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INTRODUCTION

GE turbine designs have evolved over a period of some 90 years, during which over 3,000 units were produced, with the objective of achieving the best possible performance in reliability and efficiency. To achieve and maintain these goals, GE has rigorously evaluated knowledge gained during operation; continuously fed it back into new unit designs; and where appropriate, made recommendations to owners of operating units. This paper discusses certain recommendations for in-service inspection of fossil units and the various aspects of GE's experience related to rotors with shrunk-on wheels that have led to these recommendations.

CURRENT CONSIDERATIONS

Further on in this paper, the chronological development of turbine wheel materials, nondestructive testing techniques, and fracture criteria will be summarized. As will be shown, the current criteria used to judge the suitability of a given wheel forging for service are based upon a long history of technical progress and actual field experience. The current materials, processes, techniques, etc., are all well known. However, the population of wheel forgings in service were produced to a wide variation in chemistry, mill practices, and mechanical property requirements and were evaluated for initial service using varied criteria and procedures. With these varied properties, sizes, applications, and environments, it is difficult to predict the future behavior accurately without inspection.

In fossil turbines, the major concern is stress-corrosion cracking caused by undesirable chemical species in the steam, particularly caustic. Figure 1 shows a failed 34-inch diameter, shrunk-on turbine wheel which failed as a result of caustic stress-corrosion cracking. This wheel had been in service since 1946. Its composition was 1Cr-1/2 Mo. The subsequent failure analysis indicated that the material met all the chemical and mechanical property attributes called for in the specification. Moreover, the material operated satisfactorily for almost 38 years before the failure occurred. The stress-corrosion cracks leading to the failure were attributed to caustic contamination that had occurred four years before the wheel failed. Even though the wheel had provided good service for many years, exposure to an undesirable environment led to severe service problems. It should, therefore, be recognized that a prudent inspection and wheel retirement program should be considered by the operators of such equipment.

WHEEL INSPECTION, EVALUATION, AND RECOMMENDATIONS

There are many factors and uncertainties involved with a large population of turbine-generators that span a period of over 50 years and a size range of a few megawatts to well in excess of 1000 megawatts. The operational history of the involved units are varied; some units operate with supercritical boilers, others with subcritical boilers, some in industrial environments, and others utilizing process steam. The operating practices within a given population also vary considerably. Finally, the materials, wheel geometries, size, and stresses are dependent on the period the rotors were constructed, as well as the rating of the turbine.

A common concern for all units is the potential for wheel burst and its consequence. Even if a burst were to be contained in the turbine casing, considerable damage would likely result to the unit causing a lengthy downtime and associated expense. As a worst-case scenario, missiles could exit the casing.

The most prominent factor concerning wheel burst is the initiation and propagation of stress-corrosion cracking in the bore of these wheels. Recent experience has shown, and modern state-of-the-art technology confirms, that under certain conditions cracks could be generated and cause a burst. Accordingly, GE considers it prudent to inspect these wheels if continued operation is contemplated.

The material involved and the in situ inspectability of these wheels places them in two categories:

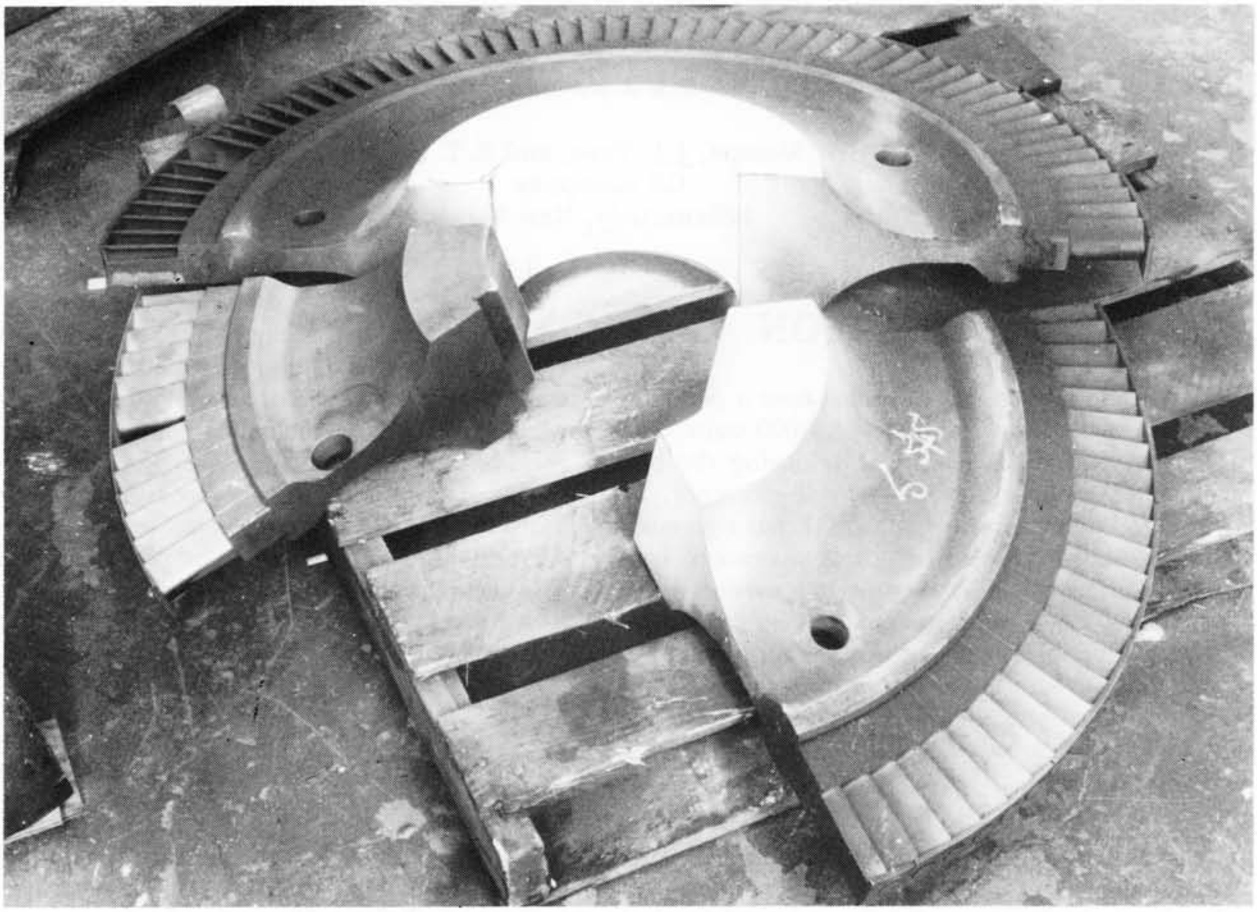

Figure 1. Shrunk-on turbine wheel failure resulting from caustic stress-corrosion cracking.

1. Wheels that can be inspected in a manner such that GE can make meaningful recommendations based on their condition and projected future operation.
2. Wheels that cannot be inspected with the in situ test. For these wheels, alternatives are presented for the owner's consideration.

WHEEL GEOMETRIES AND INFLUENCE ON INSPECTION CAPABILITIES

Wheel material properties will be covered under the Materials section of this paper. In this section the wheel geometries and their impact on testing capability will be discussed.

Figures 2-3 illustrate various wheel geometries that were typical of fossil units placed in service between the 1940s and 1960s. Figure 2 illustrates various basic designs from the standpoint of being able to conduct an ultrasonic test on the bore regions of the wheels. The first five wheels of this particular illustration have "pin-bushed" wheels that are used in higher-temperature regions of the rotor. The design consists of a bushing that has a shrink fit with the rotor shaft and is pinned to the wheel bore with a series of radial pins. The wheel does not have an axial keyway. The remaining wheels on the rotor in Fig. 2 are shrunk directly onto the rotor shaft. This figure also illustrates relatively slender (by today's standards) wheels, some with hubs and some without. These features have an impact on the ability to conduct the in situ ultrasonic test on these wheels. Figure 3 illustrates wheel designs of more recent fossil units. These wheels are shrunk directly onto the rotor shaft and have axial keys at the bore. Some have considerable axial space between them extending to the rotor shaft; others are limited to a very narrow gap between wheel hubs. These geometrical features also impact the techniques used to test the wheel bores and keyways.

