10.2 Turbine-Generator

The function of the turbine-generator is to convert thermal energy into electric power.

10.2.1 Design Basis

10.2.1.1 Safety Design Basis

The turbine-generator serves no safety-related function and therefore has no nuclear safety design basis.

10.2.1.2 Power Generation Design Basis

The following is a list of the principal design features:

- The turbine-generator is designed for baseload operation and for load follow operation.
- The main turbine system (MTS) is designed for electric power production consistent with the capability of the reactor and the reactor coolant system.
- The turbine-generator is designed to trip automatically under abnormal conditions.
- The system is designed to provide proper drainage of related piping and components to prevent water induction into the main turbine.
- The main turbine system satisfies the recommendations of Nuclear Regulatory Commission Branch Technical Position ASB 3-1 as related to breaks in high-energy and moderate-energy piping systems outside containment. The main turbine system is considered a high-energy system.
- The system provides extraction steam for seven stages of regenerative feedwater heating.

10.2.2 System Description

The Westinghouse turbine-generator is designated as a TC4F 47-inch last-stage blade unit consisting of turbines, a generator, external moisture separator/reheater, exciter, controls, and auxiliary subsystems. (See Figure 10.2-1.) The major design parameters of the turbine-generator and auxiliaries are presented in Table 10.2-1. The piping and instrumentation diagram containing the stop, governing control, intercept, and reheat valves is shown in Figure 10.3.2-2.

The turbine-generator and associated piping, valves, and controls are located completely within the turbine building. There are no safety-related systems or components located within the turbine building. The probability of destructive overspeed condition and missile generation, assuming the recommended inspection and test frequencies, is less than 1×10^{-5} per year. In addition, orientation of the turbine-generator is such that a high-energy missile would be directed at a 90 degree angle away from safety-related structures, systems, or components. Failure of turbine-generator equipment does not preclude safe shutdown of the reactor. The turbine-generator components and instrumentation associated with turbine-generator overspeed protection are accessible under operating conditions.

10.2.2.1 Turbine-Generator Description

The turbine is a 1800-rpm, tandem-compound, four-flow, reheat unit with 47-inch last-stage blades (TC4F 47-inch LRB). The high-pressure turbine element includes one double-flow, high-pressure turbine. The low-pressure turbine elements include two double-flow, low-pressure turbines and one external moisture separator/reheater (MSR) with one stage of reheating. The single direct-driven generator is gas cooled and rated at 880 MVA at 22 kV, 0.90 PF. Other related system components include a complete turbine-generator bearing lubrication oil system, a digital electrohydraulic (DEH) control system with supervisory instrumentation, a turbine steam sealing system (refer to subsection 10.4.3), overspeed protective devices, turning gear, a generator hydrogen and seal oil system, a generator CO_2 system, an exciter cooler, a rectifier section, an exciter, and a voltage regulator.

The turbine-generator foundation is a spring-mounted support system. A spring-mounted turbine-generator provides a low-tuned, turbine-pedestal foundation. The springs dynamically isolate the turbine-generator deck from the remainder of the structure in the range of operating frequencies, thus allowing for an integrated structure below the turbine deck. The condenser is supported on springs and attached rigidly to the low-pressure turbine exhausts.

The foundation design consists of a reinforced concrete deck mounted on springs and supported on a structural steel frame that forms an integral part of the turbine building structural system. The lateral bracing under the turbine-generator deck also serves to brace the building frame. This "integrated" design reduces the bracing and number of columns required in the building. Additionally, the spring-mounted design allows for dynamic uncoupling of the turbine-generator foundation from the substructure. The spring mounted support system is much less site dependent than other turbine pedestal designs, since the soil structure is decoupled from turbine dynamic effects. The turbine-generator foundation consists of a concrete table top while the substructure consists of supporting beams and columns. The structure below the springs is designed independent of vibration considerations. The turbine-generator foundation and equipment anchorage are designed to the same seismic design requirement as the turbine building. See subsection 3.7.2.8 for additional information on seismic design requirements. See subsection 10.4.1.2 for a description of the support of the condenser.

10.2.2.2 Turbine-Generator Cycle Description

Steam from each of two steam generators enters the high-pressure turbine through four stop valves and four governing control valves; each stop valve is in series with one control valve. Crossties are provided upstream of the turbine stop valves to provide pressure equalization with one or more stop valves closed. After expanding through the high-pressure turbine, exhaust steam flows through one external moisture separator/reheater vessel. The external moisture separator reduces the moisture content of the high-pressure exhaust steam from approximately 10 to 20 percent to 0.17 percent moisture or less.

The reheater uses a portion of the main steam supply to reheat the steam to superheated conditions. The reheated steam flows through separate reheat stop and intercept valves in each of four reheat steam lines leading to the inlets of the two low-pressure turbines. Turbine steam extraction connections are provided for seven stages of feedwater heating. Steam from the first two extraction points of the high-pressure turbine is supplied to high-pressure feedwater heaters No. 6 and 7. The high-pressure turbine exhaust supplies steam to the deaerating feedwater heater. The low-pressure turbine third, fourth, fifth, and sixth extraction points supply steam to the low-pressure feedwater heaters No. 4, 3, 2, and 1, respectively.

Moisture is removed at a number of locations in the blade path. Drainage holes drilled through the blade rings provide moisture removal from blade rings located in high moisture zones. The effectiveness of moisture removal at these locations is enhanced by moisture nonreturn catchers which trap a large portion of the water from the blade path and direct it to the moisture removal system.

The external moisture separator/reheater uses multiple vane chevron banks (shell side) for moisture removal. The moisture removed by the external moisture separator/reheater drains to a moisture separator drain tank and is pumped to the deaerator.

Condensed steam in the reheater (tube side) is drained to the reheater drain tank, flows into the shell side of the No. 7 feedwater heater, and cascades through the No. 6 feedwater heater shell to the deaerator.

10.2.2.3 Exciter Description

The excitation system is a brushless exciter with a solid-state voltage regulator. Excitation power is obtained from the rotating shaft, which is directly connected to the main generator shaft. The brushless exciter consists of three parts: a permanent magnet pilot exciter, a main ac exciter, and a rectifier wheel. The exciter rectifiers are arranged in a full-wave bridge configuration and protected by a series-connected fuse. The turbine building closed cooling water system (TCS) provides cooling water to the exciter air-to-water heat exchangers.

10.2.2.4 Digital Electrohydraulic System Description

The turbine-generator is equipped with a digital electrohydraulic (DEH) system that combines the capabilities of solid-state electronics and high-pressure hydraulics to regulate steam flow through the turbine. The control system has a speed control unit, a load control unit, and an automatic turbine control (ATC) unit which may be used, either for control or for supervisory purposes, at the option of the plant operator.

