Utility Power Corporation

ENGINEERING REPORT ER-8402

PROBABILITY OF DISK CRACKING DUE TO STRESS CORROSION

COMANCHE PEAK UNIT I

August 1984

Probability of Disk Cracking Due to Stress Corrosion

Introduction

The probability of turbine missiles from our 1800 r/min nuclear steam turbine-generators with 44-inch last stage blades is documented in the Engineering Report No. ER-504 of October 1975 to be

2.1×10^{-7} per unit year for a 4-flow turbine.

This number actually defines the probability of the occurrence of a ≥ 120% speed or ≥ 20% overspeed event.

Engineering Report No. ER-503 on turbine missile analysis describes our LP turbine design with the innercasings featuring crash rings at the circumference of the last stage blade rows. With this design, the threshold speed for producing an external LP turbine disk missile is:

Disk No.	Threshold Speed for External Missiles	
#1	2900 r/min	161% of rated
#2	3220 r/min	179% of rated
#3	2900 r/min	161% of rated
#4	2960 r/min	164% of rated
#5	3042 r/min	169% of rated

The following evaluation of disk cracking due to stress corrosion assumes speed operation below 120% speed and is, therefore, a probability of an LP turbine internal missile only.

Operating Speed

Evaluating the probability of stress corrosion cracking for a speed ≥ 120% of rated speed would lead to an insignificantly low probability because the probability of the accuracy of a 20% overspeed event being so small. Even an overspeed of ≥10% presumes a failure of our highly redundant control system which could, however, occur

with a probability of about

$$2 \times 10^{-3} \quad \text{per unit year.}$$

Since this again would lower the probability for a disk crack due to stress corrosion by about three magnitudes, we have, in the following report, conservatively evaluated the probability of a disk failure at 110% rated speed. This will cover any small overspeed event which can occur during speed operation when the unit is not synchrozined and which can also be the result of load rejections.

Crack Initiation

Corrosion crack initiation has occurred on LP turbine disks in U.S. nuclear power plants. To-date, 240 LP turbine disks of KWU design have been in operation in PWR and BWR power plants, accumulating approximately 1000 LP turbine disk service years. However, only three LP rotors were inspected and no crack initiation was found even after 83,000 service hours. Since we do not expect stress corrosion cracking of the KWU-designed rotors which operate in KWU-designed power plants, and because cracking has been found in U.S. power plants, we have chosen as a probability base of disk crack initiation U.S. nuclear plant experience as described below.

Based on EPRI Report 2429 LD Vol. 1 of June 1982, and EPRI Steam Turbine Disk Integrity Seminar of December 1 - 2, 1983 (General Electric Nuclear SCC Experience), the following probability of disk cracking can be established:

From 2429 LD Vol. 1 Report

	Number of Inspected Disks	Number of Disks with Indications	% of Disks with Indications	Probability of Cracks with 90% Confidence Level
Disk #1	121	5	4.1	0.078
Disk #2	121	17	14.0	0.198
Disk #3	121	11	9.1	0.136
Disk #4	121	1	0.8	0.032
Disk #5	121	1	0.8	0.032
Disk #6	118	0	0	0.019

From EPRI Seminar of December 1-2, 1983

	Number of Inspected Disks	Number of Disks with Indications 0.2 in.	% of Disks with Indications	Probability of Cracks with 90% Confidence Level
Disk #1	180	0	0	0.013
Disk #2	180	0	0	0.013
Disk #3	180	3	1.7	0.037
Disk #4	180	17	9.4	0.133
Disk #5	180	25	13.9	0.200
Disk #6	180	1	0.6	0.022
Disk #7	180	0	0	0.013
Disk #8	146	0	0	0.016

These statistics from U.S. plants reveal the highest probability for corrosion cracking is found in Disks #2 and #3 and Disks #4 and 5 respectively. Since these disks operate under similar conditions to our disks #2 and 3, we have chosen 0.2 as a conservative probability from these actual experiences. Disks which operate above the Wilson line have not shown any indication of stress corrosion. It must, therefore, be concluded that the probability of cracks in earlier disks as listed above must have been arrived from units without reheaters. Our units are reheat turbines which only would operate for very few hours without reheaters. However, we assumed 30 hours operation without MSR per year which would reduce the probability of cracks for our disks #1 to

$$0.2 \times \frac{30 \text{ Hours/Year}}{6000 \text{ Service Hours/Year}} = 0.001$$

All other disks, #4 - 6 and #6 - 8 respectively show probilities in the range from 0.032 to 0.013. Because our Disks #4 and 5 operate under similar conditions, we have chosen to apply a probability of 0.03 as basis for all of our Disks #4 and 5.

Corrosion crack initiation is influenced by:

- Operating Steam Conditions
- Stress Level and Disk Material
- Purity of the Steam/Water Cycle
- Local Stagnation of Flow
- Crevices

Operating steam conditions for all turbines in U.S. power plants are assumed to be the same. Stress levels and disk materials vary, but no significant differences have been found in regard to disk crack initiation. A major difference, however, seems to exist in the steam/water cycle cleanliness, but this fact has not been considered as part of this study.