"Pin-bushed" wheels are ultrasonically tested from the face of the wheel to check for cracks that may initiate at the end of the pin holes and possibly propagate in a radial/axial plane. Other wheels are tested by placing the ultrasonic transducers at various radial

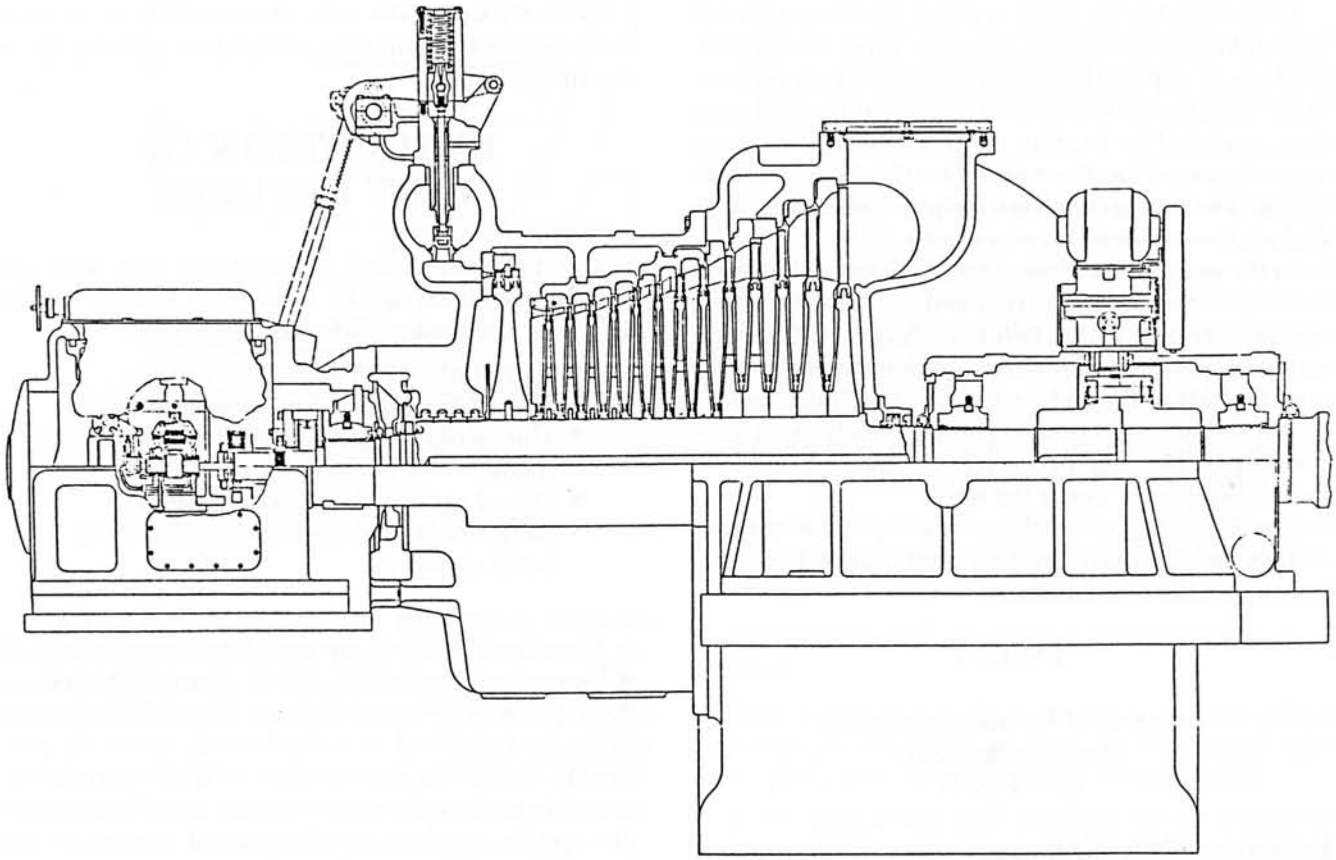

Figure 2. Early rotor shrunk-on-wheel construction.

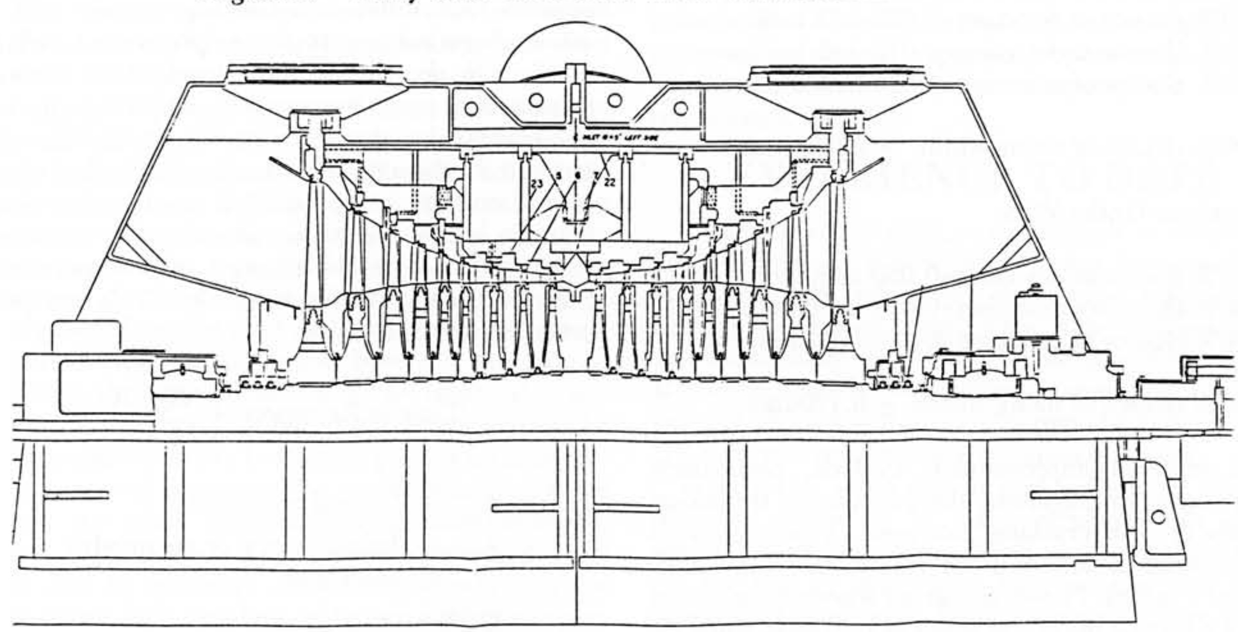

Figure 3. Recent rotor shrunk-on-wheel construction.

locations on the wheel webs and on the wheel hubs (if the specific wheel has hubs) and slowly rotating the rotor to get complete circumferential coverage.

Figure 7 illustrates a partial cross section of a typical shrunk-on wheel showing the hub and web sections of the wheel. Also shown are the locations for the ultrasonic transducers for testing the various sections of the wheel bore and keyway.

For wheels having hubs, a single transducer is used for sending and receiving the sonic wave to and from the bore or top of the keyway over the hub regions. Sonic indications are located and sized by analyzing data produced by locating the transducer at different circumferential locations and directly above the indication. The hub sections are the most reliable areas to find and size bore or keyway cracks.

In the web region of the wheel, a direct reflection of the sonic wave cannot be received by the transmitting transducer. Therefore, two transducers, a transmitting probe on one side and a receiving probe on the opposite side of the web, are used in a "pitch-catch" arrangement. With some wheel geometries, it may not be possible to get complete coverage of the bore and keyway areas under the web.

The following table illustrates typical accuracies usually achieved in locating and sizing bore and keyway cracks or indications.

TABLE 1

Accuracy of Locating and Sizing
Sonic Indications
(See Fig. 4)

Indications Under Hub:

10% chance of detecting–0.035-inch indication
50% chance of detecting–0.045-inch indication
90% chance of detecting–0.070-inch indication

90% chance of sizing within ± 0.050-inch.

Indications Under Web:

10% chance of detecting–0.050-inch indication
50% chance of detecting–0.075-inch indication
90% chance of detecting–0.135-inch indication

90% chance of sizing within ± 0.170-inch.

As material improvements evolved, particularly with respect to toughness, the tolerance of shrunk-on wheels to bore cracking increased. Modern wheels have critical crack sizes in the general range of ½ inch to over 2 inches. However, earlier wheels have critical crack sizes that may be as small as 1/10 inch, using the bottom of the K_{IC} scatterband and predicted deep-seated FATT. This approach, although conservative in most cases, is believed appropriate, given the consequence of a burst. From Table 1 it is evident that the probability of detecting a bore or keyway crack long before reaching critical crack size is very high for wheels made of modern materials. It is also evident that old wheels may have cracks in the bore region, particularly under the web, that could be at or near critical crack size and may not be detectable by the in situ ultrasonic test.

EVALUATION OF TEST RESULTS

The following wheel examination and tests are usually conducted on the fossil units having "built-up" rotors (shrunk-on wheels):

- Ultrasonic test of wheel bores.
- Ultrasonic test of wheel axial keyways.
- Ultrasonic test of "pin-bushed" wheels, if any.
- Wheel surface visual examination.
- Magnetic particle examination of wheel outer surfaces.

