage produced by the generator. Once the generator was up to speed and synchronized with the system electrical grid by operators in the control room, the output was controlled by interaction among the system loads, the turbine governor and control circuitry in the regulator.[225] The generator produced 19,000 volts at 22,000 amps. Prior to the low-pressure rotor replacement, the average output was 605 mw. The improved performance with the new rotors boosted that to 612 mw.[226]

The generator output was directed out of the south end of the Turbine Building through an isolated-phase bus duct system.[227]Each phase was contained in a separate metal enclosure. A fan forced air through the ducts to draw off resistance heated air. The air was cooled in heat exchangers fed by the service water system.[228] The bus was split, connecting to two outdoor number-designated transformers in the 12R Switchyard at the south end of the building.[229] The 319 Transformer was the step-up device to raise the voltage to the system grid's 345 kilovolts (kv). This high voltage allowed transmission for long distances economically since it allowed small copper conductors to carry power at lower current. The heart of the transformer unit was the laminated silicon steel core with primary (entrance) and secondary (exit) windings. The core had separately insulated windings for each of the three phases.[230] The high amperage/low voltage output of the generator produced high voltage/low amperage current in the secondary windings via electromagnetic induction. The laminated construction of the cores served the same purpose as that of the generator stator; the reduction of wasteful eddy currents. The core and windings were secured inside an aluminum oil tank.[231] Heat produced by the current flow was drawn off by the oil around the windings. Heated oil was continuously pumped into tubed heat exchanger units attached to the outer casing and cooled by fans. As the load on the station increased and oil temperatures rose, the fans came on automatically to maintain the full rating (power capacity) of the transformers. Current was taken out of the tank by three wires with insulated oil-tight bushings and sent via the 320 Line to the 14B 345 kv Switchyard, at the southeast end of the plant site, for distribution to the system grid.[232] The output voltage could be adjusted (though not under load) with a tap changer hand wheel which changed the ratio of primary to secondary wiring.[233] There were no isolating breakers or switches between the main generator and the 319 Transformer. When de-energized it could be isolated from the 320 line to main 14B Switchyard by motor-operated disconnect (MOD) switches, which could also be manually cranked open/closed.[234] When under load, the 319 unit was switched by gas-quenched power circuit breakers (PCBs) in the 14B yard.[235] Between the transformer and MODs were the lightning arresters.[236]

The 19,000 KV generator output was also sent to the 309 step down transformer. It was of similar construction to the 319 unit, and produced a lower voltage of 4.16 KV for supplying the reactor coolant pumps.[237] A series of primary and backup protective relays in the control room prevented damage to the reactor, turbines and generator from electrical problems. The relays could be activated by faults in either the turbine power into the generator, generator output, or the distribution grid.[238] Faults in the system such as grounds in the generator, leads, and transformers automatically activated relays in the switchyard to protect the grid. The exciter would have also tripped dropping the generator output. Relays protected against two conditions which could lead to over speeding of the generator turbine: loss of field and reverse current.[239] Some of the protective relays had time delays if a too rapid shutdown could endanger other equipment up or downstream of the fault.

Other anomalies such as loss of service water for cooling the hydrogen system, low bearing or seal oil, and loss of exciter cooling air would either trigger alarms to warn operators to make manual adjustments or the relays could initiate an automatic shutdown if warranted.[240]

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3 Connecticut Yankee Atomic Power Company 1987b: 5; Connecticut Yankee Atomic Power Company. Stone & Webster Engineering Corp. 1964f drawings].

4 Connecticut Yankee Atomic Power Company. Stone & Webster Engineering Corp. 1964-1992 [drawings].

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13 Ibid: Chapter 16, page 46.

14 Ibid: Chapter 19, page 16.

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16 Ibid: Chapter 22, page 46.

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[17] Ibid: 16, page 13.

[18] Ibid: page 33.

[19] Ibid: Chapter 16, page 5.

[20] Connecticut Yankee Atomic Power Company 1966-1974: 8.1-1.

[21] Ibid: 8.1-4; Connecticut Yankee Atomic Power Company 1998a [drawings].

[22] Connecticut Yankee Atomic Power Company 1987-1993: Chapter 17, page I.

[23] Ibid: 3

[24] Connecticut Yankee Atomic Power Company 1966-1974: 8.1-1.

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[27] MacNaughton 1967: 513.

[28] Connecticut Yankee Atomic Power Company 1998:1.2-11; Gray 1917: 14.

[29] Morgan 1950: 9.

[30] Connecticut Yankee Atomic Power Company 1987-1993: Chapter 22, page 1.

[31] Church 1935: 9.

[32] Morgan 1950: 8.

[33] Church 1953:10.

[34] Sinton 1966: 112.

[35] Connecticut Yankee Atomic Power Company 1987-1993: Chapter 22, page 42.

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[36] Ibid: chapter 22, page 42.

[37] Connecticut Yankee Atomic Power Company 1966-1974: 8.2-1.

[38] Ibid: 8.2-2.

[39] Connecticut Yankee Atomic Power Company 1987-1993: Chapter 22, page 43.

[40] Ibid.

[41] Ibid: Chapter 22, page 6.

[42] Connecticut Yankee Atomic Power Company 1966-1974: 8.2-2.

[43] Clark 2004.

[44] Connecticut Yankee Atomic Power Company 1987-1993: Chapter 23, page 3.

[45] Ibid: Chapter 23, page 4.

[46] Connecticut Yankee Atomic Power Company 1987-1993: Chapter 23, page 3; MacNaughton 1967: 507.