Flow stagnation and crevices play a vital part in initiating corrosion cracks. These phenomena are design-related and do not exist with our disk-type rotor design. Our keyways are located where the metal temperature is higher than the temperature of the surrounding saturated steam which eliminates condensation (see **Figure 1**). The keyway areas are stress relieved by a large circumferential groove in the disk as shown in **Figure 2**. The groove is open over the entire circumference to the outside by a 1 mm (40 mil) gap between the disk and shaft which allows breathing and therefore, keeps the keyway from becoming a crevice trapping corrosion products.

Crack initiation testing under various conditions revealed that disk material with 145 Ksi yield strength is not susceptible to stress corrosion under controlled environmental conditions, even when oxygen is present. However, crack initiation must be expected when carbon dioxide or other impurities are present from air-in leakages, as described in the American Power Conference Paper "Design, Operating and Inspection Considerations to Control Stress Corrosion of LP Turbine Disks".

Further test results shown in **Figure 3** indicate that not only tests with carbon dioxide, but also with air, led to similar crack initiation. An even more important finding is that tests with oxygen did not initiate cracks after up to 30,000 hours, but it took only approximately 2,000 hours until crack initiation when the refreshing of the test cycle with mixed bed ion filters was shut off and the low conductivity level was not any longer maintained. This test closely simulates conditions such as flow stagnation and crevices because all these circumstances drastically increase the conductivity. Such conditions do not exist with our keyway design. Therefore, it must be conluded that our advanced keyway design is a reason why stress corrosion cracking has not been found with our disk-type rotors.

In accordance with this finding, it must be conservatively concluded that the time until crack initiation with KWU-designed disks is at least 15 times longer:

$$\frac{\text{30,000 Test Hours in Oxygen without Crack Initiation}}{\text{2,000 Hours until Crack Initiation without Refreshment}} = 15$$

This quotient for crack initiation time can directly be used for the reduction of the crack initiation probability in a given time:

Crack Initiation Probability of the KWU-designed LP turbine disks for Comanche Peak Units #1 and #2 are therefore:

LP Turbine Disks	Crack Initiation Probability
Disk #1	$0.001 \div 15 = 6.7 \times 10^{-5}$
Disk #2	$0.2 \div 15 = 1.3 \times 10^{-2}$
Disk #3	$0.2 \div 15 = 1.3 \times 10^{-2}$
Disk #4	$0.03 \div 15 = 2.0 \times 10^{-4}$
Disk #5	$0.03 \div 15 = 2.0 \times 10^{-4}$

Crack Growth

Crack growth in LP turbine disks can be defined as a function of the operating temperature of a disk and the yield strength of the disk material. The empirical equation for crack growth in LP turbine disks of nuclear units as given in the ASME paper 82-JPGC-PWR-31 seems to reflect the findings in nuclear plants and has, therefore, been used in this study:

$$R = e^{\left(-4.968 - \frac{7302}{T} + 0.0278 \cdot R_{pO.2}\right)}$$

The yield strength value has been taken from Engineering Report ER-8102 Nov. 81 Rev. 1, which is the actual yield strength in Ksi for each disk measured at 20°C (68°F) ambient temperature. The disk metal temperature T used in the equation for crack growth is the maximum temperature in the keyways when operating at full load, arrived from a calculation of the isothermic lines in the disk/shaft system (see **Figure 1**). The relationship of crack growth probability density over the crack depth of a corrosion crack in a disk i at the time t has been arrived from a normal distribution for the natural logarithm of the crack growth rate assuming the standard deviation of s=0.587. The distribution of $f_t(a_{o\,i})$ is calculated up to 3 s as the assumed maximum crack depth and is shown in **Figure 4.**

Critical Crack Depth

Crack Initiation has been assumed to occur at the most critical locations with the smallest critical crack size which are the keyways. Critical crack depth is calculated from the calculated local stress at 10% overspeed and the fracture toughness arrived from the $R_{p0.2}$ strength and the notch impact test results as measured from the individual disk material (see ER-8102). The remaining influence factors of the critical crack depth have been used as follows:

- Variation of crack form from cracks of unlimited length to half circle cracks through a uniformly distributed random variable from 0.77 to 2.2.
- Reduction effect of stress corrosion crack configuration on stress intensity through a normal distributed random variable with a mean value of μ=0.65 and a standard deviation of s = 0.175 which covers the presently available data on crack configuration, as shown in **Figure 5.**

The resulting density function for the critical crack depth g $(a_{c\ i})$ has been cut off at the smallest possible critical crack depth which is the theoretical corrosion crack of infinitive length without branching (see **Figure 6.**)

The following Linear Elastic Fracture Mechanics (LEFM) equation is used:

$$a_c = \frac{Q}{1.21\ \pi} \left(\frac{K_{IC}}{k/K\ .\ \sigma} \right)^2 - \frac{d}{2}$$

a_c = critical crack depth

Q = crack form parameter with random variation from 0.77 to 2.2

K_{IC} = fracture toughness from tests for each disk (yield strength and notch impact tests)