The ultrasonic data reported for evaluation consist of location and estimated sizes of all ultrasonic indications in the wheel bore region. The indicated crack sizes are compared to critical crack sizes. As previously discussed, the critical crack sizes are determined from the material properties and chemistry for the specific forgings or for general classes of the materials used for wheels, operating stress and temperature for different operating modes, and the assumed crack shape. If the size of the measured indication is at or near the critical crack size, a recommendation is made to remove the wheel from the rotor before returning the unit to service. If the size of the measured indication or an assumed indication (for the case of no indications found) is considerably smaller than the critical crack size, an estimation is made for crack growth for determining the recommended period of time to the next inspection. This time period is determined as follows:

$$\text{Time to Reinspect} = \frac{A_{cr} - A_i}{CGR}$$

where: A_{cr} = Critical crack size
A_i = Initial (actual or assumed) crack size
CGR = Crack growth rate.

AVAILABLE OPTIONS FOR CONTINUED OPERATION

Given different shapes and materials for wheels in a rotor, further inspection/evaluation classifications are required for these rotors.

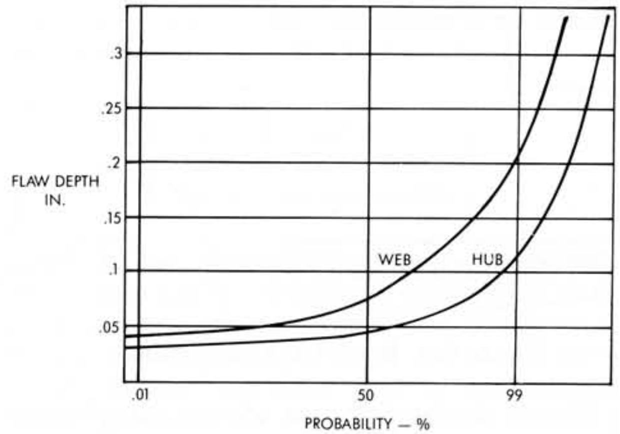

Figure 4. Probability of detection.

1. **The wheel materials and geometries are such** that a meaningful test can be conducted on all the shrunk-on wheels. For rotors in this category, the test results will allow GE to formulate recommendations to the owner on the operation/reinspection interval. These may include retesting after an appropriate operation interval or removal of the wheel with unacceptable conditions.

2. **The wheel materials and geometries are such that a meaningful test cannot be conducted on some or all of the shrunk-on wheels.** If the limitation in running a meaningful test is due to the material (i.e., the critical crack size is near or less than the detectable size by the ultrasonic test), there is no basis for recommending operation or a reinspection period; a crack of critical size may already exist or may develop soon after return to service. Such wheels may be inspected by removing them from the shaft and conducting a magnetic particle test on the wheel bores. If cracking is found, the wheel(s) should not be returned to service. If no cracking is found, the wheel(s) could be returned to service; but again, there is no reinspection interval because of the small critical crack size and the crack initiation/propagation uncertainties. If the limitation in running a meaningful test is due to geometry **only**, the wheels may be removed from the shaft and given a magnetic particle test on the wheel bores. If cracking is found, the depth can be estimated by an ultrasonic test from the bore. The test results can be used to make meaningful recommendations.

Each owner must decide which of the various options available is best for his particular circumstances. Some of these are:

a. Conduct periodic in situ inspections on those rotors having wheels that can be given a meaningful test and found to be suitable for continued service.

b. Remove and not replace those wheels that can receive meaningful tests but are found to have defects that preclude continued service. This option may adversely affect unit rating and heat rate but may be viable if unit retirement is planned in the near future or if the unit is needed for service while replacement parts are being obtained.

c. Remove and replace wheels that either have known defects or cannot be given meaningful tests due to material properties and/or geometries.

d. Replace existing "built-up" rotors with integral (monoblock) rotors thus eliminating the shrunk-on-wheel construction.

e. Do nothing and accept the associated unknown risks.

Since GE is not in the position to evaluate all the involved factors, the owners must determine their own appropriate course of action for these units.

In the preparation and planning for an ultrasonic test on your rotor, it is recommended that you contact your GE Service Engineer to obtain the specific rotor information. This will include sonic inspectability of the involved wheels, expected properties, and under appropriate circumstances, anticipated GE recommendations.

EXPERIENCE TO DATE

During the past eight years, shrunk-on wheels on 16 low-pressure rotors from eleven large turbines operating with subcritical **drum-type** boilers have been ultrasonically tested. One rotor had one sonic indication in one wheel which was caused by pitting. Recommendations were given to reinspect after six years of additional operation, a period consistent with GE's normal maintenance recommendations.

During this same time period, wheels on 25 low-pressure rotors in 13 large turbines with **once-through-type** boilers have been ultrasonically tested. All but one of these units have supercritical main steam inlet conditions. Sonic indications were found in wheel bores and/or keyways on 16 of 25 rotors. Appropriate recommendations were made to the involved utilities, based on the wheel properties and ultrasonic test results.

Experience to date shows that wheel keyway crack-like indications may be found in essentially any stage of the low-pressure turbine, although the first and last stages appear to be considerably less susceptible. At the time of preparation of this paper, no high-temperature rotors (high-pressure or reheat turbine sections) had received ultrasonic testing of shrunk-on wheels. Therefore, no definitive statement can be made regarding the susceptibility of these wheels to bore cracking.

The succeeding sections of this paper will summarize the chronological development of turbine wheel materials, nondestructive testing techniques, and fracture criteria that have led to the current considerations previously discussed.

BACKGROUND

GE shrunk-on turbine rotor design practice goes back to the early days of turbine design. The earlier rotors were constructed by assembling a series of wheels with large (by today's standards) slenderness ratios (narrow wheels), onto a shaft. Typically, the loading between the wheel and shaft was carried by the shrink between the involved parts; but a key was also used for torque transmission during loss of shrink, which can occur during thermal transients. The keying arrangement consisted of a through keyway for both the shaft and the wheel.

As rotor sizes increased, the steam leakage across the wheel through the keyway caused unsymmetrical heating of the shaft which resulted in bowed rotors. This bowing caused excessive vibration which necessitated design changes. These changes consisted of sealing arrangements on the affected units which would not permit through flow, as shown in Fig. 5.

With the advent of photoelastic stress analysis, decades before the development of finite-element analysis, the keyway region was investigated with the objective of optimizing the stress distribution. These investigations led to a ''bathtub type'' keyway shape with an elliptical ''keyway roof,'' which produced the lowest concentrated stress in this region (shown in Fig. 6). This keyway construction was initially used on large fossil ''built-up'' rotors, and was later carried over to the nuclear rotors.

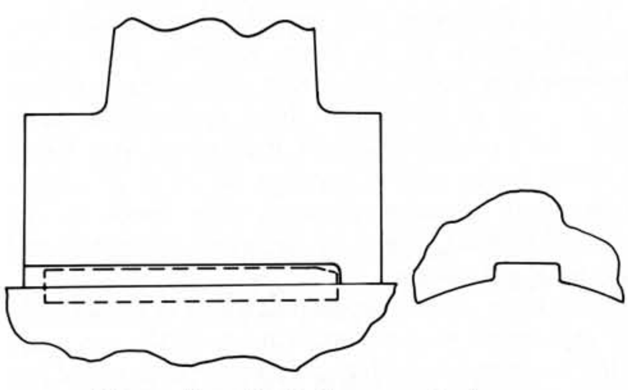

Figure 5. Early keyway design.

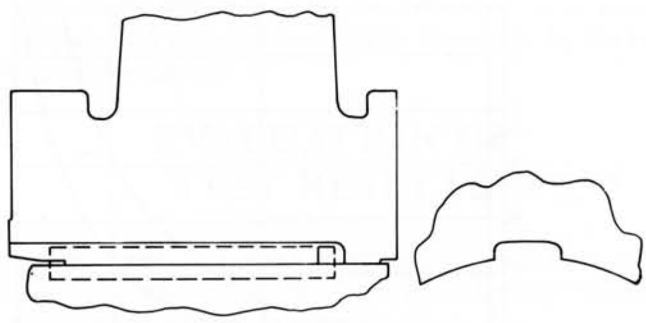

Figure 6. Recent keyway design.

During the late '60s, an offshore manufacturer's unit experienced a burst on a low-pressure ''built-up'' rotor at Hinkley Point Generating Station in England[1]. The wheel burst was attributed to stress-corrosion cracks in the bore of the wheels coupled with low toughness (small critical crack sizes) of the involved material.

Subsequent to this failure, GE began developing means for inspecting the critical regions of shrunk-on nuclear turbine wheels without removing them from the turbine shaft. Development was completed, and the testing program is well established for such units. Specially designed ultrasonic transducers positioned on the hub and web of the wheel are used to transmit ultrasound toward the bore. If an indication is present, a portion of the ultrasonic energy is reflected either back to a dual transmitting/receiving crystal assembly or to a receiver at the appropriate location of the wheel as shown in Fig. 7. An analysis of the reflected signal is made to determine whether a crack is present. The material within two to three inches of the bore of the nuclear wheels, including the keyway, is inspected by continuously varying the location of the transmitting and receiving crystals.