[47] Connecticut Yankee Atomic Power Company 1987-1993: Chapter 23, page 18.

[48] Connecticut Yankee Atomic Power Company 1966-1974: 8.2-2.

[49] Connecticut Yankee Atomic Power Company 1987-1993: Chapter 23, page 38.

[50] Ibid: Chapter 23, page 22.

[51] Ibid: Chapter 22, page 18.

[52] Ibid.

[53] Ibid: page 18.

[54] Ibid.

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57 Ibid: 477, Richardson: 191): 5.

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68 MacNaughton 1967: 487.

69 Ibid. Chapter 27, page 3.

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73 Bourne 1846: 229, Knight 1/205

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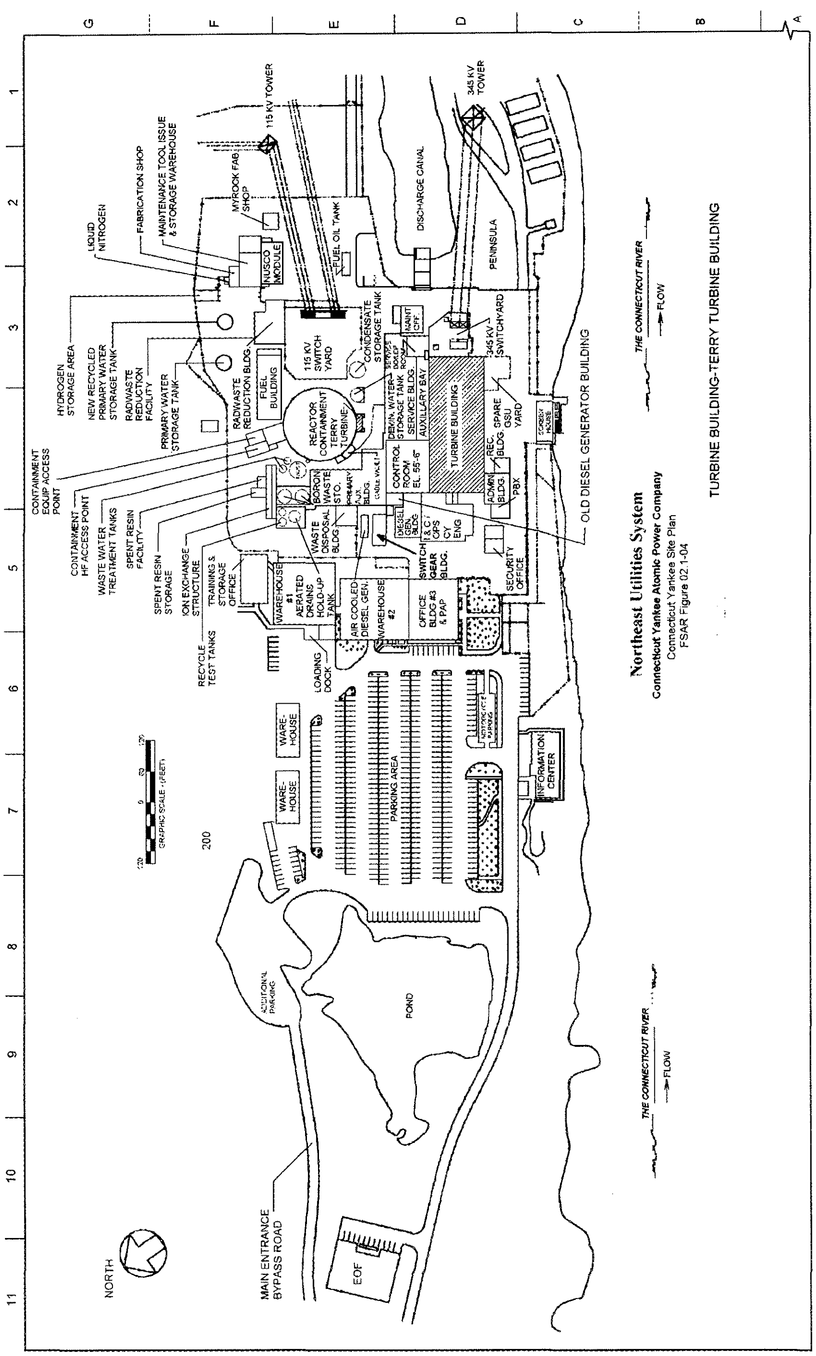


