ENCLOSURE I

CALCULATION METHOD

FOR

CRITICAL CRACK SIZES

10PR03a

During August, 1979, Westinghouse discovered the occurrence of disc keyway cracking on a nuclear low pressure turbine. As a result of this experience, Westinghouse has developed a procedure to rank uninspected operating units for purposes of developing inspection schedules that allow for inspection of units prior to expected occurrence of disc fracture.

The ranking of uninspected operating units is done on the basis of an index which is defined by the ratio of maximum expected crack depth, a to effective critical crack depth, a_{cr} (eff).

Several factors must be taken into account in the computation of the maximum expected crack depth. The most important of these factors are material composition and [ ] b,c the [ ] b,c operating time, steam quality. These factors are used as the basis for ranking. The composition and operating temperature have been incorporated into a graph describing the crack growth rate based on actual disc cracking experience. The expected crack depth is determined by multiplying the crack growth rate taken from this graph by the total operating hours of the unit, or by the elapsed time until the next scheduled inspection of the unit. To determine the maximum expected crack depth, the growth rate described by the upper bound of this graph is multiplied by the time:

$$a = \left(\frac{da}{dt}\right)_T \times t$$

where: t = operating time

$\left(\frac{da}{dt}\right)_T$ = maximum crack growth rate at temperature T

The material strength factor is taken into account for high strength discs by means of a correction to the maximum growth rate. Since experience shows that under normal conditions cracks are not formed in dry regions of a turbine, steam quality is taken into account by assuming that the crack growth rate in dry steam is negligible. The final factor, steam purity, is taken into account whenever an event involving corrosive impurities is known to have occurred. In the event significant corrosion problems become evident, an early inspection may be necessary.

The critical crack depth, a_{cr}, is calculated using the following fracture mechanics expression:

$$a_{cr} = \frac{Q}{1.21\eta}\left[\frac{K_{IC}}{\sigma}\right]^2$$

where: Q = flaw shape parameter. Depth to length ratio of flaw was flaw was conservatively assumed to be [ ] a,c

K_{IC} = fracture toughness of disc

σ = maximum bore stress [ ] b,c

Finally, the effective critical crack depth is calculated as follows:

$$a_{cr}\,(eff) = a_{cr} - [\qquad]\ a\ c$$

where: [ ] a,c = depth of keyway

Using the parameters described above, the ratio of [ ] b,c is calculated for each of the first four discs in a turbine. So long as this ratio is less than [ ] a,c there is reasonable assurance that the turbine can be operated without a rupture of the disc occurring.

10.2.3 TURBINE DISK INTEGRITY

As a result of Westinghouse testing, new criteria have evolved for predicting the missile containing ability of the low pressure turbine structures. The previous calculations have been redone using these new criteria and the results show the original position on the containment of disk fragments within the turbine casing can no longer be maintained.

The Turbine Overspeed Protection System is completely independent of the normal turbine governing and mechanical overspeed protective devices. In the event of a turbine trip, this system ensures that the turbine-generator unit will not exceed the design overspeed which is 120 percent of rated speed.

Present manufacturing and inspection techniques for turbine rotor and disk forging makes the possibility of an undetected flaw extremely remote. Forgings are subject to inspection and testing both at the forging suppliers and at Westinghouse. Current design procedures are well established and conservative, and analytical tools such as finite element and fracture mechanics techniques allow in depth analysis of any potential trouble spots such as area of stress concentration or inclusions which could give rise to crack propagation.

10.2.3.1 Materials Selection

10.2.3.1.1 High Pressure Turbine

The high pressure turbine element, as shown in Figure 10.2-7 is of a double flow design. Flow design is thrust balanced. Steam from the four control valves enters the turbine element through four inlet pipes. These pipes feed four double-flow nozzle chambers flexibly connected to the turbine casing. Steam leaving the nozzle chambers passes through the rateau control stage and flows through the reaction blading. The reaction blading is mounted in the blade rings shown in Figure 10.2-8 which in turn are mounted in the turbine casing.