The DEH system employs three electric speed inputs whose signals are processed in redundant microprocessors. Valve opening actuation is provided by a hydraulic system that is independent of the bearing lubrication system. Valve closing actuation is provided by springs and steam forces upon reduction or relief of fluid pressure. The system is designed so that loss of fluid pressure, for any reason, leads to valve closing and consequent turbine trip.

Steam valves are provided in series pairs. A stop valve is tripped by the overspeed trip system; the control valve is modulated by the governing system and is actuated by the trip system.

10.2.2.4.1 Speed Control Unit

The speed control unit provides speed control, acceleration, and overspeed protection functions. The speed control unit produces a speed error signal, which is fed to the load control unit. The speed error signal is derived by comparing the desired speed with the actual speed of the turbine at steady-state conditions or by comparing the desired acceleration rate with the actual acceleration rate during startup.

The speed select algorithm receives three speed signals, performs a two-out-of-three comparison, compares the result to the speed reference signal, and transmits the error signal demanding the appropriate speed to the speed controller. A failure of one speed input generates an alarm. Failure of two or more speed inputs also generates an alarm and changes speed control to a manual mode of operation where automatic compensation for speed changes (except overspeed protection) will not occur.

The speed control unit uses two redundant channels, a primary and a backup. If the primary channel fails, the backup channel takes over automatically. If the backup channel fails, the primary channel will maintain control. In the event that both channels are lost, the turbine trips.

A trip signal is sent to a fast acting solenoid valve which actuates each control valve and intercept valve. Energizing these solenoid valves releases the hydraulic fluid pressure in the valve actuators, allowing springs to close each valve.

The speed control unit is designed to slowly vary the rotor speed above and below critical frequencies when operating near critical speed. This will prevent the turbine from running at a constant speed near critical blade resonances.

10.2.2.4.2 Load Control Unit

The load control unit develops signals that are used to regulate unit load. Signal outputs are based on a proper combination of the speed error, impulse pressure, and actual load (turbine megawatt) reference signals.

Steam flow is not controlled directly but rather by a characterization of turbine megawatt and valve position. Under normal conditions, the turbine requests a certain megawatt load target. Through a coordinated mode of control, the turbine valves adjust the steam flow from the steam generators supplied to the turbine.

10.2.2.4.3 Valve Control

The flow of the main steam entering the high-pressure turbine is controlled by four stop valves and four governing control valves. Each stop valve is controlled by an electrohydraulic actuator, so that the stop valve is either fully open or fully closed. The function of the stop valves is to shut off the steam flow to the turbine when required. The stop valves are closed by actuation of the emergency trip system devices. These devices are independent of the electronic flow control unit.

The turbine control valves are positioned by electrohydraulic servo actuators in response to signals from their respective flow control unit. The flow control unit signal positions the control valves for wide-range speed control through the normal turbine operating range, and for load control after the turbine-generator unit is synchronized.

The reheat stop and intercept valves, located in the hot reheat lines at the inlet to the low-pressure turbines, control steam flow to the low-pressure turbines. During normal operation of the turbine, the reheat stop and intercept valves are wide open. The intercept valve flow control unit positions the valve during startup and normal operations and closes the valve rapidly on loss of turbine load. The reheat stop valves close completely on turbine overspeed and turbine trip.

The control, stop, reheat stop, and intercept valves have dump valves connected to the hydraulic portion of their respective valve actuators. Opening a dump valve causes the connected control or stop valve to rapidly close. The dump valve actuators are connected to trip headers and open in response to loss of pressure in the connected trip header. The control and intercept dump valves are connected to the DEH overspeed protection control trip header and the stop and reheat stop dump valves are connected to the auto stop emergency trip header.

10.2.2.4.4 Power/Load Unbalance

A rate sensitive power/load unbalance circuit initiates fast closing intercept valve action under load rejection conditions that might lead to rapid rotor acceleration and consequent overspeed.

Valve action occurs when the power exceeds the load by 30 percent or more, and when the generator current is lost in a time span of 35 milliseconds or less. Cold reheat pressure is used as a measure of power. Generator current is used as a measure of load to provide discrimination between loss of load incidents and occurrences of electric system faults.

When the detection circuitry provides a signal indicating a power/load unbalance condition, the load reference signal is grounded, and the load reference motor begins to run back toward the no-load flow point. Should the condition disappear quickly, the power/load unbalance circuitry resets automatically, and the load reference signal is reestablished near its value prior to the loss of load.

10.2.2.4.5 Overspeed Protection

The DEH has two modes of operation to protect the turbine against overspeed. The first is the speed control that functions to maintain the desired speed as discussed in subsection 10.2.2.4.1. The second mode is the overspeed protection control which operates if the normal speed control should fail or upon a load rejection. The overspeed protection control opens a drain path for the hydraulic fluid in the overspeed protection control header if the turbine speed exceeds 103 percent of rated speed. The loss of fluid pressure in the header causes the control and intercept valves to close. If the speed falls below rated speed following an overspeed protection controller action, the header pressure is reestablished, the control and intercept valves are reopened, and the unit resumes speed control. Refer to Table 10.2-2 for a description of the sequence of events following a full-load rejection and the nominal trip setpoints. An emergency trip system is also provided to trip the turbine in the event that speeds in excess of the overspeed protection control trip points are reached. The emergency trip system is discussed in subsection 10.2.2.5.1.

Redundancy is built into the DEH overspeed protection control. The failure of a single valve will not disable the trip functions. The overspeed protection components are designed to fail in a safe position. Loss of the hydraulic pressure in the emergency trip system causes a turbine trip. Therefore, damage to the overspeed protection components, results in the closure of the valves and the interruption of steam flow to the turbine.

Quick closure of the steam valves prevents turbine overspeed. Valve closing times are given in Table 10.2-4.

10.2.2.4.6 Automatic Turbine Control

Automatic turbine control provides safe and proper startup and loading of the turbine generator. The applicable limits and precautions are monitored by the automatic turbine control programs even if the automatic turbine control mode has not been selected by the operator. When the operator selects automatic turbine control, the programs both monitor and control the turbine. The DEH controller takes advantage of the capability of the computer to scan, calculate, make decisions, and take positive action.

The automatic turbine control is capable of automatically:

- Changing speed
- Changing acceleration
- Generating speed holds
- Changing load rates
- Generating load holds

The thermal stresses in the rotor are calculated by the automatic turbine controls programs based on actual turbine steam and metal temperatures as measured by thermocouples or other temperature measuring devices. Once the thermal stress (or strain) is calculated, it is compared with the allowable value, and the difference is used as the index of the permissible first stage temperature variation. This permissible temperature variation is translated in the computer program as an allowable speed or load or rate of change of speed or load.