Figure 1 - Location of Turbine Building and Terry Turbine Building

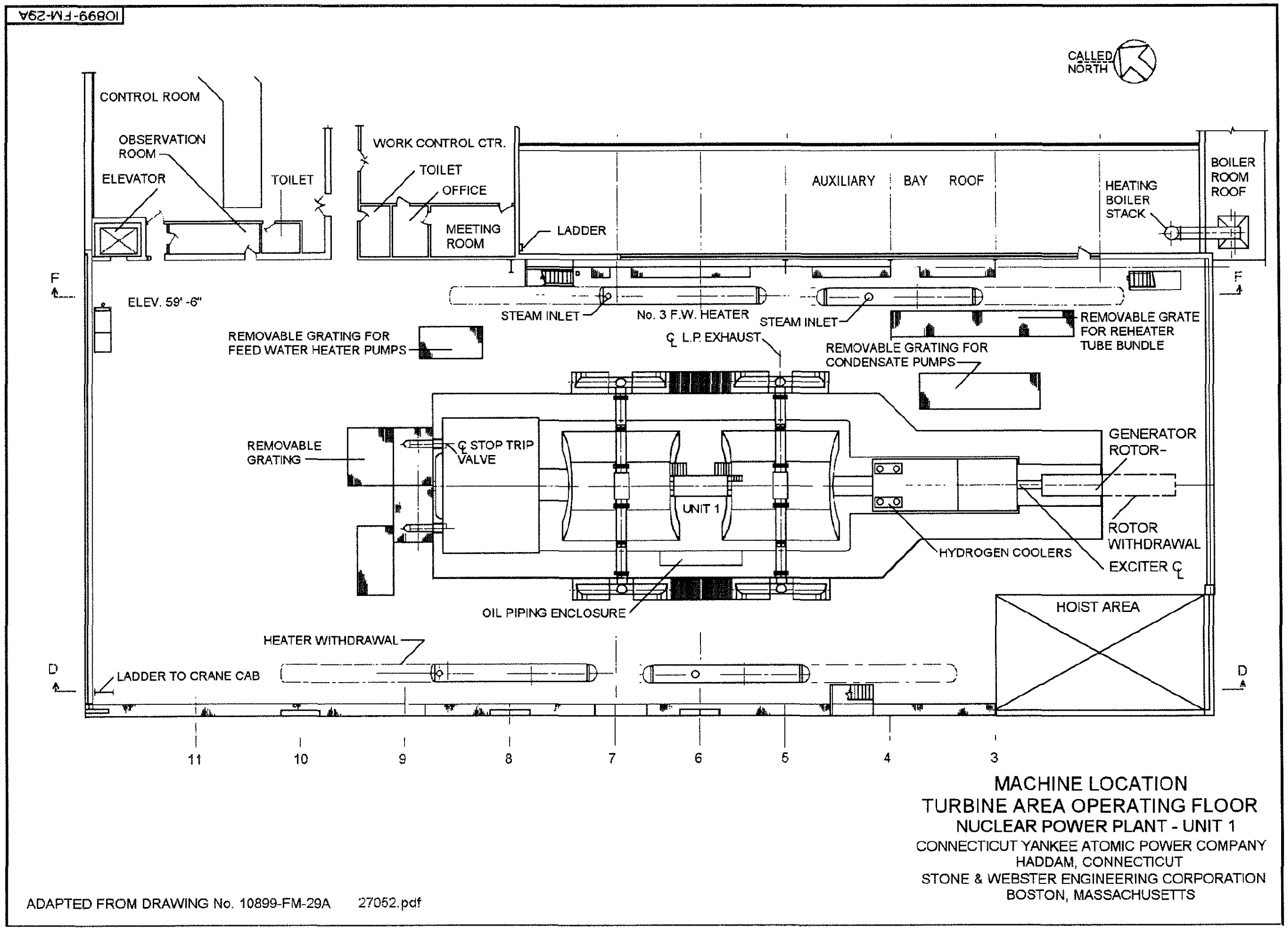


Figure 2 - Plan View of Turbine Building