The high pressure rotor is made of NiCrMoV alloy steel. The specified minimum mechanical properties are as follows:

Tensile strength, psi, min.	100,000
Yield strength, psi, min. (0.2 percent offset)	80,000
Elongation is 2 in. percent, min.	18
Reduction of Area, percent, min.	45
Impact Strength, Charpy V-Notch, ft. lbm. (min. at room temperature)	60
50 percent fracture appearance transition temperature, F, maximum	50

The main body of the rotor weighs approximately 100,000 pounds. The approximate values of the transverse centerline diameter, the maximum diameter, and the main body length are 36 in., 66 in., and 138 in., respectively.

The blade rings (ASTM A356-68) and the casing cover and base (both ASTM A216-66) are made of carbon steel castings. The specified minimum mechanical properties are as follows:

Tensile Strength, psi, min.	70,000
Yield Strength, psi, min.	36,000
Elongation in 2 in. percent, min.	22
Reduction of Area, percent, min.	35

The bend test specimen is capable of being bent cold through an angle of 90 degrees and around a pin one inch in diameter without cracking on the outside of the bent portion.

The approximate weights of the four blade rings, the casing cover, and the casing base are 80,000 lbm., 115,000 lbm. and 115,000 lbm. respectively.

The casing cover and base are tied together by means of more than 100 studs. The stud material is a hot rolled alloy steel (ASTM A193-66 Gr.B16) having the following mechanical properties:

	2 1/2 In. and Less	Over 2 1/2 to 4 In.	Over 4 To 7 In.
Tensile Strength, psi, min.	125,000	115,000	110,000
Yield Strength, psi, min. (0.2 percent offset)	105,000	95,000	85,000
Elongation in 2 in., percent, min.	13	16	16
Reduction of Area, percent min.	50	50	45

The studs have lengths ranging from 17 to 66 in. and diameters ranging from 2.75 to 4.5 in. About 90 percent of them have diameters ranging between 2.75 and 4 in. The total stud cross-sectional area is approximately 900 sq. in. and the total stud free length volume is approximately 36,000 cu. in.

10.2.3.1.2 Low Pressure Turbines

The double flow low pressure turbines incorporate high efficiency blading and diffuser type exhaust design. The low pressure turbine cylinder is fabricated from carbon steel plate to provide uniform wall thickness, reducing thermal distortion to a minimum. The entire outer casing is subjected to low temperature exhaust steam.

The temperature drop of the steam from its inlet to the LP turbine to its exhaust from the last rotating blades is taken across three walls, an inner cylinder number 1, a thermal shield, and an inner cylinder number 2. This precludes a large temperature drop across any one wall, except the thermal shield which is not a structural element, thereby virtually eliminating thermal distortion. The fabricated inner cylinder number 2, is supported by the outer casing at the horizontal centerline and is fixed transversely at the top and bottom and axially at the centerline of the steam inlets, thus allowing freedom of expansion independent of the outer casing. Inner cylinder number 1 is, in turn, supported by inner cylinder number 2, at the horizontal centerline and fixed transversely at the top and bottom and axially at the centerline of the steam inlets, thus allowing freedom of expansion independent of inner cylinder number 2. Inner cylinder number 1 is surrounded by the thermal shield. The steam leaving the last row of blades flows into the diffuser where the velocity energy is converted to pressure energy.

The disks are made of NiCrMoV alloy steel. There are two identical sets of five shrunk-on disks, one set for each of the two flows. Each disk in a set is numbered; the disk closest to the transverse centerline is designated number 1. When the turbine is in operation each disk experiences a different stress and is, consequently, machined from a suitable grade of alloy steel. Disk number 2 experiences the highest stress, while disk number 5 experiences the lowest. The specified mechanical properties disk materials are shown in Table 10.2-3.