Values of some parameters are stored for use in the prediction of their future values or rates of change, which are used to initiate corrective measures before alarm or trip points are reached.

The rotor stress (or strain) calculations used in the program, and its decision-making counterpart are the main controlling sections. They allow the unit to roll with relatively high acceleration until the anticipated value of stress predicts that limiting values are about to be reached. Then a lower acceleration value is selected and, if the condition persists, a speed hold is generated. The same philosophy is used on load control in order to maintain positive control of the loading rates.

The automatic turbine controls programs are stored and executed in two redundant distributed processing units, one of which contains the rotor stress programs and the other a majority of the automatic turbine controls logic programs. These units communicate with each other and the base system via a data highway. Once the turbine is latched, the automatic turbine controls programs are capable of rolling the turbine from turning gear to synchronous speed with supervision from a single operator.

Once the turbine-generator reaches synchronous speed, the startup or speed control phase of automatic turbine control is completed and no further action is taken by the programs. Upon closing the main generator breaker, the DEH automatically picks up approximately 5 percent of rated load to prevent motoring of the generator. At this time, the DEH is in load control.

The DEH unit is equipped with a remote control interface. Selection of the remote mode provides for control of the turbine-generator from an operator console. In the remote mode of control, the rate of this load change is controlled by the amount of this load change.

In the combined mode of both remote control and automatic turbine control, the automatic turbine control allows the remote control system control of load changes until an alarm condition occurs. If the operating parameters being monitored (including rotor stress) exceed their associated alarm limit, a load hold is generated in conjunction with the appropriate alarm message. The DEH generates the load hold by ignoring any further load increase or decrease until the alarm condition is cleared or until the operator overrides the alarm condition. At the same time that the DEH generates the load hold based on the automatic turbine control alarm condition, the DEH also informs the remote control system of its action. In the combined mode of control, both the load reference and the load rate are implicitly controlled by the remote control system while the automatic turbine control supervises the load changes with overriding control capability.

The operator may remove the turbine-generator from automatic turbine control. This action places the automatic turbine control in a supervisory capacity.

10.2.2.5 Turbine Protective Trips

Turbine protective trips, when initiated, cause tripping of the main stop, control, intercept, and reheat stop valves. The protective trips are:

- Low bearing oil pressure
- Low electrohydraulic fluid pressure
- High condenser back pressure
- Turbine overspeed
- Thrust bearing wear
- Remote trip that accepts external trips

A description of the trip system for turbine overspeed is provided below.

10.2.2.5.1 Emergency Trip System

The purpose of the emergency trip system is to detect undesirable operating conditions of the turbine-generator, take appropriate trip actions, and provide information to the operator about the detected conditions and the corrective actions. In addition, means are provided for testing emergency trip equipment and circuits.

The system utilizes a two channel configuration which permits on line testing with continuous protection afforded during the test sequence. A mechanical overspeed trip is also provided as described in 10.2.2.5.3.

The emergency trip system includes the emergency trip control block, trip solenoid valves, test panel, the mechanical overspeed trip device, speed sensors, and a test panel. These items and the function of the overspeed trips are describe in the following three subsystems.

10.2.2.5.2 Emergency Trip Control Block

The auto stop emergency trip header pressure is established when the auto stop trip solenoid valves are energized closed. The valves are arranged in two channels for testing purposes—the odd numbered pair correspond to channel 1, and the even numbered pair correspond to channel 2. This convention is carried throughout the emergency trip system in designating devices; e.g., channel 1 devices are odd-numbered, and channel 2 devices are even-numbered. Both valves in a channel will open to trip that channel. Both channels must trip before the auto stop trip header pressure collapses to close the turbine steam inlet valves. Each tripping function of the electrical emergency trip system can be individually tested from the operator/test panel without tripping the turbine by separately testing each channel of the appropriate trip function. The solenoid valves may be individually tested. Spool-type solenoid valves are not used in the emergency trip control block.

A trip of the emergency trip system opens a drain path for the hydraulic fluid in the auto stop emergency trip header. The loss of fluid pressure in the trip header causes the main stop and reheat stop valves to close. Also, check valves in the connection to the overspeed protection control header open to drop the pressure in the overspeed protection control header and cause the control and intercept valves to close. The control and intercept valves are redundant to the main stop and reheat stop valves respectively.

10.2.2.5.3 Overspeed Trip Functions and Mechanisms

The emergency overspeed trips for the AP600 turbine consist of a mechanical and an electrical trip. The mechanical emergency overspeed trip trips before the electrical emergency trip. The emergency overspeed trip setpoints are identified in Table 10.2-2.

The mechanical overspeed trip device consists of a spring-loaded trip weight mounted in the rotor extension shaft. At normal operating speed, the weight is held in the inner position by the spring. When the turbine speed reaches the trip setpoint, the centrifugal force overcomes the compression force of the spring and throws the trip weight outward striking a trigger. As the trigger moves, it unseats a cup valve which drains the mechanical overspeed and manual trip header. The mechanical overspeed and manual trip header can be tripped manually via a trip handle mounted on the governor pedestal.

The electrical overspeed trip system has separate, redundant speed sensors and provides backup overspeed protection utilizing the trip solenoid valves in the emergency trip control block to drain the emergency trip header. The hydraulic fluid in the trip and overspeed protection control headers is independent of the bearing lubrication system to minimize the potential for contamination of the fluid.

The speed control and overspeed protection function of the DEH combined with the emergency trip system electrical and mechanical overspeed trips provide a level of redundancy and diversity at least equivalent to the recommendations for turbine overspeed protection found in III.2 of Standard Review Plan (NUREG-0800) Section 10.2. Additionally, the issues and problems with overspeed protection systems identified in NUREG-1275 (Reference 3) have been addressed.

10.2.2.5.4 Test Blocks

Low bearing oil pressure, low electrohydraulic fluid pressure, and high condenser back pressure are each sensed by separate test block instrumentation. Each test block assembly consists of a steel test block, two pressure transmitters, two shutoff valves, two solenoid valves, and three needle valves. Each assembly is arranged into two channels. The assemblies, mounted on the governor pedestal, are connected to pressure sensors mounted in a nearby terminal box. The assemblies have an orifice on the system supply side and are connected to a drain or vent on the other side. An orifice is provided in each channel so that the measured parameter is not affected during testing. An isolation valve on the supply side allows the test block assembly to be serviced.

If the medium (pressure or vacuum) reaches a trip setpoint, then the pressure sensors cause the auto stop emergency trip header mechanism to operate. When functionally testing an individual trip device, the medium is reduced to the trip setpoint in one channel either locally through the hand test valves or remotely from the trip test panel via the test solenoid valves.