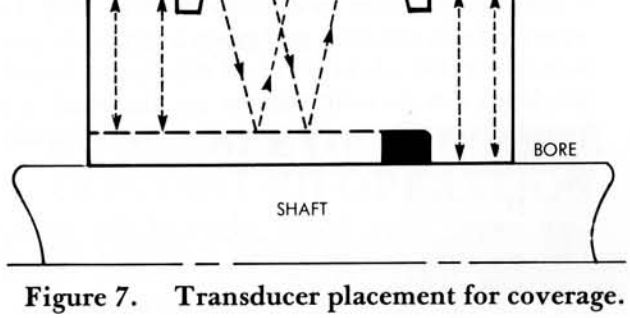

Figure 7. Transducer placement for coverage.

There are three possible mechanisms for initiating and/or growing cracks in wheels in service:

1. Creep rupture.
2. Stress cycling.
3. Stress-corrosion cracking.

Typically, the design, temperature, and material used for these wheels preclude the possibility of creep rupture cracking for most cases. The likelihood of initiating and/or growing a crack due to the stress cycling (associated with starts, stops, or load changes) is small. The variation in stress amplitude resulting from operating transients is too low to produce significant crack growth in the unlikely event that a defect exists in the wheel when it was placed in service. A few shrunk-on wheels operate within the high-temperature region of the turbine, where creep rupture and stress cycling due to thermal stresses are of concern. The testing and conditions for these special cases are not addressed by this paper. For these cases, however, appropriate periodic inspections can minimize the probability of in-service failure. The major concern with respect to the in-service initiation and growth of cracks discussed here is that associated with stress corrosion.

The effective utilization of moderately high-strength steels, where properties can be enhanced by heat treatment, and of correspondingly higher stresses in the design and construction of steam turbines has been an essential factor in the progress that has been made. In general, these steels have performed admirably in the long-term service expected of turbine components with few forced outages due to material problems. Because substantial energies are involved in the burst of rotors and/or wheels, special attention has always been given to rotating parts, with particular emphasis on the rotors and wheels.

There have been instances of stress-corrosion cracking of fossil "shrunk-on" wheels, indicating the need for additional attention. Stress-corrosion cracking is a very complex phenomenon, influenced by many factors, such as environment, material properties, stress levels, etc.; and there are considerable uncertainties about their interaction. These cracks are brittle in nature, usually branching, and are typically intergranular, as shown in Fig. 8, for the involved materials and turbine environments.

The traditional methods for solving stress-corrosion cracking problems are to eliminate the chemical contaminant and/or to reduce the susceptibility of cracking of the involved components.

Figure 8. Example of component failed in service by caustic stress-corrosion cracking.

STEAM ENVIRONMENT

Good control of water chemistry in a power generation steam system to prevent depositions of solids and corrosion of components is vital in preventing problems. However, very dilute solutions in the turbine steam cycle can be concentrated during operation. Contaminants in the turbine prior to start-up and during shutdown will become more concentrated as the turbine heats up and water is evaporated. Each solution has a unique partial pressure temperature concentration equilibrium relationship, and any dilute solution will increase in concentration until equilibrium is achieved. This is not a major problem with exposed surfaces where the residues will be swept away by the large volume of steam flow during operation. In stagnant areas, however — spaces between buckets and wheels or crevices between wheels and shafts, such as keyways — the solutions can concentrate and remain for long periods during operation.

Contamination of the turbine with dilute chemicals could be caused by:

1. Cutting fluids used in manufacturing which contain chlorine or sulfur that are not cleaned in a timely manner.
2. Use of cleaning fluids with unacceptable levels of caustic, chlorine, or sulfur for removing protective materials prior to start-up.

3. Cleaning solutions used to remove deposits from the turbine or associated components.

4. Untreated attemperating sprays used to control superheat and/or reheat temperatures.

5. Untreated exhaust hood sprays used to control temperature in the low-pressure hoods during low-load operation.

6. Improper regeneration of feedwater demineralizers.

7. Contamination from cooling water in the event of condenser tube failures.

8. Use of sodium sulfite as an oxygen scavenger for high-pressure boilers. Decomposition of the sodium sulfite can produce hydrogen sulfide in the early moisture region of the turbine.

9. Improper control of the coordinate phosphate treatment process, which can result in free caustic in the turbine.

With this knowledge, GE has exercised great care not to introduce contaminants during manufacturing, shipment, or installation of the rotor. However, with the inadvertent addition of chemicals to the steam cycle during operation — for example, by improper feedwater treatment — turbine materials are washed by droplets containing contaminants that concentrate in the liquid phase and lead to stress-corrosion cracking. The low-pressure sections are particularly vulnerable to this kind of attack because there is a natural concentrating mechanism associated with the steam cycle.

As steam expands through the turbine, the solubility of most impurities in the steam decreases. Deposits form in the turbine when the concentration of the impurity exceeds its solubility in the steam. The concentration of the impurity when it deposits can be much greater than its concentration in the steam. This mechanism applies to caustic impurities, as illustrated by the estimated caustic solubility diagram shown schematically in Fig. 9 (References 2, 3, 4, 5, 6, 7). The estimated steam solubility lines indicate that the solubility of caustic in superheated steam decreases with decreasing pressure and temperature. If the concentration of caustic in superheated steam exceeds its solubility, droplets of a concentrated caustic solution will precipitate and deposit. The concentration of caustic in the droplets is shown by the liquid concentration lines.

The relevance of Fig. 9 to turbine operation is indicated by the turbine steam expansion lines for a typical large fossil unit. At the pressure and temperature typical of high-pressure turbines, the solubility of caustic in steam exceeds 100 ppb. However, as the steam expands and approaches saturation in the low-pressure turbine, the caustic solubility in steam decreases.

Note that the caustic steam solubility lines in Fig. 9 are only estimates obtained by extrapolating solubility data from the work of Styrikovich[8]. The Styrikovich data are for drum steam conditions and must be extrapolated by at least three orders of magnitude to obtain the caustic steam solubility lines for low-pressure steam turbine conditions. Other studies, including those conducted under EPRI sponsorship by Babcock & Wilcox and GE, have supported these predictions.

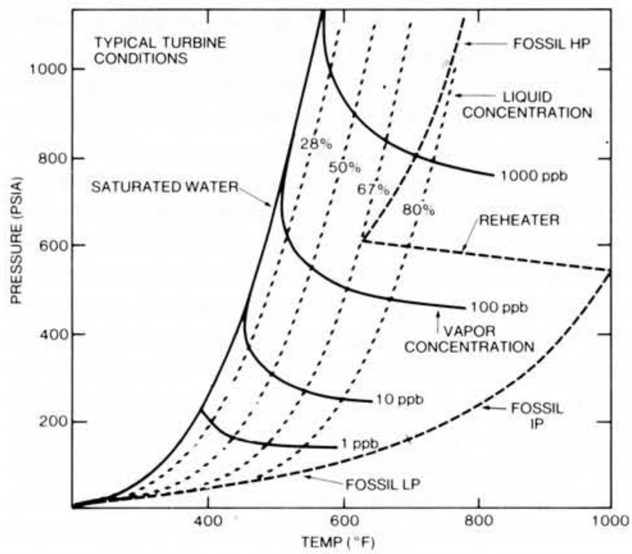

Figure 9. Caustic solubility pressure-temperature diagram.

MATERIAL SUSCEPTIBILITY TO STRESS-CORROSION CRACKING

GE has conducted extensive research in the area of turbine materials susceptibility to cracking in turbine environments. Results have been published over the past several years, e.g., References 9, 10, 11, 12, and 13.

An example of such testing is presented in Reference 12. Various test techniques were used in a caustic environment, including dead weight loading, to provide uniaxial tensile stress on a string of five specimens submersed in an environment of 28 percent NaOH at 150 F. The apparatus used is shown in Fig. 10 without the environment container so that specimens can be observed. The information obtained from these tests is shown in Fig. 11, which is a plot of stress versus time-to-failure for rotor/wheel turbine alloys in caustic environments.

Figure 10. Apparatus used for dead weight load testing.