The outer cylinder and the two inner cylinders are fabricated mainly of ASTM A515-65 material. The specified minimum mechanical properties are shown in Table 10.2-3. 4

The rotors are made of NiCroMoV alloy steel. Ths specified minimum mechanical properties are shown in Table 10.2-3.

10.2.3.2 Fracture Toughness

Fracture of the disks into 90, 120 and 180 degree segments was considered as criteria in selecting number of disk segments.

A 120 degree segment has an initial translational kinetic energy 12.5 percent greater than that of a 90 degree segment, however it also has a 33 percent greater rim periphery resulting in greater energy loss while penetrating the turbine casing. This results in nearly equal kinetic energy of the 90 and 120 degree segments leaving the turbine casing. However, since the 90 degree segments have the smaller impact areas they represent a more severe missile.

The initial translational kinetic energy of a half disk is equal to that of a quarter disk. Because of kinematic considerations, a half segment will always impact with the rotor after fracture. The 180 degree segment, due to its larger size, will subject the stationary parts to greater deformation. As a result the 180 degree segment will leave the turbine casing with lower energy than the 90 degree segment.

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For the purpose of evaluating the missile containing ability of the turbine structure, the shrunk-on disks have been postulated to fail in four quarters.

To evaluate the missile containing ability of its steam turbines, Westinghouse conducted a test program at its research laboratories.

The tests involved spinning alloy steel disks to failure within various carbon steel containments. The disks were notched to ensure failure in a given number of segments at the desired speed. Test results were correlated with various parameters descriptive of the missile momentum and energy and the geometry of the missile and containment.

The containments were of varying geometry but all were axisymetric and concentric with the rotation axis of the disk. They ranged in complexity from a circular cylinder to containments which approximated actual turbine construction.

From these tests, logical criteria has evolved for predicting the missile containing ability of various turbine structures. In addition, the tests also served to determine the mode of failure which certain structural shapes common to turbine construction undergo when impacted by a missile. This is important since the mode of failure has a great influence on the amount of energy absorbed by the containment.

Normal operating temperatures of each key point at high pressure and low pressure turbines are shown in Figure 10.2-2. The minimum throttle steam temperature required for rolling the HP turbine from a cold start is 388 F with a corresponding pressure of 200 psig. The maximum LP turbine exhaust hood temperature is limited to 175 F.

A detail analysis of brittle rupture probability of low pressure turbine disks is presented in Reference 1.

10.2.3.3 High Temperature Properties

Calculations for effects of a postulated failure of the HP turbine rotor at design overspeed (120 percent of the rated speed) show that all fragments. generated by any postulated failure of the HP turbine rotor would be contained by the HP turbine blade rings and casing.

Since the steam at the turbine stop valve only has a temperature of 526 F for Waterford-3, it is not considered that creep processes will occur on the HP rotors and therefore, stress rupture properties are not relevant. 6

Probability and fatigue crack growth rate data and stress rupture data of the high pressure rotor are given in Reference 1.

10.2.3.4 Turbine Disk Design

The turbine is designed to withstand normal conditions, anticipated transients, and accidents resulting in a turbine trip without loss of structural integrity. A record search for compliance with Branch Technical Position MTEB10-1 has not been performed, because the turbine has been manufactured and placed in storage prior to issuance of the Branch Position. However, the turbine is designed to the following criteria:

a) The highest anticipated speed from loss of load is less than 110 percent of rated speed. The turbine is designed for 120 percent of rated speed. The Branch Position requires design overspeed five percent above the highest anticipated speed.

b) At 115 percent of rated speed, the average tangential stress in low-pressure discs or high-pressure rotors due to centrifugal force, interference fit, and thermal gradients do not exceed 0.75 of the minimum specified yield strength of the materials. 6

c) The rotors are designed so that the response levels at the natural critical frequency of the turbine shaft assemblies are controlled between 0 speed and 20 percent overspeed, so as to cause no distress to the unit during operation.

d) The bore of the high-pressure rotors can be inspected in-service with the rotors removed from the cylinder. The rims of the low-pressure discs can also be inspected. There are, however, no reliable methods for in-service inspection keyways and bores without disassembling.