10.2.2.5.5 Thrust Bearing Trip Device

Two position pickups, which are part of the turbine supervisory instrument package, monitor movement of a disc mounted on the rotor near the thrust bearing collar. Axial movement of this collar is reflected in movement of the disc. Excessive movement of the disc is an indication of thrust bearing wear. Should excessive movement occur, relay contacts from the supervisory instrument modules close to initiate a turbine trip.

The thrust bearing trip function can be checked by a test device that simulates movement of the rotor to activate the trip outputs from the modules.

10.2.2.5.6 Remote Trip

The emergency trip system also has provisions to trip the turbine in response to a signal from the plant control system or plant safety and monitoring system.

10.2.2.6 Other Protective Systems

Additional protective features of the turbine and steam system are:

- Moisture separator reheater safety relief valves
- Rupture diaphragms located on each of the low-pressure turbine cylinder covers
- Turbine water induction protection systems on the extraction steam lines

10.2.2.7 Plant Loading and Load Following

The AP600 turbine-generator control system and control strategy has the same loading and load following characteristics as the control system described in Section 7.7. In addition, the turbine-generator has the following capabilities:

- Daily load change between 100 and 30 percent of rated power
- Transition between baseload and load follow operation
- Extended weekend reduced power operation
- Rapid return to up to 90 percent of rated power

For the AP600, this load following capability is maintained for more than 90 percent of cycle life.

10.2.2.8 Inspection and Testing Requirements

Major system components are readily accessible for inspection and are available for testing during normal plant operation. Turbine trip circuitry is tested prior to unit startup. To test governor valves with minimal disturbance, the load is reduced to that capable of being carried with one governor valve closed.

10.2.3 Turbine Rotor Integrity

Turbine rotor integrity is provided by the integrated combination of material selection, rotor design, fracture toughness requirements, tests, and inspections. This combination results in a very low probability of a condition that could result in a rotor failure.

10.2.3.1 Materials Selection

Fully integral turbine rotors are made from ladle refined, vacuum deoxidized, Ni-Cr-Mo-V alloy steel by processes which maximize steel cleanliness and provide high toughness. Residual elements are controlled to the lowest practical concentrations consistent with melting practices. The chemical property limits of ASTM A470, Classes 5, 6, and 7 are the basis for the material requirements for the turbine rotors. The specification for rotor steel used in the AP600 has lower limitations than indicated in the ASTM standard for phosphorous, sulphur, aluminum, antimony, tin, argon, and copper. This material has the lowest fracture appearance transitions temperatures (FATT) and the highest Charpy V-notch energies obtainable on a consistent basis from water-quenched Ni-Cr-Mo-V material at the sizes and strength levels used. Charpy tests and tensile tests in accordance with American Society of Testing and Materials (ASTM) specification A370 are required from the forging supplier.

The production of steel for the turbine rotors starts with the use of high-quality, low residual element scrap. An oxidizing electric furnace is used to melt and dephosphorize the steel. Ladle furnace refining is then used to remove oxygen, sulphur, and hydrogen from the rotor steel. The steel is then further degassed using a process whereby steel is poured into a mold under vacuum to produce an ingot with the desired material properties. This process minimizes the degree of chemical segregation since silicon is not used to deoxidize the steel.

10.2.3.2 Fracture Toughness

Suitable material toughness is obtained through the use of materials described in Subsection 10.2.3.1 to produce a balance of material strength and toughness to provide safety while simultaneously providing high reliability, availability, and efficiency during operation. The restrictions on phosphorous, sulphur, aluminum, antimony, tin, argon, and copper in the specification for the rotor steel provides for the appropriate balance of material strength and toughness. The impact energy and transition temperature requirements are more rigorous than those given in ASTM 470 Class 6 or 7.

Bore stress calculations include components due to centrifugal loads and thermal gradients where applicable. The ratio of material fracture toughness, K_{IC} (as derived from material tests on each rotor) to the maximum tangential stress for rotors at speeds from normal to design overspeed, will be at least 200 ksi x √in (or at least 2) at minimum operating temperature. Material fracture toughness needed to maintain this ratio is verified by mechanical property tests on material taken from the rotor.

The rotor is evaluated for fracture toughness by criteria that include the design duty cycle stresses, number of cycles, ultrasonic examination capability and growth rate of potential flaws. Conservative factors of safety are included for the size uncertainty of potential or reported ultrasonic indications, rate of flaw growth (da/dN versus dK) and the duty cycle stresses and number.

Reported rotor forging indications are adjusted for size uncertainty and interaction. A rotor forging with a reported indication that would grow to critical size in the applicable duty cycles is not accepted. The combined rotation and maximum transient thermal stresses used in the applicable duty cycles are based on the brittle fracture and rotor fatigue analyses described below.

Maximum transient thermal stresses are determined from historical maximum loading rates for nuclear service rotors.

10.2.3.2.1 Brittle Fracture Analysis

A brittle fracture analysis is performed on the turbine rotor to provide confidence that small flaws in the rotor, especially near the centerline, do not grow to a critical size with unstable growth resulting in a rotor burst. The brittle fracture analysis process includes determining the stresses in the rotor resulting from rotation, steady-state thermal loads, and transient thermal loads from startup and load change. These stresses are combined to generate the maximum stresses and locations of maximum stress for the startup and load change transients. A fracture mechanics analysis is performed at the location(s) of maximum stress to verify that an initial flaw, equal to the minimum reportable size, will not grow to critical crack size over the life of the rotor under the cumulative effects of startup and load change transients.

A fracture mechanics analysis is done at the location(s) of maximum stress to determine the critical crack size and the initial flaw area that would just grow to the critical size when subjected to the number of startup and load change cycles determined to represent the lifetime of the rotor. This initial flaw area is divided by a factor of safety to generate an allowable initial flaw area. The minimum reportable flaw size is multiplied by a conservative factor to correct for the imperfect nature of a flaw as an ultrasonic reflector, as compared to the calibration reflector. The resulting area is the corrected flaw area. For an acceptable design, the allowable initial flaw area must be greater than or equal to the corrected flaw area.

A flaw is assumed to be an internal elliptical crack on the centerline for rotors without bores. For rotor contour or for flaws near the rotor bore (for bored rotors), a surface connected elliptical crack is assumed. Flaw analysis is done assuming various flaw aspect ratios and the most conservative results are used. The flaw is assumed to be orientated normal to the maximum principle stress direction.

The beginning-of-life fracture appearance transition temperature for the high pressure and low pressure rotor is specified in the material specification for the specific material alloy selected. Both the high pressure and low pressure turbines operate at a temperature at which temperature embrittlement is insignificant. The beginning-of-life fracture appearance transition temperature is not expected to shift during the life of the rotor due to temperature embrittlement.