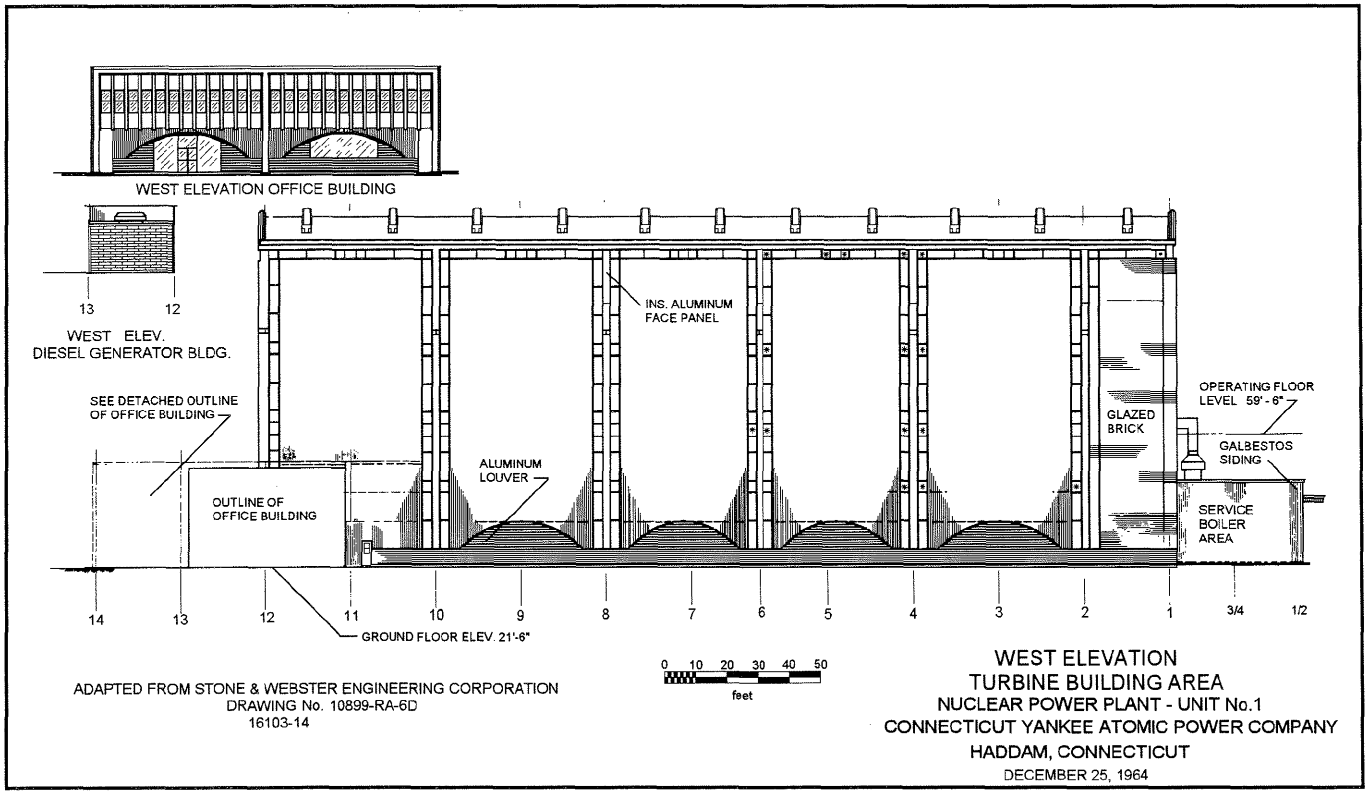


Figure 3 - West Elevation - Turbine Building

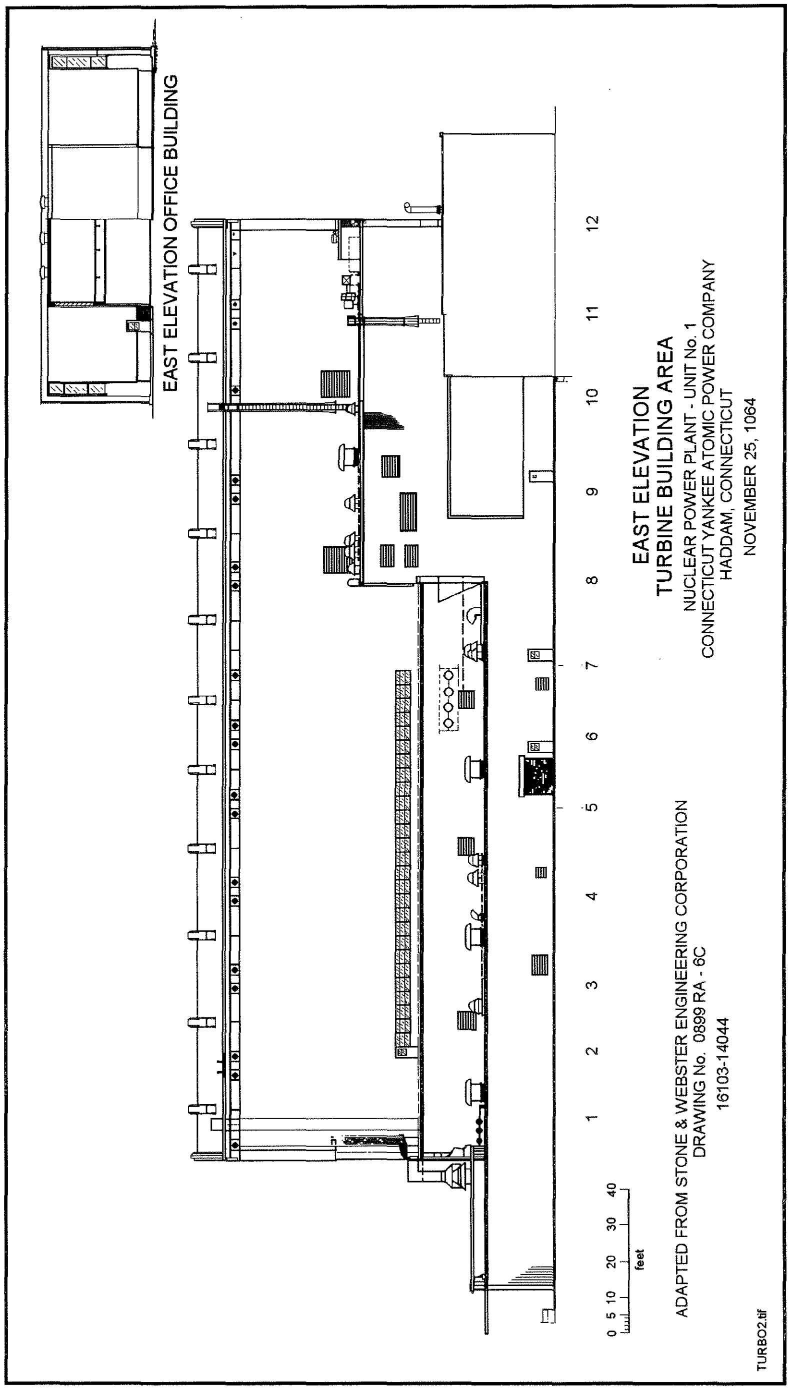