10.2.3.5 Preservice Inspection

The preservice inspection and test methods applied during the manufactur-

ing process assure that the product complies with the specifications.

The low pressure turbine rotor body and disk are heat treated nickel-chromium-molybdenum-vanadium alloy steel procured to specifications that define the manufacturing method, heat treating process, and the test and inspection methods. Specific tests and test documentation, in addition to dimensional requirements, are specified for the forging manufacturer.

Inspection and tests for the low pressure turbine rotor body are conducted at the forging manufacturer's plant.

a) A ladle analysis of each heat of steel for chemical composition is to be within the limits defined by the specification.

b) Following preliminary machining and heat treatment for mechanical properties but prior to stress relief, all rotor diameters and faces are subjected to ultrasonic tests defined in detail by a Westinghouse specification which exceeds the requirements of ASTM A 418-64.

c) After all heat treatment has been completed, the rotor forging is subjected to a thermal stability test defined by a Westinghouse specification which is more restrictive than the requirements of ASTM A 472-69.

d) The end faces of the main body and the fillet areas joining the body to the shaft ends of the machined forging are subjected to a magnetic particle surface inspection as defined by ASTM A 275-71.

e) After the bore of the rotor is finished machined, the bore is given a visual examination followed by a wet magnetic particle inspection defined in detail by a Westinghouse specification which exceeds the requirements of ASTM A 275-71.

f) Utilizing specimens removed from the rotor forging at specified locations, tensile, Charpy V Notch impact and FATT properties are determined following the test methods defined by ASTM A 370-67.

After the rotor body is finished machined at Westinghouse, the rotor surface is given a fluorescent magnetic particle examination as defined by a Westinghouse specification which is similar to ASTM E 138-63.

Inspection and tests for the low pressure turbine rotor disks are conducted at the forging manufacturer's plant.

a) The ladle analysis of each heat of steel is to be within the composition limits defined by the specification.

b) After all heat treatment, rough machining and stress relief operations, the hub and rim areas of the completed disk forging are subjected to ultrasonic examinations. These ultrasonic tests are defined by a Westinghouse specification which exceeds the requirements of ASTM A 418-64.

c) The tensile, Charpy V Notch impact and FATT properties are determined

from specimens removed from the disks at specific locations. The test method used for determining these mechanical properties are defined by ASTM A 370-67.

After the disks are finished machined at Westinghouse, the disk surfaces except blade grooves are given a fluorescent magnetic particle examination as defined by a Westinghouse specification which is similar to ASTM E 138-63.

After the preheated disks are assembled to the rotor body to obtain the specified interference fit, holes are drilled and reamed for axial locking pins at the rotor and disk interface. These holes are given a fluorescent penetrant inspection defined by a Westinghouse specification which is similar to ASTM E 165-65.

Prior to shipping, each fully bladed rotor is balanced and tested to 120 percent of rated speed in a shop heater box.

The high pressure turbine rotor has the same basic material composition as the low pressure rotors. This nickel-chromium-molybdenum-vanadium alloy steel forging is procured, processed, and subjected to test and inspection requirements the same as the low pressure rotor which includes:

a) Ladle analysis

b) Ultrasonic tests

c) Magnetic particle inspection

d) Thermal stability test

e) Bore inspection

f) Tensile and impact mechanical properties

g) Fluorescent magnetic particle inspection

h) Heater box and 120 percent speed test

10.2.3.6 In-service Inspection

Various parameters for the turbine generator and accessories are recorded and alarmed in the main control room and logged on the plant computer. A full compliment of controls and instruments are provided in order that the turbine-generator may be started, operated, tested, and shutdown from the main control room.