Minimum material toughness is provided in the turbine rotors by specification of maximum fracture appearance transition temperature and minimum upper shelf impact energy for the specific material alloy selected. There is not a separate material toughness (K_{IC}) requirement for AP600 rotors.

10.2.3.2.2 Rotor Fatigue Analysis

A fatigue analysis is performed for the turbine rotors to show that the cumulative usage is acceptable for expected transient conditions including normal plant startups, load following cycling, and other load changes. The fatigue design curves are based on mean values of fatigue test data. Margin is provided by assuming a conservatively high number of turbine start and stop cycles. The Westinghouse-designed turbine rotors in operating nuclear power plants were designed using this methodology and have had no history of fatigue crack initiation due to duty cycles.

In addition to the low cycle fatigue analysis for transient events, an evaluation for high cycle fatigue is performed. This analysis considers loads due to gravity bending, bearing elevation misalignment, control stage partial arc admission bearing reactions, and steady-state unbalance stress. The local alternating stress is calculated at critical rotor locations considering the bending moments due to the loads described above. The maximum alternating stress is less than the smooth bar endurance strength modified by a size factor.

The AP600 turbine generator is supported by a spring-mounted system to isolate the dynamic behavior of the turbine-generator equipment from the foundation structure. The support system includes a reinforced concrete deck on which the turbine generator is mounted. The deck is sized to maintain the gravity load and misalignment load bending stresses within allowable limits. The evaluation of the loads includes a dynamic analysis of the combined turbine-generator and foundation structure.

10.2.3.3 High Temperature Properties

The operating temperatures of the high-pressure rotors are below the creep rupture range. Creep rupture is, therefore, not considered to be a significant factor in providing rotor integrity over the lifetime of the turbine. Basic data are obtained from laboratory creep rupture tests.

10.2.3.4 Turbine Rotor Design

The turbine assembly is designed to withstand normal conditions and anticipated transients, including those resulting in turbine trip, without loss of structural integrity. The design of the turbine assembly meets the more restrictive of the following criteria:

- The maximum tangential stress resulting for centrifugal forces does not exceed 65 percent of the 0.2 percent offset yield strength at design temperature and speed; or,
- The tangential stresses will not cause a flaw that is twice the corrected ultrasonic examination reportable size to grow to critical size in the design life of the rotor.

The high-pressure turbine has fully integral rotors forged from a single ingot of low alloy steel. This design is inherently less likely to have a failure resulting in a turbine missile than previous designs with shrunk-on discs. A major advantage of the fully integral rotor is the elimination of disc bores and keyways. In the fully integral rotor design, the location of peak stresses are in the lower stress blade fastening areas. This difference results in a substantial reduction of the rotor peak stresses, which in turn reduces the potential for crack initiation. The reduction in peak stress also permits selection of a material with improved ductility, toughness, and resistance to stress corrosion cracking.

The non-bored design of the high-pressure turbine element provides the necessary design margin by virtue of its inherently lower centerline stress. Metallurgical processes permit fabrication of the rotors without a center borehole. The use of solid rotor forgings was qualified by evaluation of the material removed from center-bored rotors for fossil power plants. This evaluation demonstrated that the material at the center of the rotors satisfied the rotor material specification requirements. Forgings for no-bore rotors are provided by suppliers who have been qualified based on bore material performance.

The low-pressure turbine element is a fully integral rotor fabricated from a single forging with a central bore. There are no keyways, which can be potential locations for stress risers and corrosive contaminate concentration, exposed to a steam environment. The integral disc profiles are carefully designed to limit the surface stress in areas vulnerable to stress corrosion if a less than ideal steam environment exists to 50 percent of the yield strength to reduce the chances of stress corrosion as far as practicable.

10.2.3.5 Preservice Tests and Inspections

Preservice inspections for turbine rotors include the following:

- Rotor forgings are rough machined with a minimum stock allowance prior to heat treatment.
- Each rotor forging is subjected to a 100-percent volumetric (ultrasonic) examination. Each finish-machined rotor is subjected to a surface magnetic particle and visual examination. Results of the above examination are evaluated by use of criteria that are

more restrictive than those specified for Class 1 components in ASME Code, Section III and V. These criteria include the requirement that subsurface sonic indications are either removed or evaluated to verify that they do not grow to a size which compromises the integrity of the unit during the service life of the unit.

- Finish-machined surfaces are subjected to a magnetic particle examination. No magnetic particle flaw indications are permissible in bores (if present) or other highly stressed regions.
- Each fully bladed turbine rotor assembly is spin tested at 20 percent overspeed, the maximum speed following a load rejection from full load.

Rotor areas which require threaded holes are not subjected to a magnetic particle examination of the threaded hole. The number of threaded holes is minimized, and threaded holes are not located in high stress areas.

10.2.3.6 Maintenance and Inspection Program Plan

The maintenance and inspection program plan for the turbine assembly and valves is based on turbine missile probability calculations, operating experience of similar equipment, and inspection results. The methodology for analysis of the probability of generation of missiles for fully integral rotors was submitted in WSTG-4-P (Reference 1). The methodology used for analysis of the missile generation probability calculations used to determine turbine valve test frequency is described in WCAP-11525 (Reference 2). The maintenance and inspection program includes the activities outlined below:

- Disassembly of the turbine is conducted during plant shutdown. Inspection of parts that are normally inaccessible when the turbine is assembled for operation (couplings, coupling bolts, turbine rotors, and low-pressure turbine blades) is conducted.

  This inspection consists of visual, surface, and volumetric examinations as indicated below:

  - Each rotor and stationary and rotating blade path component is inspected visually and by magnetic particle testing on accessible surfaces. Ultrasonic inspection of the side entry blade grooves is conducted. These inspections are conducted at intervals of about 10 years for low-pressure turbines and about 8 years for high-pressure turbines.
  - A 100 percent surface examination of couplings and coupling bolts is performed.
  - Fluorescent penetrant examination is conducted on nonmagnetic components.

- At least one main steam stop valve, one main steam control valve, one reheat stop valve, and one intercept valve are dismantled approximately every 4 years during scheduled refueling or maintenance shutdowns. A visual and surface examination of valve internals is conducted. If unacceptable flaws or excessive corrosion are found in a valve, the other valves of its type are inspected. Valve bushings are inspected and cleaned, and bore diameters are checked for proper clearance.

- Main stop valves, control valves, reheat stop and intercept valves may be tested with the turbine online. The DEH control test panel is used to stroke or partially stroke the valves.

- Extraction nonreturn valves are tested prior to each startup.

- Turbine valve testing is performed at quarterly intervals. The quarterly testing frequency is based on nuclear industry experience that turbine-related tests are the most common cause of plant trips at power. Plant trips at power may lead to challenges of the safety-related systems. Evaluations show that the probability of turbine missile generation with a quarterly valve test is less than the evaluation criteria.