Figure 4 - East Elevation Turbine Building

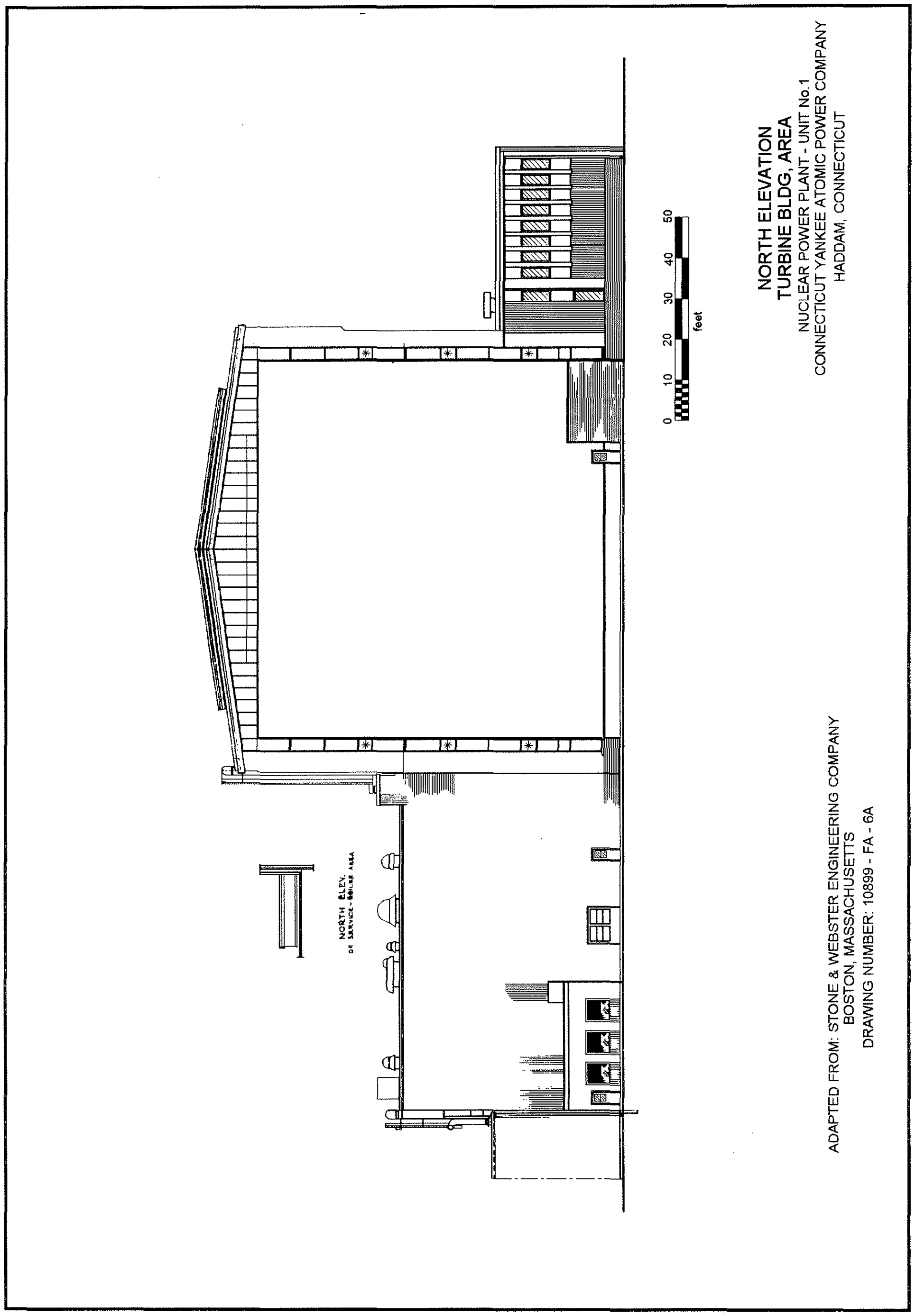


Figure 5 - North Elevation - Turbine Building