Periodic turbine generator inspections, including inspections and tests of the main steam stop and control valves and reheat stop and control valves, will be performed on Waterford-3 with the goal of maximizing turbine generator reliability and efficiency and thus minimizing long-term power generation costs. 6

Factors that determine the timing of inspections include:

a) Operating symptoms: vibration, abnormal pressures and temperatures, loss of capability, increase in heat rate, etc.

b) Mode of Operation: number of start-ups, cyclic or base loading, etc.

c) Findings from prior inspections both in-house and at other utilities,

d) Recommendations of the turbine-generator manufacturer.

The purpose of these inspections are to search for, correct, and minimize the causes of items, such as:

a) Wear: bearings, gears, linkages, valve parts, packings, spill strips, hydrogen seals, collector rings, etc.

b) Erosion: solid particle in dry regions, moisture in wet regions.

c) Depositions: collections in the stream path that result in loss of capability or efficiency and possible exposure to undesirable chemicals.

d) Distortions and misalignment.

e) Cracking: thermal or fatigue. 6

f) Mechanical damage: buckets, diaphragms, stator core, etc.

g) Contamination of fluid systems.

h) Reduction in integrity of insulation on stator bars, field winding, or core laminations.

i) Loosening of generator hardware, blocking, supports, core, etc.

j) Generator contamination (oil or dirt) blocking of ventilation passages.

k) Excessive heating in electrical systems.

l) Excitation system electrical and mechanical problems.

When the turbine is disassembled, a visual, ~~and a~~ magnetic particle and an ultrasonic examination is made externally on accessible areas of the high pressure rotor, low pressure turbine blades and low pressure discs. The coupling bolts are visually examined.

INSERT A →

a) Throttle, governor, reheat stop and interceptor valves are inspected after initial start-up of a turbine. As per the following program some valves are inspected 12-15 months after start-up, others 24-27 months, and the remainder 36-39 months so that all valves are inspected at least once in the 39 months of operation following ini-

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The methodology used to calculate the sizes of the critical cracks in the low pressure rotor discs and the frequency of inspection is described in Westinghouse's document 10PRO3 entitled "Calculation Method for Critical Crack Size" and its attachment "L. P. Turbine Disc Information."

tial start-up and throttle and reheat stop valves are inspected twice in this period. After this initial inspection program is completed, all valves are inspected at least once every 36-39 months.

b) Functional test of the turbine steam inlet valves are performed weekly. This test can be made while the unit is carrying load. The purpose of the test is to insure proper operation of throttle, governor, reheat stop and the interceptor valves. The operation of these valves are observed during the test by an operator stationed at the valves. Movements of the valves should be smooth and free. Jerky or intermittent motion may indicate a buildup of deposits on shafts. 6

These frequent in-service inspections, coupled with a comprehensive monitoring program during operation, will assure efficient and reliable turbine generator performance over the life of the plant.

10.2.4 EVALUATION

The steam generated in the two steam generators is not normally radioactive. Only in the event of primary-to-secondary system leakage (due to steam generator tube leak) is it possible for the SPCS to become radioactively contaminated. In this event, monitoring of condenser air discharge will detect any contamination. A full discussion of the radiological aspects of primary-to-secondary leakage, including anticipated operating concentrations of radioactive contaminants, means of detection of radioactive contamination, anticipated releases to the environment, and limiting conditions for operation, are included in Chapters 11 and 12.

A description of the protection provided by bypassing and dumping main steam to the condenser and atmosphere in case of sudden load rejection by the turbine-generator is included in Subsection 10.4.4. A description of the protection provided by exhausting steam to the atmosphere through the safety valves in the event of a turbine generator trip and coincident failure of the SBS is given in Section 10.3.

An internal energy method as outlined in Power Test Code PTC20.2 was utilized to determine the expected speed rise upon full load dump. The results are with full load dump of 1199.91 MW and successful operation of the OPC, the expected speed rise is 1.065 percent; with failure of OPC and operation of the mechanical trip weight the expected speed rise is 1.18 percent. 4

The overspeed protection devices showing provided redundancy is shown in Table 10.2-2.