- Extraction nonreturn valves are tested locally by stroking the valve full open with air, then equalizing air pressure, allowing the spring closure mechanism to close the valve. Closure of each valve is verified by direct observation of the valve arm movement.

The valve inspection frequency of four years noted above is consistent with a 24-month fuel cycle for AP600 and is based on evaluations performed to support this valve inspection interval at operating plants with 24-month fuel cycles. A monitoring program is in place at operating nuclear power plants to verify the success of longer valve inspection intervals. A Combined License holder recommendation for a valve inspection frequency longer than four years may be justified when a longer interval is supported by operating and inspection program experience and supported by the missile generation probability calculations.

10.2.4 Evaluation

Components of the turbine-generator are conventional and typical of those which have been extensively used in other nuclear power plants. Instruments, controls, and protective devices are provided to confirm reliable and safe operation. Redundant, fast actuating controls are installed to prevent damage resulting from overspeed and/or full-load rejection. The control system initiates a turbine trip upon reactor trip. Automatic low-pressure exhaust hood water sprays are provided to prevent excessive hood temperatures. Exhaust casing rupture diaphragms are provided to prevent low-pressure cylinder overpressure in the event of loss of condenser vacuum. The diaphragms are flange mounted and designed to maintain atmospheric pressure within the condenser and turbine exhaust housing while passing full flow.

Since the steam generated in the steam generators is not normally radioactive, no radiation shielding is provided for the turbine-generator and associated components. Radiological considerations do not affect access to system components during normal conditions. In the event of a primary-to-secondary system leak due to a steam generator tube leak, it is possible for the steam to become contaminated. Discussions of the radiological aspects of primary-to-secondary leakage are presented in Chapters 11 and 12.

10.2.5 Instrumentation Applications

The turbine-generator is provided with turbine supervisory instrumentation including monitors for the following:

- Speed
- Stop valve position
- Control valve position
- Reheat intercept and stop valve positions
- Temperatures as required for controlled starting, including:
  - External valve chest inner surface
  - External valve chest outer surface
  - First-stage shell lower inner surface
  - Crossover pipe downstream of reheat stop valve No. 1
  - Crossover pipe downstream of reheat stop valve No. 2
  - Crossover pipe downstream of reheat stop valve No. 3
  - Crossover pipe downstream of reheat stop valve No. 4
- Casing and shaft differential expansion
- Vibration of each bearing
- Shaft eccentricity
- Bearing metal temperatures

Alarms are provided for the following abnormal conditions:

- High vibration
- Turbine supervisory instruments common alarm

In addition to the turbine protective trips listed in subsection 10.2.2.5, the following trips are provided:

- High exhaust hood temperature
- Low emergency trip system pressure
- Low shaft-driven lube oil pump discharge pressure
- High or low level in moisture separator drain tank

Indications of the following miscellaneous parameters are provided:

- Main steam throttle pressure
- Steam seal supply header pressure
- Steam seal condenser vacuum
- Bearing oil header pressure
- Bearing oil coolers coolant temperature
- DEH control fluid header pressure

- DEH control fluid temperature
- Crossover pressure
- Moisture separator drain tank level
- First-stage pressure
- High-pressure turbine exhaust pressure
- Extraction steam pressure, each extraction point
- Low-pressure turbine exhaust hood pressure
- Exhaust hood temperature for each exhaust

Generator supervisory instruments are provided, with sensors and/or transmitters mounted on the associated equipment. These indicate or record the following:

- Multiple generator stator winding temperatures; the detectors are built into the generator, protected from the cooling medium, and distributed around the circumference in positions having the highest expected temperature

- Stator coil discharge gas temperature (two detectors per phase)

- Hydrogen cooler inlet gas temperature (two detectors at each point)

- Hydrogen gas pressure

- Hydrogen gas purity

- Generator winding overtemperature

- Generator ampere, voltage, and power

Additional generator protective devices are listed in Table 10.2-3.

10.2.6 Combined License Information on Turbine Maintenance and Inspection

The Combined License holder will submit to the staff for review and approval within 3 years of obtaining a Combined License, and then implement a turbine maintenance and inspection program. The program will be consistent with the maintenance and inspection program plan activities and inspection intervals identified in subsection 10.2.3.6. The Combined License holder will have available plant-specific turbine rotor test data and calculated toughness curves that support the material property assumptions in the turbine rotor analysis.

10.2.7 References

1. WSTG-4-P, Proprietary and WSTG-4-NP, Nonproprietary, "Analysis of the Probability of the Generation of Missiles from Fully Integral Nuclear Low Pressure Turbines," October 1984.

2. WCAP-11525, Probabilistic Evaluation of Reduction in Turbine Valve Test Frequency, 1987.
3. NUREG-1275, Vol. 11, Operating Experience Feedback Report - Turbine-Generator Overspeed Protection Systems, Commercial Power Reactors, H. L. Ornstein, Nuclear Regulatory Commission, April 1995.

Table 10.2-1

TURBINE-GENERATOR AND AUXILIARIES DESIGN PARAMETERS

Manufacturer Westinghouse

Turbine

Type	TC4F 47-in. last row blades
No. of elements	1 high pressure; 2 low pressure
Last-stage blade length (in.)	47
Operating speed (rpm)	1800
Condensing pressure (in. HgA)	2.5
Turbine cycle heat rate (Btu/kWh)	9812

Generator

Generator rated output (kW)	792,000 (nominal)
Power factor	0.90
Generator rating (kVA)	880,000 (nominal)
Voltage (kV)	22
Hydrogen pressure (psig)	75

Moisture separator/reheater

Moisture separator	Chevron vanes
Reheater	U-tube
Number	1 shell
Stages of reheating	1

Table 10.2-2

TURBINE OVERSPEED PROTECTION

Percent of Rated Speed (Approximate)	Event
100	Turbine is initially at valves wide open. Full load is lost. Speed begins to rise. When the breaker opens, the load drop anticipator immediately closes the control and intercept valves if the load at time of separation is greater than 30 percent.
101	Control and intercept valves begin to close.
103	The overspeed protection controller closes the control and intercept valves until the speed drops below 103 percent.
108	Peak transient speed with normally operating speed control system. If the power/load unbalance and speed control systems had failed prior to loss of load, then:
110	The mechanical overspeed trip device closes the turbine stop and reheat valves.
111	The electrical overspeed trip system closes the main stop and reheat stop valves based on a two-out-of-three trip logic system.

Note:
Following the above sequence of events, the turbine will approach but not exceed 120 percent of rated speed.