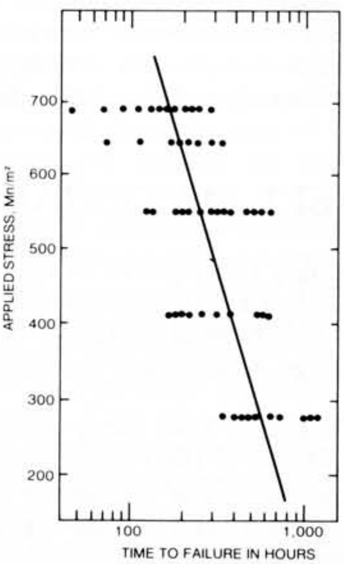

Figure 11. Influence of applied tensile stress on time to failure for rotor/wheel material in 40% NaOH at 100 C with potential controlled at -750mVH.

Another test program consisted of constant extension rate testing. In this test, a tensile specimen is loaded and pulled to failure at a very slow extension rate in the environment of concern. The test is useful for comparing the relative stress-corrosion resistance of alternate materials in a given environment, in a relatively short time.

An important factor that must be considered in evaluating the stress-corrosion cracking of a material is the crack growth rate. Crack growth rate is very important because it determines how long it will take the crack to grow to critical size. Fatigue precracked wedge open-loaded (WOL) type specimens, shown in Fig. 12, have been employed to develop crack growth data for wheel/rotor alloys in caustic environments. These crack growth tests have provided information (Fig. 13) which relates crack growth rate to crack tip stress intensity for wheel materials in two environments[14]. It is evident that the corrosiveness of the environment exerts a large influence on the crack growth rate. In an aggressive caustic environment, cracks grow very fast at stress intensities expected at wheel keyways. However, extremely slow crack growth rates are observed in normal steam/water environments, and the probability of crack initiation is also low.

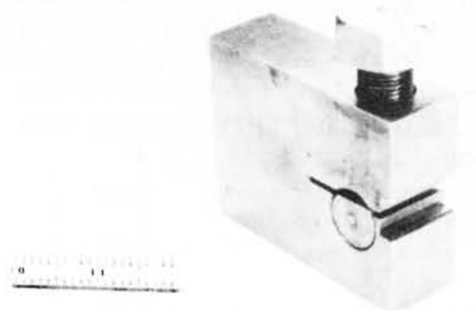

Figure 12. Fatigue precracked wedge open-loaded specimen used for determining stress-corrosion crack growth rate.

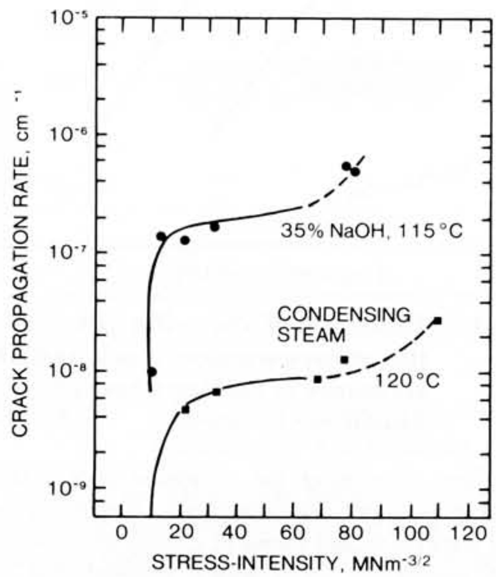

Figure 13. Crack growth rate for turbine wheel alloys as a function of stress intensity.

All of the corrosion testing described has been, of necessity, conducted in only a few of the infinite number of turbine environments. To increase our understanding of turbine corrosion damage, several studies have been conducted based on an electrochemical approach. The primary goal of these tests was to reduce the vast number of tests needed to completely characterize a given alloy/environment corrosion behavior. For example, the electrochemical role of impurities often is to alter the corrosion potential of an alloy in a given environment. Since susceptibility of an alloy to corrosion damage in a given environment can be strongly dependent on corrosion potential, knowledge of the effects of impurities on corrosion potential may be sufficient to predict susceptibility. The role of corrosion potential on caustic cracking of turbine wheel/rotor alloys has been investigated[9], and the results indicate that the corrosion potential has a strong influence on both the likelihood of initiating a stress-corrosion crack and on the crack growth rate. The effect of corrosion potential on initiation is illustrated in the stress versus time-to-failure plot shown in Fig. 14. A familiar effect of corrosion potential on crack growth rate has also been observed[15], as shown schematically in Fig. 15.

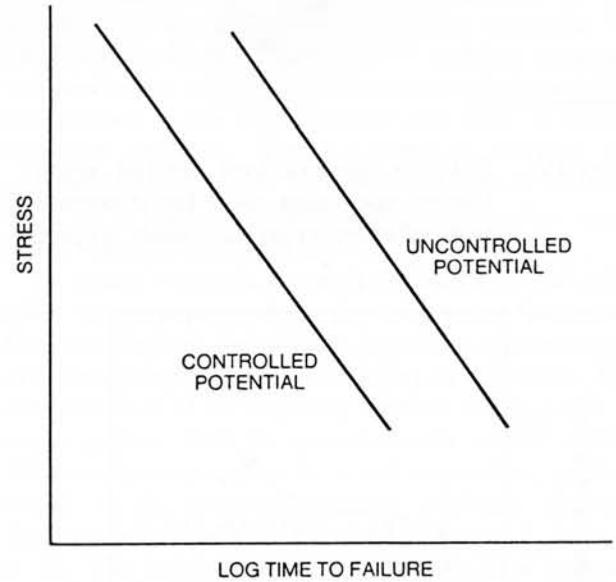

Figure 14. Influence of corrosion potential on the stress-corrosion crack initiation resistance of turbine wheel alloys in a caustic environment.

Impurities often alter the corrosion potential of a material in a given environment. Stress-corrosion cracking tests on wheel alloys in caustic environments to which impurities were added showed that those impurities cause a shift in corrosion potential, resulting in an enhanced susceptibility to stress corrosion[16].

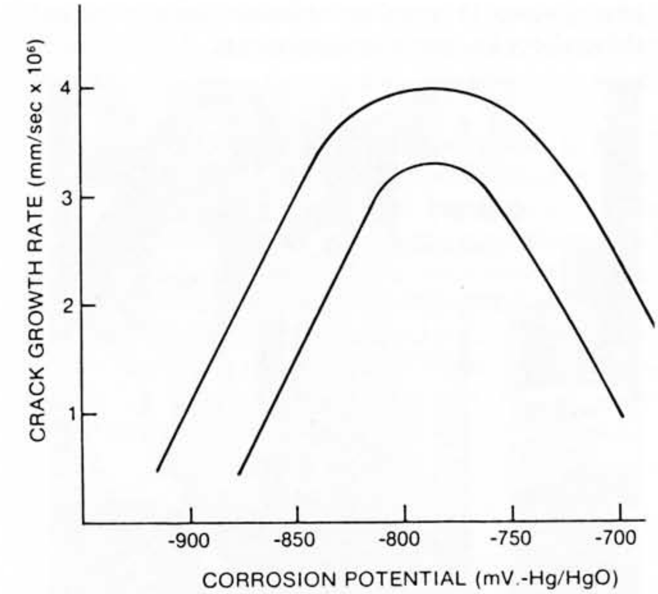

Figure 15. Influence of corrosion potential on the stress-corrosion crack growth rate for turbine wheel alloys in a caustic environment.

The implication of all the information on turbine materials and designs described is that, for worst-case (very aggressive) environments, corrosion-induced cracks may initiate and grow on virtually all potentially useful turbine materials, even at moderate stress levels.

WHEEL MATERIALS

The evolutionary development of materials used for shrunk-on wheels in GE turbines resulted from a combination of technological advances in process and physical metallurgy, nondestructive testing, and fracture analysis.

The wheel materials used today incorporate the integrated knowledge of these three disciplines and are made to a chemistry that is optimally balanced to have high hardenability and to achieve good fracture toughness at the required tensile strength, low tramp elements to minimize temper embrittlement, and low sulfur to minimize harmful segregation. In addition, the steel is melted in a basic electric furnace and is vacuum carbon-dioxidized to eliminate the possibility of hydrogen flakes and to minimize the presence of nonmetallic inclusions which reduce fracture toughness. The molten metal is poured into ingot molds optimized to minimize segregation with sufficient material for top and bottom discard practices. After solidification, the forging is done under stringent temperature limits, using forge presses with adequate capacity to work the metal deep within the forging. The final heat treatment is optimized to achieve small grain sizes. Following final austenitize, the wheel is quenched in water and submerged for a prescribed time, depending on the hub thickness. This quenching procedure was derived based on a complex finite-element heat transfer analysis and testing of full-size wheels in the laboratory. This critical step in the manufacturing cycle is done to ensure good deep-seated fracture toughness, so that the critical crack size is relatively large. After quenching, the wheel is tempered and cooled at a prescribed rate to minimize temper embrittlement, as well as to ensure freedom from high residual stresses. After the wheel is heat treated, it is rough machined to near the final dimensions and given a thorough nondestructive test inspection, including ultrasonic inspection. Also, specimens taken from prescribed locations on every wheel are subjected to destructive mechanical property tests.