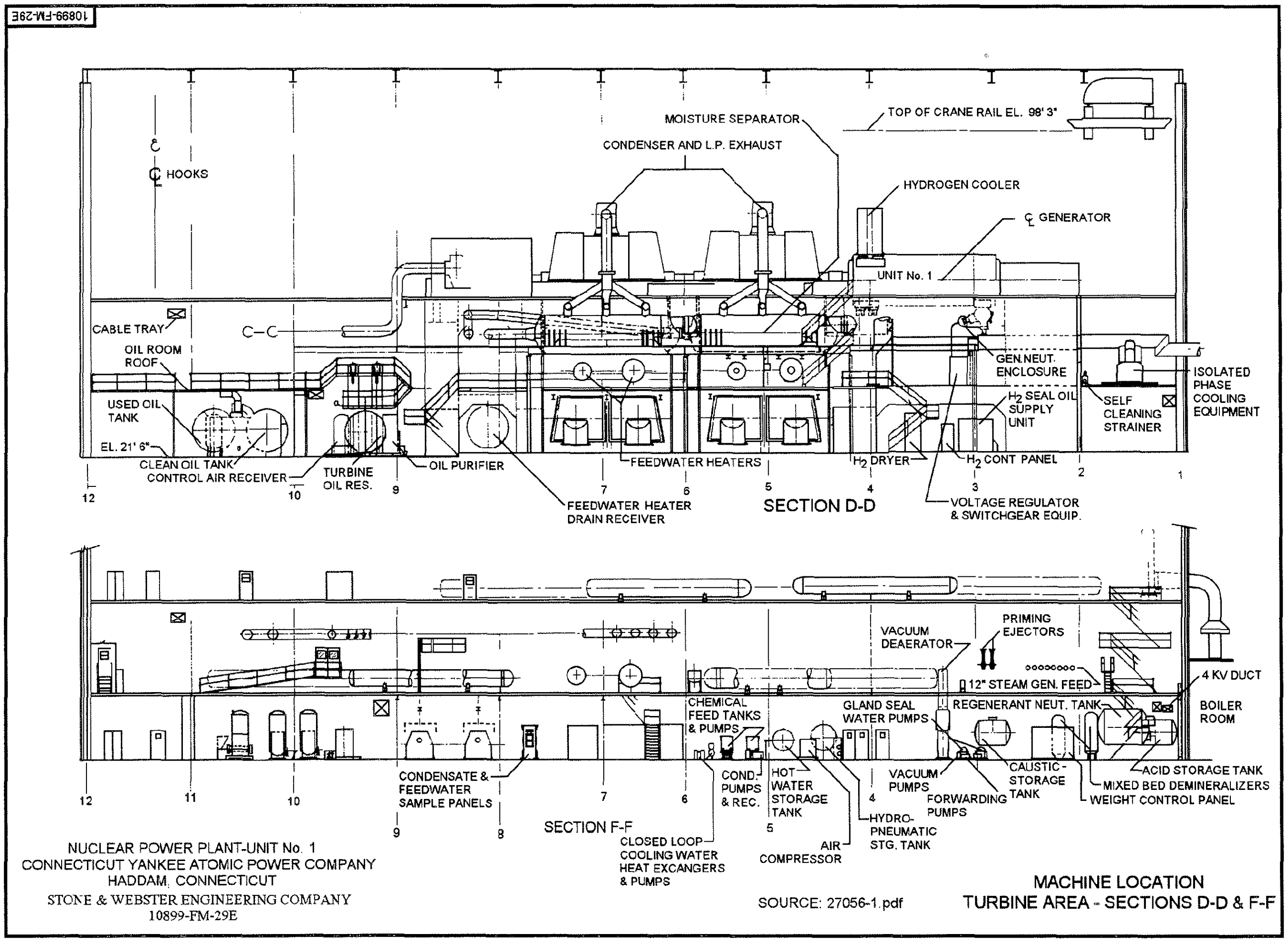


Figure 6 - Section of Turbine Building

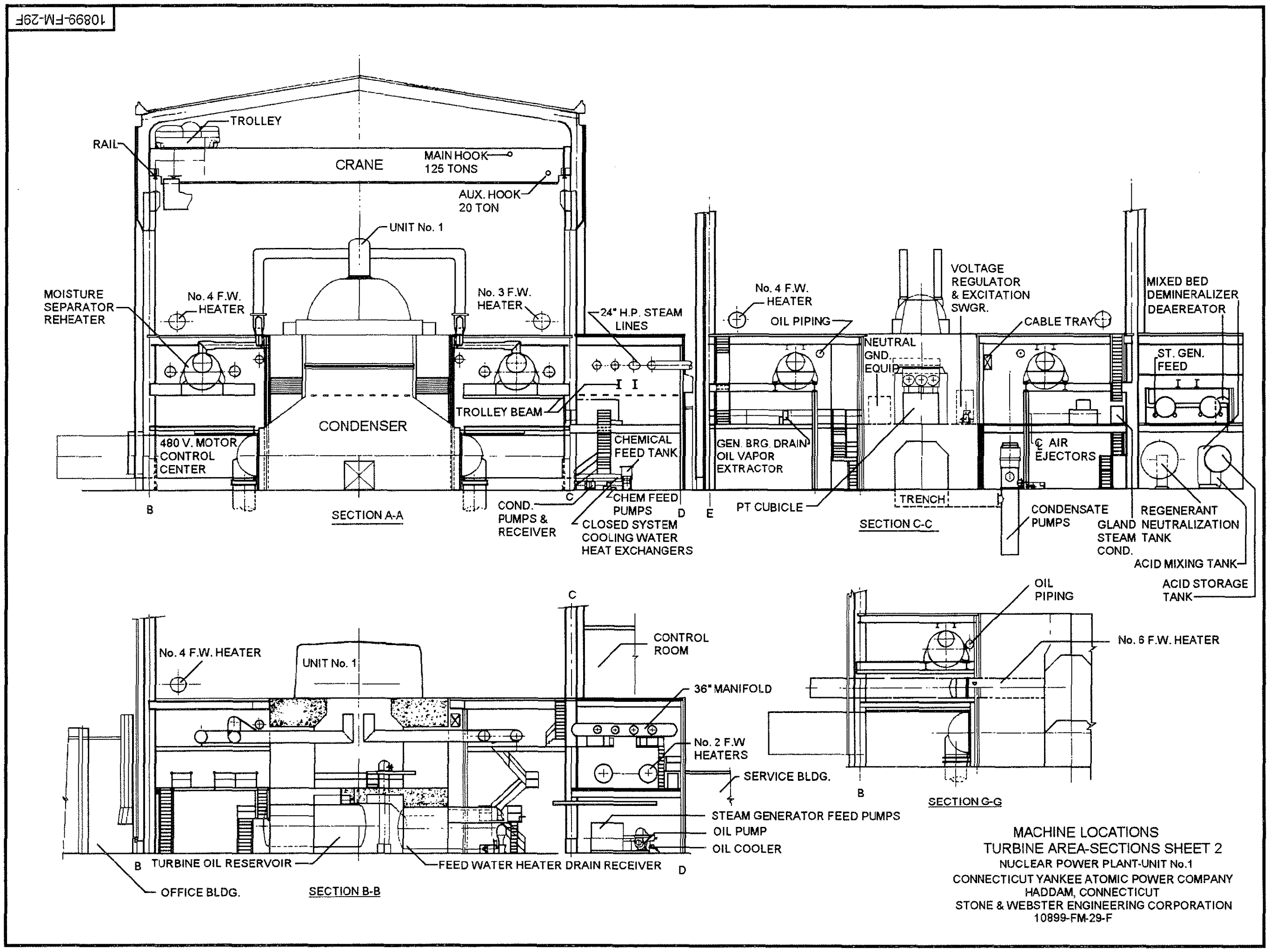