Table 10.2-3 (Sheet 1 of 2)

GENERATOR PROTECTIVE DEVICES FURNISHED WITH THE VOLTAGE REGULATOR PACKAGE

Device	Action	
• Generator Minimum Excitation Limiter	Limiter	- maintains generator reactive power output above certain level (normally steady-state stability limit level)
	Alarm	- when limiter is limiting
• Generator Maximum Excitation Limiter	Limiter	- maintains generator field voltage below certain voltage inverse time characteristics
	Alarm	- when limiter is timing
	Alarm	- when limiter is limiting
• Generator Overexcitation Protection	Alarm	- repositions the dc regulator adjuster to a preset position when overexcitation protection pickup level is exceeded
Inverse Timer	Alarm	- when timing commences
	ac regulator trip	- when timed out
Fixed Timer	Alarm	- when timing
	Unit trip	- when timed out
• Generator Volts/Hertz Limiter	Limiter	- maintains machine terminal volts/Hertz ratio below certain level
	Alarm	- when limiter is limiting
• Generator Dual Level Volts/Hertz Protection	Alarm	- when above either preset volts/Hertz level
	Unit trip	- if timed out at either alarm level
• Generator Automatic Field Ground Detection	Alarm	- brush failure (alarms about 20 seconds)
	Alarm	- ground
• Regulator Firing Circuit - Loss of Thyristor Firing Pulse Protection	Alarm	- loss of one firing circuit
	Unit Trip	- loss of both firing circuits
• Thyristor Blown Fuse Detection	Alarm	- When one or more thyristor fuses in power drawers open

Table 10.2-3 (Sheet 2 of 2)

GENERATOR PROTECTIVE DEVICES FURNISHED WITH THE VOLTAGE REGULATOR PACKAGE

Device	Action	
• Regulator Forcing Indication	Alarm	- online forcing
	Alarm	- offline forcing (blocks "Raise" controls of dc regulator and ac regulator adjustors)
• Regulator Loss of Power Supply (s)	Alarm	- loss of one power supply
Protection	Unit trip	- loss of both power supplies
• Regulator Loss of Sensing Protection	Alarm and AC regulator trip	- when regulator voltage transformer sensing is lost
• Excitation Supply Breaker	Alarm Excitation trip	
• Alternate Excitation Removal Equipment	Alarm	- For fast de-excitation, phase-back thyristor firing pulses for specified time, then trip excitation supply breaker
• Power System Stabilizer (PSS) Excessive Output Protection	Alarm Power System Stabilizer trip	- When PSS output exceeds specified level for specified time
• Power System Stabilizer Inservice Instrumentation Indication	Indicator	- lamps and contacts
• Exciter - Air Temperature Detection	Alarm	
• Exciter - Rotation Vibration Pick-up	Alarm Unit Trip	
• Exciter - Bearing Metal Detection	Alarm	
• Generator - Overvoltage Protection	Alarm	- Phase-back thyristor firing pulses if overvoltage condition persists for a specified time
• Exciter Diode Fuse Detection	Indicator	- Flag on rotating fuse raises when fuse opens; detected by periodic checks with strobe light.

Table 10.2-4

Turbine-Generator Valve Closure Times

Valve	**Closing Time (seconds)**
Main Stop Valves	0.3
Control Valves	0.3
Intercept Valves	0.3
Reheat Stop Valves	0.3
Extraction Nonreturn Valves	<1.0