GE has continually used state-of-the-art materials. For example, the materials used for shrunk-on wheels manufactured in the 1920s and 1930s, and perhaps even as late as the 1960s, although not up to today's standards, were at the forefront of technology at the time of their manufacture.

Shrunk-on wheels go back to the original Curtis turbine of 1897. It is interesting to note that the buckets for the original Curtis turbines were machined out of the wheel rim or out of segments of metal that were then riveted to the wheels[17]. The wheel material for these early turbines was cast iron. It was not until about the time of World War I that nickel steel was adopted as the primary wheel material.

A number of wheel failures during the 1920s caused GE considerable concern and required considerable effort to investigate and resolve. These failures, which were without parallel in the history of the steam turbine business and prompted a significant research effort, were eventually attributed to mechanical design factors. Early wheel designs carried more than one row of buckets per wheel. However, as single-row wheels became more common, the transverse stiffness was significantly reduced. On occasion, a resonant condition occurred, causing a fatigue failure. The technical details of these early wheel failures have been documented in the classic paper by W. Campbell[18]. This pioneering work, which was done in Schenectady, is still used as a design standard around the world. These failures also resulted in a great deal of research on the fatigue strength of steel. This effort identified the benefits of reducing stress concentrations and improving surface finishes to increase fatigue strength. In addition, GE installed wheel testing machines to study wheels under actual operating conditions.

While most of the research and development initiated by these failures focused on mechanical design, wheel material integrity was also becoming an important design consideration. The first test machine to inspect wheels by magnetic examination was installed in 1920. Since then all wheel forgings have been examined magnetically. X-ray equipment became a regular shop tool in 1931 and was used to further ensure sound wheel forgings.

By the early 1930's it was apparent that further increases in turbine efficiency, which required higher steam temperatures, would be impossible without materials capable of resisting deformation at high temperatures. By that time the steam conditions had stabilized at 750 F and 1200 psig. Figure 16 from Reference 17 shows the changes in steam pressure and temperature up to 1936. During the early 1930s, the effect of molybdenum and chromium on high-temperature properties was becoming known. By 1935 GE had a wheel material specification with a nominal composition of 0.4C-1Cr-0.3Mo. The use of the CrMo steel for shrunk-on wheels permitted a significant increase in steam temperature during this period.

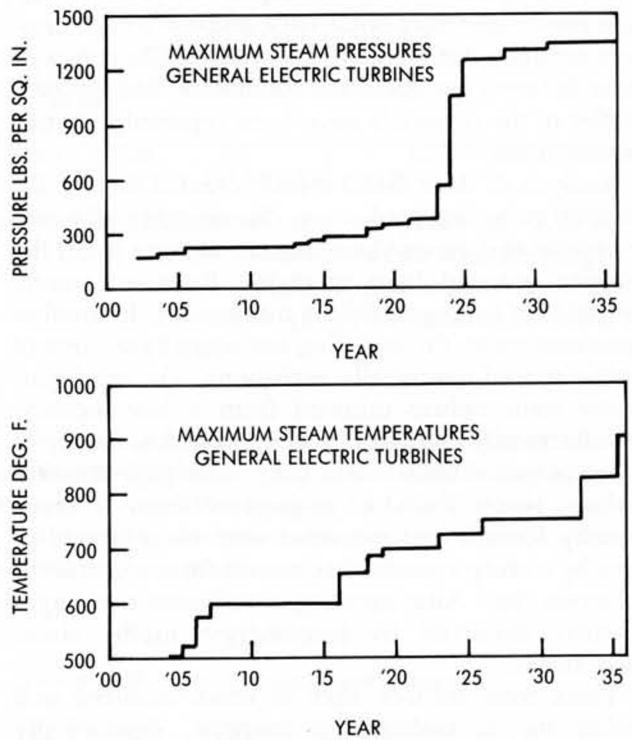

Figure 16. Maximum steam pressures and temperatures — GE turbines.

Within the same time frame that steam temperatures and pressures increased, it became necessary to increase turbine speeds to 3600 rpm to provide compact designs. With this increase in rotor speed, the stresses in wheels, particularly in the exhaust region of the turbine rotor, began to approach a significant fraction of the yield strength of the available carbon and nickel steels. Experiments with low-alloy steels such as NiCr, NiMo, and CrMoV steels eventually led to new wheel materials.

Because of stress considerations, rotor forgings for the larger 3600 rpm units were machined from solid forgings rather than the shrunk-on design.

By the early 1950s, rudimentary knowledge in the art of steel forgings leading to modern turbine wheels was emerging. The effects of nickel, chromium, and vanadium on hardenability were better understood. The newest of the major nondestructive testing techniques (ultrasonic testing) was routinely being used. Mainly as a result of the Liberty ship failures during World War II, fracture mechanics was emerging as a new technology, with much of its advance made in the GE Laboratories in Schenectady.

However, it was not until after the industry experienced major turbine rotor failures between 1953 and 1956 that all these disciplines came together. Rotor fracture failures occurred in at least five turbine-generator units. Of these, three were generator rotors made from NiMoV forgings, one a low-pressure turbine rotor made from NiCrMoV and one a high-pressure turbine rotor made from CrMoV. The nature of these failures, the operating conditions, and the properties of the materials have been reported in considerable detail[19-22].

Analysis of these failed rotors revealed that all the failures were initiated at a discontinuity. In one generator and the one low-pressure turbine rotor, the fracture initiated from crack-like flaws apparently caused by a hydrogen flaking mechanism. In another generator rotor, the initiating site was a large area of closely spaced nonmetallic inclusions. The third generator rotor failure initiated from a low-ductility, metallurgically segregated region located at the top of a severe geometrical stress riser. The high-pressure turbine wheel fracture propagated from a crack initially formed and extended over some period of time by a creep rupture mechanism from a geometrical stress riser. After growing to sufficient size, rapid fracture occurred by low-energy ductile shear mechanism.

These rotor failures, each of which occurred well within the normal design margins, dramatically revealed the need for development of criteria relating fracture strength to stress level, geometry, temperature and mechanical properties, and acceptance test methods capable of ensuring adequate fracture toughness.

In summary, these failures identified the need to improve:

1. Nondestructive testing techniques.
2. Fracture-resistant materials.
3. New fracture-based design methodologies.

While the major research and development efforts initiated during the mid-1950s were prompted by and concentrated on rotor materials, the wheel materials were nominally of the same composition. Moreover, it was well recognized that the same factors causing integral rotor failures could also cause a wheel failure. Consequently, while the effort was to solve the rotor problem, all solutions, techniques, and improvements in nondestructive testing, fracture analysis, and metallurgical quality were simultaneously applied to wheel materials. In fact, because of the smaller size of wheels, many of the fixes developed for rotors were first applied to turbine wheels.

FRACTURE-BASED DESIGN METHODOLOGY

By 1955 only qualitative measures of fracture toughness had been developed. While the Izod test was first developed in 1903 in Great Britain during the investigation of burst gun barrel material, it was never popular in the United States. The Charpy test, which is similar to the Izod test, was not used frequently in the United States until the early 1950s. GE, while not requiring its forging vendors to meet impact requirements until 1956 (Keyhole) and 1960 (V-notch), had been requiring test blanks, which were used to determine impact data on wheels since 1950. During that decade, the forging suppliers were developing manufacturing procedures that would consistently meet the impact requirements of GE.

An excellent review of the early history of fracture mechanics and the evolution of an overall design analysis procedure based on test data taken from the rotor failures and analytical concepts of the GE engineering community can be found in the paper by Yukawa, Timo, and Rubio[23]. Because all the rotor failures occurred within normal design stress levels, the early stage of the investigation focused on the effect of "size" on fracture strength. The major findings pertaining to the effect of increasing specimen size on fracture strength were reported by Lubahn and Yukawa[24]. Their work with large-notched bend bars revealed a large decrease in fracture strength with size if the notch depth increased in proportion to the specimen size, providing the notch was very sharp.

To determine the significance of this finding on rotating components, spin burst fracture tests were conducted on small and large notched and unnotched disks. The test results led to the adoption of a "standard" geometry for large notched spin disks. The dimensions of this standard disk were 24 inches OD, three to four inches ID, and three to six inches thick. Some of the details of these comprehensive studies can be found in References 25 and 26.

Numerous disks of this type, and from a wide variety of materials, were burst at different temperature levels. The results of these tests are shown in Fig. 17, which shows the mean stress in the vicinity of the notch at bursting divided by tensile strength as a function of Charpy V-notch impact energy at the bursting temperature. Figure 18 shows the same data plotted against the difference between the test temperature and the transition temperature of the disk. All of the points falling below the lower dashed line were found either to have segregates at the notch, low ductility, or both. It was believed that a metallographic examination of the four failed disks whose data fell below the lower dashed line would have revealed segregation in them also, since the presence of segregate stringers frequently produces low tensile reduction of area but is not reflected in Charpy energy values unless the segregate occurs at the root of the notch.