Figure 7 - Section of Turbine Building

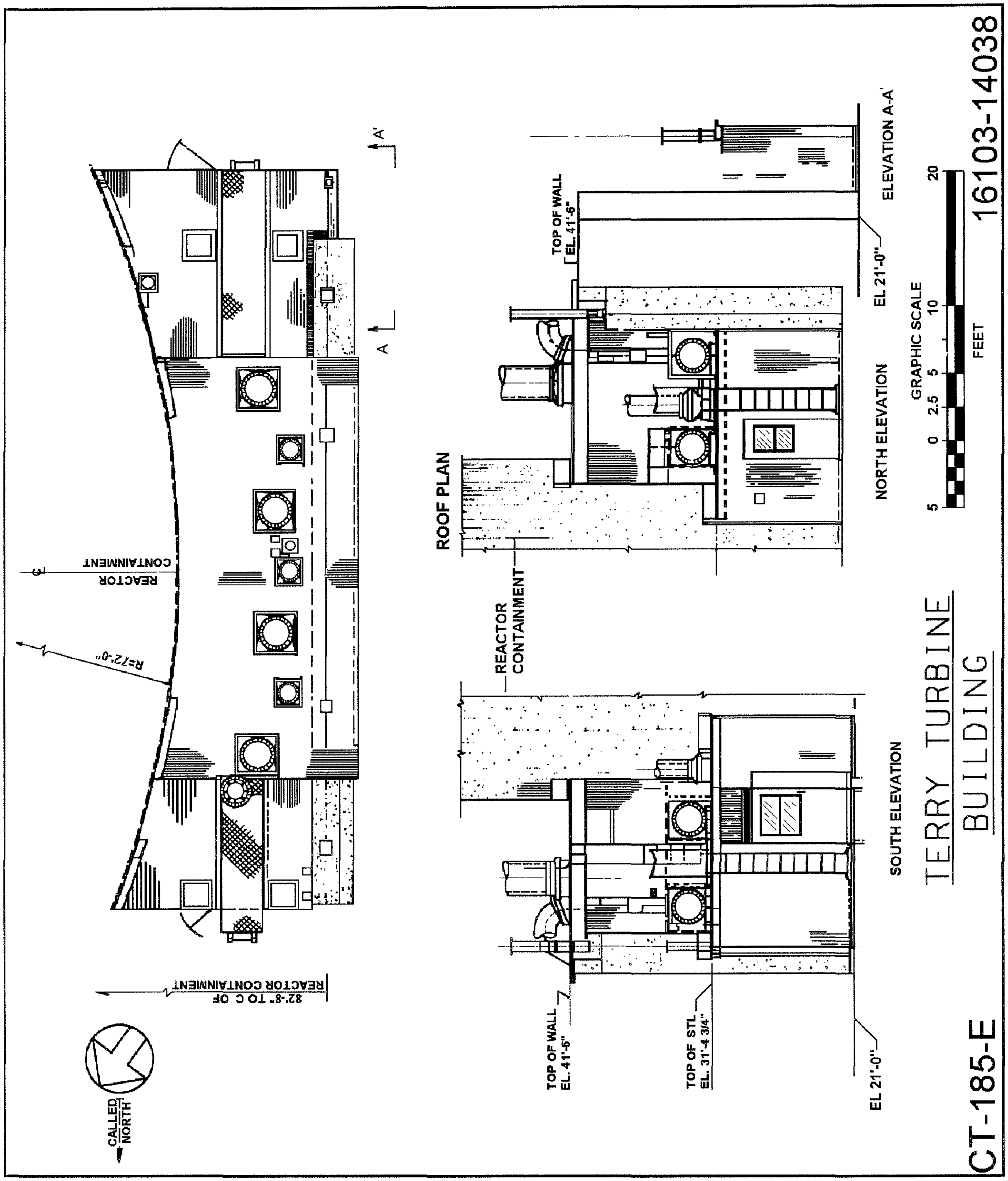
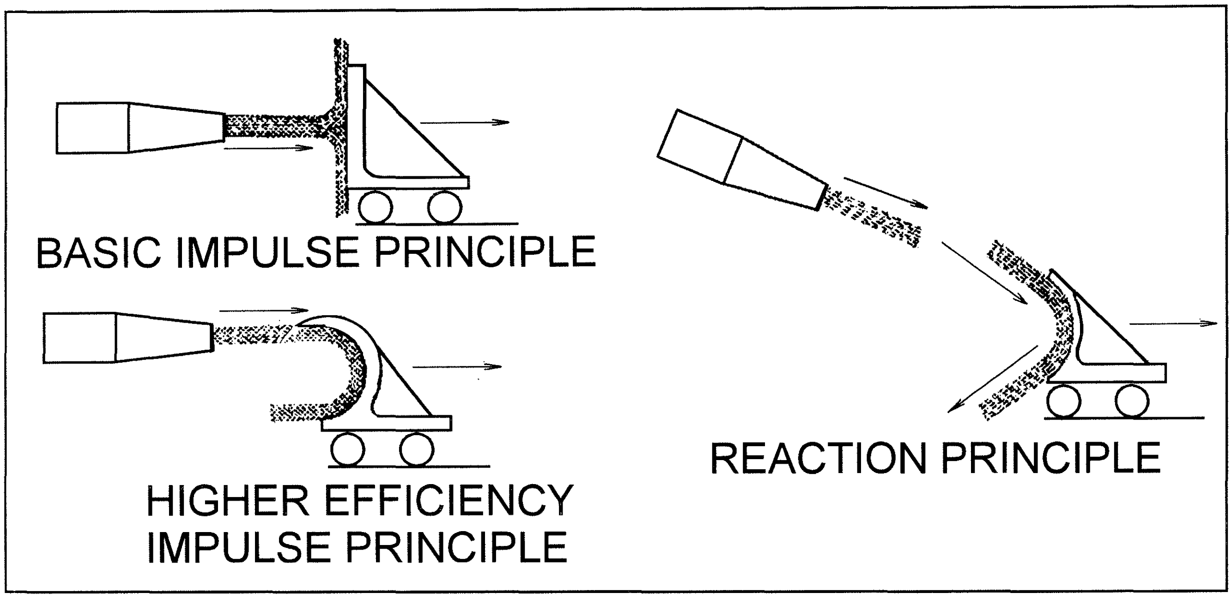