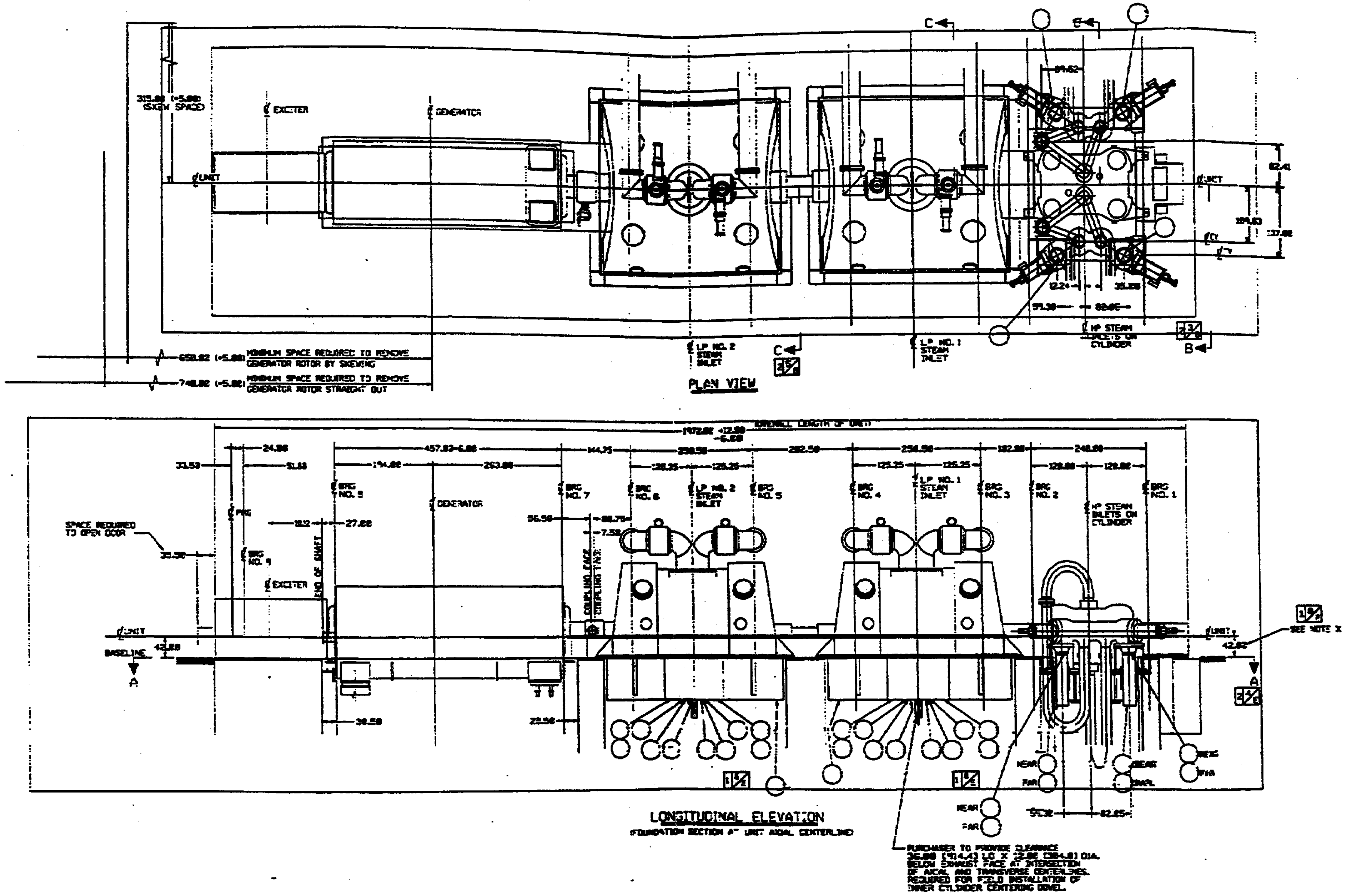
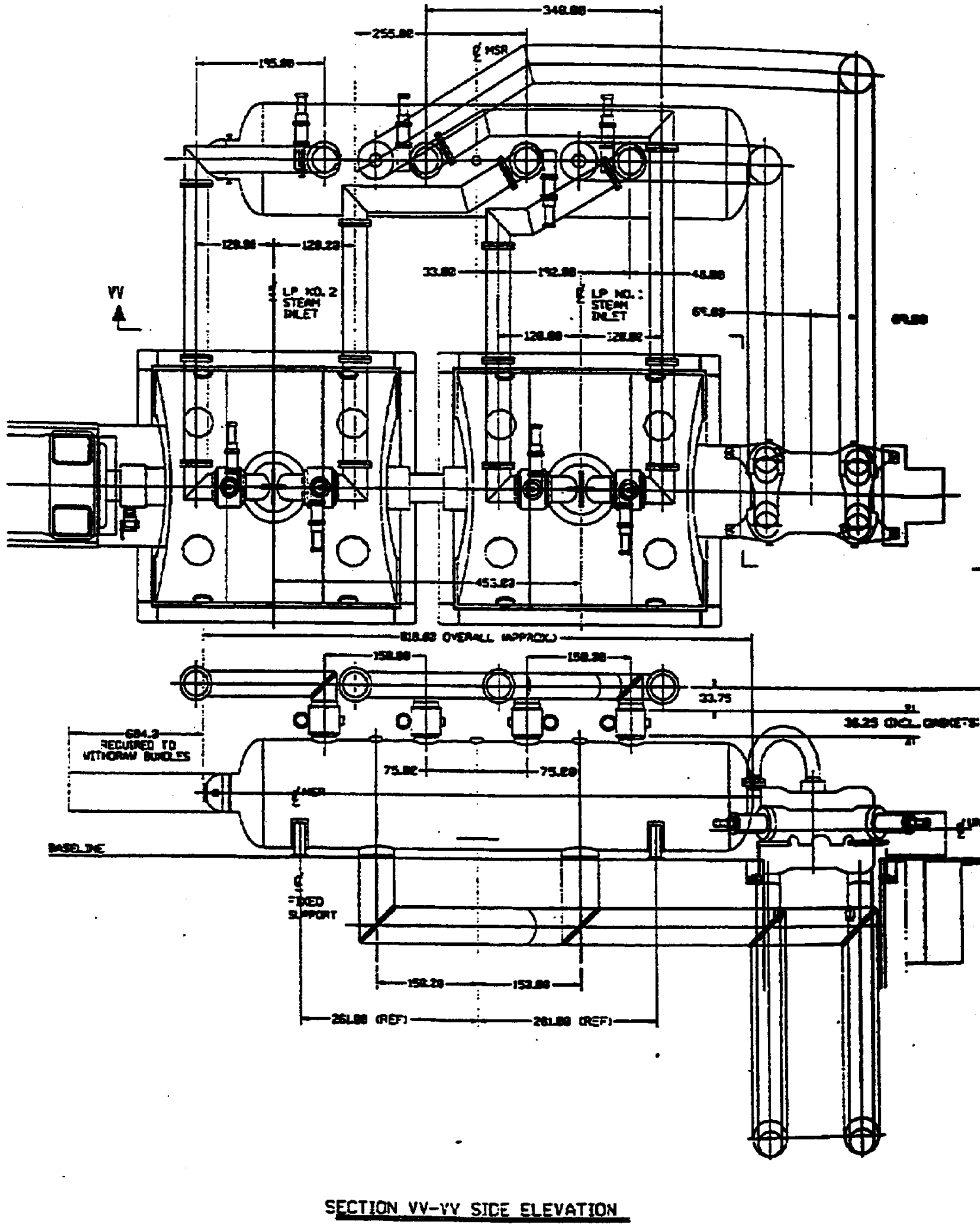


Figure 10.2-1 (Sheet 1 of 2)

Turbine Generator Outline Drawing



SECTION VV-VV SIDE ELEVATION

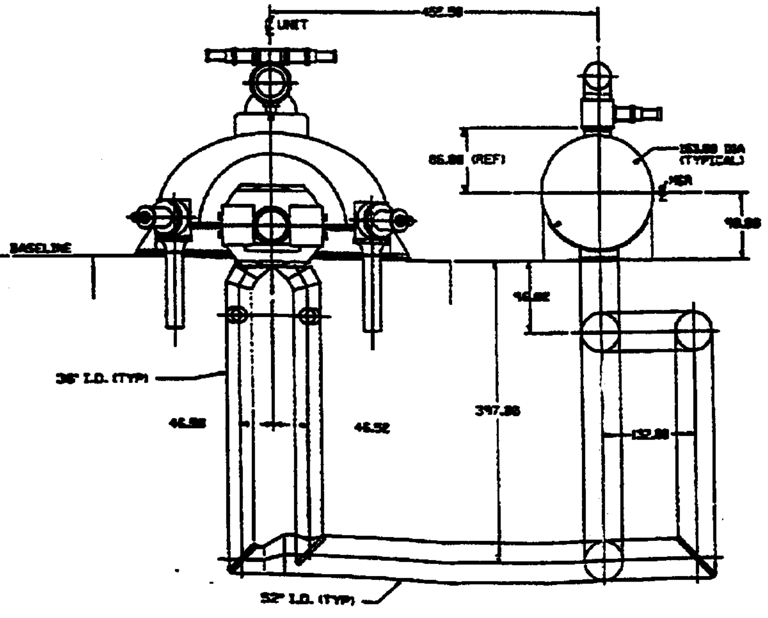
SPECIFICATIONS

MOISTURE SEPARATOR REHEATER ASSEMBLY BY OTHERS:

WEIGHT	POUNDS
DRY (*)	300,000
OPERATING (*)	
FLOODED (*)	
TUBE-BUNDLE & HEAD	

(*) WEIGHT INDICATED INCLUDES POUNDS TOTAL OF TWO (2) FOOT-SUPPORTS.

DESIGN CONDITIONS	PRESSURE PSIG	TEMPERATURE DEGS. F
SHELL-SIDE	280	500
TUBE-SIDE	1250	600



GOVERNOR END VIEW

Figure 10.2-1 (Sheet 2 of 2)

Turbine Generator Outline Drawing