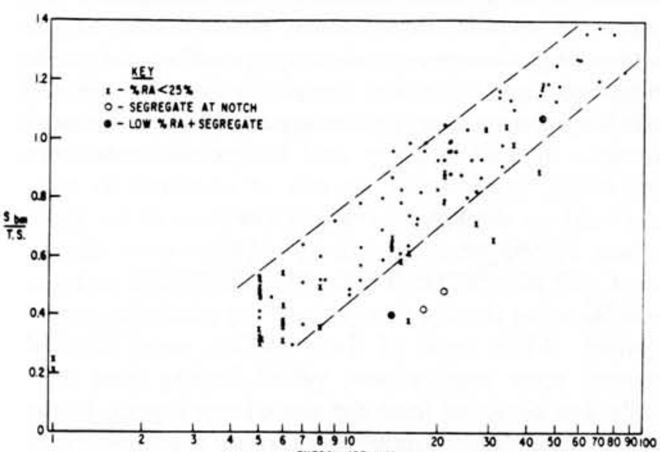

Figure 17. Charpy energy at the spin test temperature plotted against ratio of mean str notch (S_{bm}) to tensile strength.

The role of chemical segregation, particularly sulfide segregation, was not fully appreciated before the disk burst tests. The significance of the finding will be discussed later. In about the same period that GE was determining the cause of rotor bursts, Irwin[27] was introducing his formulation of a new fracture criterion which would become the basis of linear elastic fracture mechanics. In fact, the work by Yukawa of GE on the rotor failures contributed to the engineering acceptance of fracture mechanics. Eventually an empirical relationship was developed between the fracture toughness value (K_{IC}) derived from nitrided disks as a function of test temperature and Charpy V-notch Fracture Appearance Transition Temperature (FATT). The quantity ($T-T_{FATT}$) is now more commonly referred to as excess temperature. Figure 19 is an early version of this simple engineering correlation. In this figure, the FATT is related to fracture toughness obtained from the large nitrided disks. As the field of fracture mechanics developed, much simpler and less costly specimens were developed to measure fracture toughness. However, this curve has significant engineering value because it relates an easily measured quantity, i.e., FATT, to fracture toughness. Much more experimental data has been added to the initial curve. The lower bound of Fig. 20 is the basis on which fracture mechanics analyses of modern wheels are made.

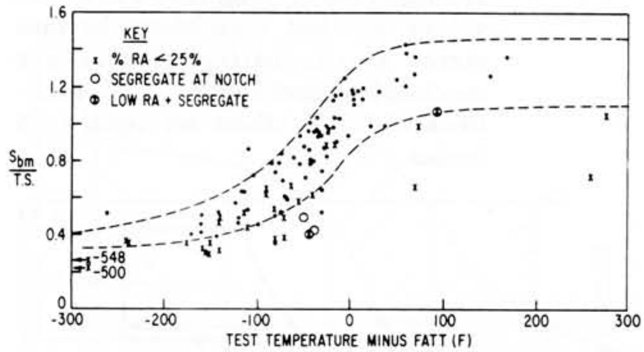

Figure 18. Effects of test temperature, FATT, tensile reduction of area and segregation on ratio of mean stress field at the notch (S_{bm}) to tensile strength (TS).

The relationship between excess temperature and the fracture toughness, (K_{IC}), forms the basis for the modern fracture analysis done by GE. The crack size at which brittle fracture will occur is related to the material fracture toughness as follows:

$$K_{IC} = c\sigma\sqrt{a_{Cr}}$$

where σ = nominal bore stress

a_{Cr} = critical crack size

c = constant which is dependent on geometry.

Therefore, the critical crack size is:

$$a_{Cr} = \frac{(K_{IC})^2}{(C\sigma)^2}.$$

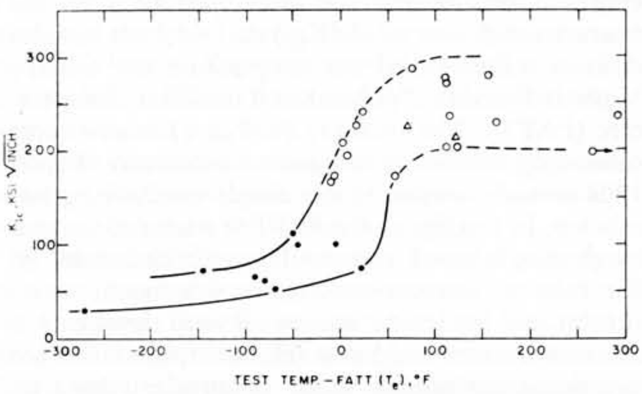

Figure 19. Fracture toughness values (K_{IC}) derived from nitrided notched disk tests as a function of test temperature and Charpy FATT for medium-strength alloy steels. KEY: Open symbols denote nominally calculated values for test conditions beyond strict applicability of fracture mechanics procedure; , 17-inch-thick disk, all others are equal to 3 inches.

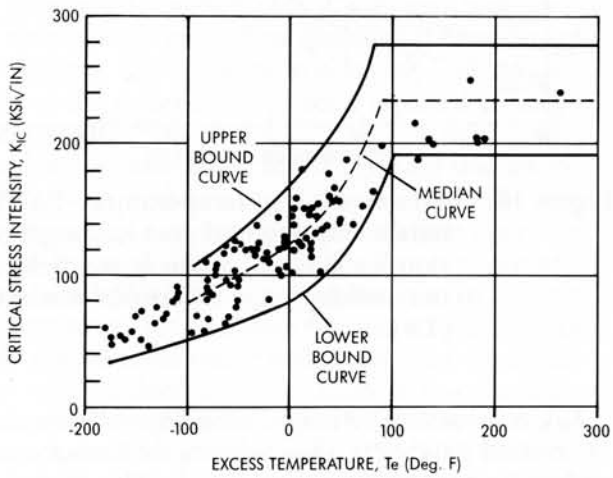

Figure 20. Critical stress intensity vs. excess temperature scatterband based on data for NiCrMoV steels.

From this expression it is apparent that the critical crack size increases as the square of the material toughness, KIC, and decreased as the square of the applied stress. This single equation combines design methodology and metallurgical behavior. It is very clear that for a given design stress, the greater the fracture toughness, the greater the critical crack size. Figure 20 indicates that the lower the FATT, i.e., the greater the excess temperature, the greater the fracture toughness. Therefore, recently the main goal of metallurgical efforts to improve the fracture toughness of materials has been to drive the FATT to as low a temperature as possible and to minimize harmful segregation which would cause the actual local fracture toughness to drop below the expected scatterband correlating fracture toughness to FATT (see examples shown in Figs. 17 and 18).

METALLURGICAL ADVANCES

As mentioned previously, the role of chemical segregation, particularly sulfide segregation, was not fully appreciated prior to the disk burst tests. These tests, plus the known role of hydrogen flakes in the Cromby and Ridgeland rotor failures, led GE toward new steelmaking practices. Many of the historical details can be found in References 28-32. The mid-1950s represented a period of transition in steelmaking. Large forgings were typically made from basic open hearth, acid open hearth, and basic electric furnace practices. Electric furnace steel was recognized as a cleaner steel (fewer nonmetallic inclusions) than acid open hearth steel, but its higher hydrogen content made it more susceptible to hydrogen flaking. Efforts to improve soundness were made in every phase of steelmaking practice. In addition to the impending changes in melting practice, the mills modified ingot practices to obtain more desirable solidification patterns by changes in hot top and stool design. In addition, top and bottom discards were increased, minimizing the risk of extremes in alloy and carbon segregation. Those portions of the ingot where defects were most likely to occur were eliminated. GE also initiated computer simulation of ingot solidification during this period[33] to minimize segregation. While most of these studies were directed toward rotor applications, wheel forging steel typically was obtained from the same large ingots. In the case of wheels, an ingot yielded more than one wheel forging.

The installation of vacuum-pouring equipment[34-35], and the universal adaptation of electric furnace melting during the period 1957-1959, however, resulted in a marked reduction in the sonic indications in rotors and wheels and a major decrease in the rate of rejections from this cause. The reduction in hydrogen content, resulting from vacuum pouring, practically eliminated the possibility of flaking and decreased the incidence of nonmetallic inclusion. The likelihood of a large nonmetallic inclusion segregate in a vacuum-poured forging, similar to that which caused the Pittsburg rotor burst[21], is considered to have been greatly reduced.