Figure 8 - Plan and Elevation of Terry Turbine Building

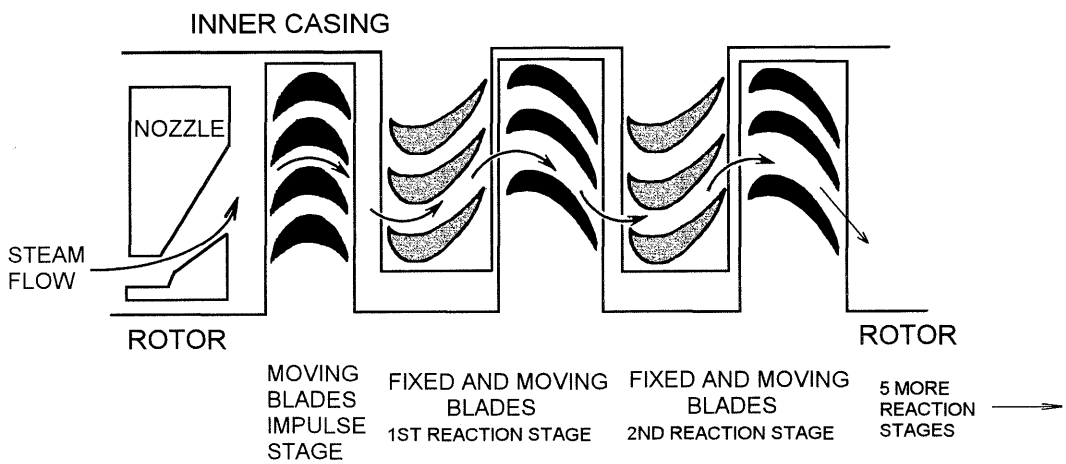
APPENDIX A



SCHEMATIC DIAGRAMS OF IMPULSE AND REACTION TURBINE PRINCIPLES
(base images: Church 1935)

The basic principal of an impulse turbine wheel may be visualized as a jet of water directed against a flat plate which is moved back by the steady pressure on it. To have a continuous action a succession of plates would have to be struck by the jet. In the steam turbine these are the blades attached to the rotating turbine wheel. In fact, a cup-shaped surface is much more efficient at utilizing the energy in the fluid, so the blades are twisted. The twist causes the steam to leave the blades at an angle of 180 degrees which increases the propulsive force 100 percent. The reaction turbine wheel is analogous to a rocket engine or spinning lawn sprinkler. In a rocket, a jet of combustion products ejected out of a nozzle causes the motor to move in the opposite direction in an equal reaction. In the lawn sprinkler the water leaving the arm at a right angle creates the thrust. In the reaction steam turbine the action is more complex. The steam traveling from the fixed guide blades to the moving blades is turned twice and incorporates an impulsive component. The critical shape of the blading causes the steam to expand and speed up as it leaves the moving blades creating the reaction force on the rotating blade wheel (Church 1935: 113).

The impulse or Rateau stage consisted of one row of nozzles and one row of moving blades. As steam passed through the nozzles, it accelerated until its velocity in the direction of rotation was about twice that of the moving blade. The moving blade absorbed this impulse and transferred it to the rotor in the form of kinetic energy. Steam pressure decreased as it passed through the nozzle, and then remained practically constant as it passed through the rotating blades, dropping only enough to maintain the forward flow of the steam. The velocity of the steam increased as it passed through the nozzle and decreased as it passed through the blades and performed work on the rotor. Ideally, the velocity of the steam exiting the blades was the same as that of the steam entering the nozzles.



SCHEMATIC DIAGRAM OF HIGH-PRESSURE TURBINE BLADE STAGING (base image: Connecticut Yankee Atomic Power Company 1987-1993: Chapter 22, page 79).

The seven reaction stages consisted of alternating rows of stationary and rotating blades that were practically identical in design and function. Each stage had one row of fixed blades and one row of moving blades. Blades on both rows were shaped so that the area between two adjacent blades of the same row formed a nozzle. Steam pressure dropped progressively as it passed through both stationary and rotating blading. The expansion of the steam in the fixed blading served only to give it the velocity necessary to enter the moving blading. Further steam expansion in the moving blading created a reaction force which worked on the moving blading. Steam velocity was sufficient to allow the steam to escape from the moving blading and enter the next row of fixed blading. Thus, velocity rose and then dropped completely in each stage. The pressure drop for a reaction stage is much less than that of an impulse stage. A reaction turbine is moved by three main forces. The reaction force produced on the moving blades as the steam increases in velocity as it expands through the nozzle-shaped spaces between the blades, the reaction force produced on the moving blades when the steam changes direction and the impulse of the steam impinging upon the blades. Each set of reaction blades utilized an additional expansion of the steam, and the rows got larger in diameter as the steam gained volume in its flow through the turbine (Connecticut Yankee Atomic Power Company 1987 & 1993: Chapter 22, pages 13-14).