As mentioned previously, it became clear in the fracture studies on rotor bursts that high fracture toughness and low transition temperatures were necessary for reliable rotor performance. The major metallurgical modifications and changes that were developed and instituted to improve these properties during the early 1960s were:

1. Lowering the austenitizing temperature to achieve a finer grain size.
2. Reducing the C, Mn, and Mo content and increasing the Ni content in the NiMoV grade to obtain an improved transformation structure.
3. Development of the NiCrMoV grade, which has increased hardenability and a lowered bainite transformation temperature.
4. Use of water quenching to accelerate cooling from the austenitizing temperature to provide an improved transformation product.

Figures 21 and 22, respectively, show the variation in FATT as a function of grain size (austenitizing treatment) and the improvement in FATT resulting from water quenching. Figure 23 shows the change in FATT versus year of manufacture due to the cumulative changes from all development efforts. These improvements came at the same time the tensile strength requirements for the components increased. Figures 24 and 25 show the historical strength increase and a corresponding increase in tensile reduction in area.

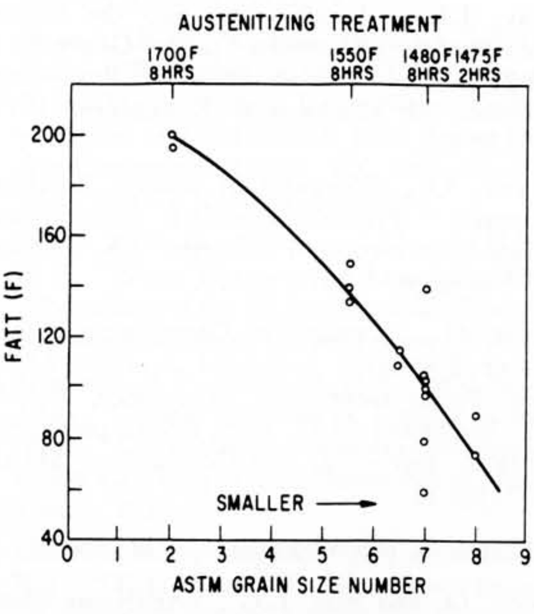

Figure 21. **Effect of austenitizing conditions and resultant grain size in Charpy fracture appearance transition temperature for NiMoV stress.**

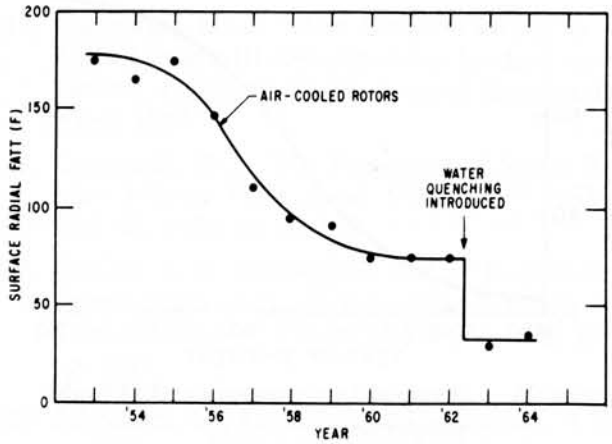

Figure 22. **Trend of average Charpy fracture appearance transition temperature in NiMoV generator rotor forgings, surface radial tests.**

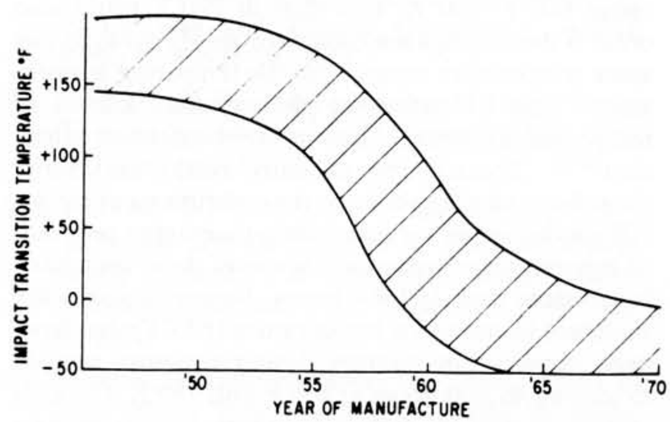

Figure 23. **Trends in impact transition temperatures of low-pressure rotors.**

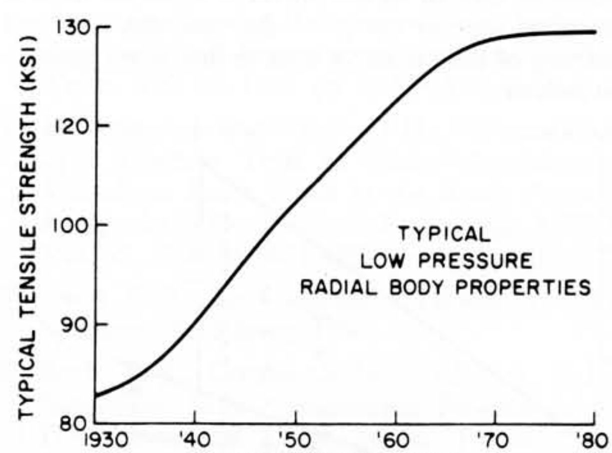

Figure 24. **Typical low-pressure radial body properties.**

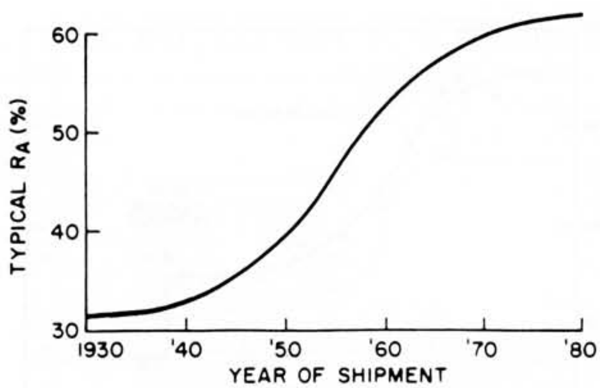

Figure 25. Typical low-pressure radial body properties.

While the improvements in as-received fracture toughness described above were dramatic, it also became recognized that the presence of certain tramp elements in steel could cause a shift in the FATT if the material is exposed for long times in the temperature range 600 F-900 F. This shift in FATT could also occur if the forgings are cooled too slowly through this same temperature range from the tempering temperature. This embrittlement phenomenon, known as temper embrittlement, has received extensive attention[36-38]. Because low-pressure rotors and some shrunk-on wheels operate in the embrittlement range, GE conducted an extensive long-time aging program of representative materials. Some of these tests have lasted more than 100,000 hours. Figure 26 shows the increases in transition temperature (FATT) that have been observed in samples during exposure periods exceeding 40,000 hours at 650 F and 750 F. Through careful control of tramp elements — particularly phosphorus, tin, arsenic, and antimony — it has been possible to reduce the tendency for this embrittlement. This study, until recently, had been funded entirely by GE. EPRI has provided funds to continue the aging and to complete the consolidation and reporting of the extensive data to the power generation industry.

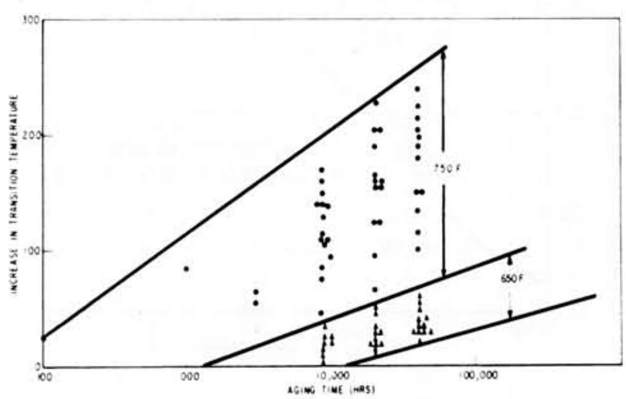

Figure 26. Temper embrittlement in NiCrMoV rotors.

NONDESTRUCTIVE TESTING

GE has had a long history in pioneering nondestructive test techniques. The inspection of forgings during the 1920s was made by visual examination, aided only by the "kerosene and whiting" test. The magnetic particle test, introduced in the early 1930s, provided a much more sensitive means of detecting surface defects. As mentioned previously, the first x-ray equipment applied routinely as a shop tool began in 1931.

The use of ultrasonics to detect flaws in metals has commonly been attributed to Muhlhauser (German Patent No. 569,598) in 1931. As early as 1937, GE engineers devised an apparatus that detected flaws in much the same way that ultrasonics do today. World War II caused major advances in ultrasonics as a result of the intensive efforts in developing radar. Since that time, GE has made many advances in ultrasonic techniques. In addition, a very large database has been accumulated to correlate the ultrasonic indications to actual physical defects. In addition, numerous internal laboratory test programs have been conducted over the years to determine the effect of natural defects on a variety of mechanical properties, including fracture toughness, low and high cycle fatigue, etc.

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