σ = calculated keyway stress for 10% overspeed

k/K = reduction of stress intensity due to branched stress corrosion cracking (mean value μ=0.65, standard deviation s=0.175)

$d/2$ = radius of keyway in disk hub bore

Probability of Disk Rupture

The probability of a disk i with an initiated crack to fail in the time period t is equal to the probability of a crack having grown to the critical crack size in the same time t.

$$P_i(t) = \text{Probability}\,[a_{o\,i}(t) \geq a_{c\,i}]$$

The failure probability of a disk can be evaluated through the density functions $f_t(a_{o\,i})$ and $g(a_{c\,i})$ with the convolution integral:

$$P_i(t) = \int_0^{\infty} f_t(a_{o\,i}) \cdot \int_0^{a_{ci}} g(a_{c\,i}) \cdot d\,a_{o\,i} \cdot d\,a_{c\,i}$$

This equation, with the data for crack growth and critical crack size for each specific disk allows the evaluation of the probability of disk rupture by numerical integration. A distribution density from such evaluation is shown in **Figure 7.**

The probability $P(t)$ of a disk failure within a turbine-generator with n disks that would occur in the time t, is with small value of $P_i(t)$ equal the sum of the failure probabilities of all disks. With a probability of the crack initiation of q_i the following equation is applied:

$$P(t) \simeq \sum_{i=1}^{n} P_i(t) \cdot q_i$$

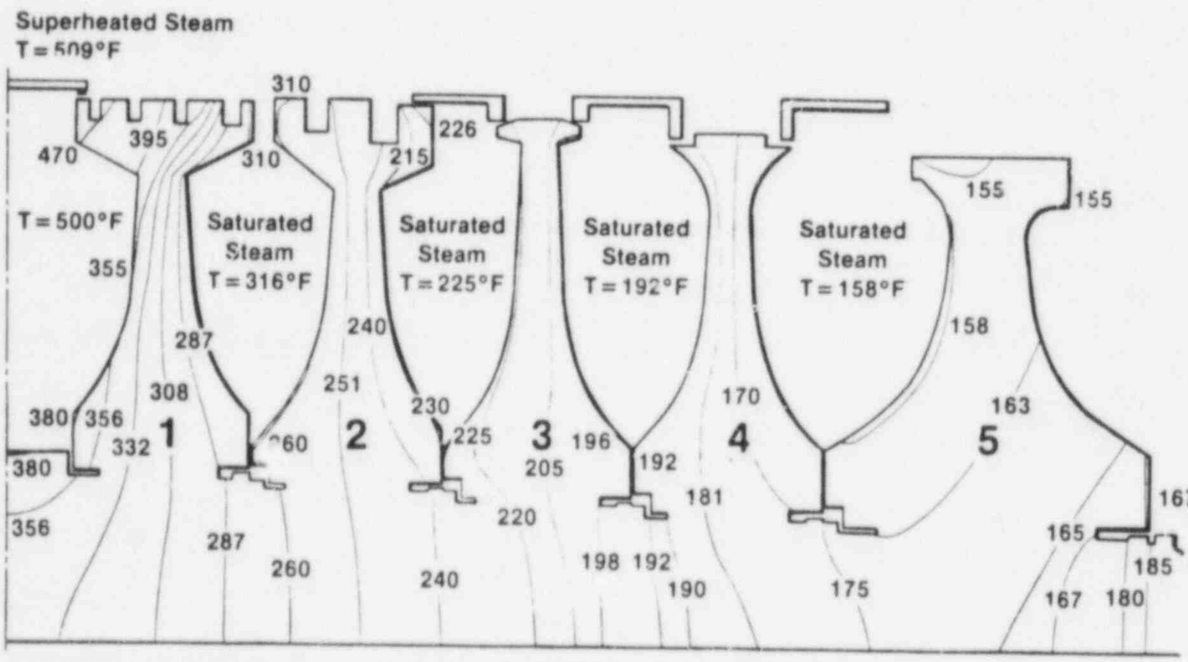
Conclusion

The probability of a postulated disk failing within an LP turbine of the Comanche Peak unit #1 within a time span of 50,000 service hours has been evaluated and listed in **Tables I and II.** The total probability for the turbine-generator from both LP turbines amounts to:

$$P(t) = 2.38 \cdot 10^{-5}$$

This result covers any overspeed event with ≤ 110% speed, since the probability of a 10% overspeed has been assumed to be 1. The probability of reaching an overspeed of more than 10% assumes a failure of our control system. The probability of such a control system failure is about $2 \cdot 10^{-3}$ which reduces the total probability of disk cracks at higher than 10% overspeed to be an insignificantly small value.

REVISION		
a		
b		
c		
d		
e		



LP Turbine Rotor Half with Disk #1 through #5

ISOTHERMAL LINES OF
DISK-TYPE NUCLEAR
LP ROTOR

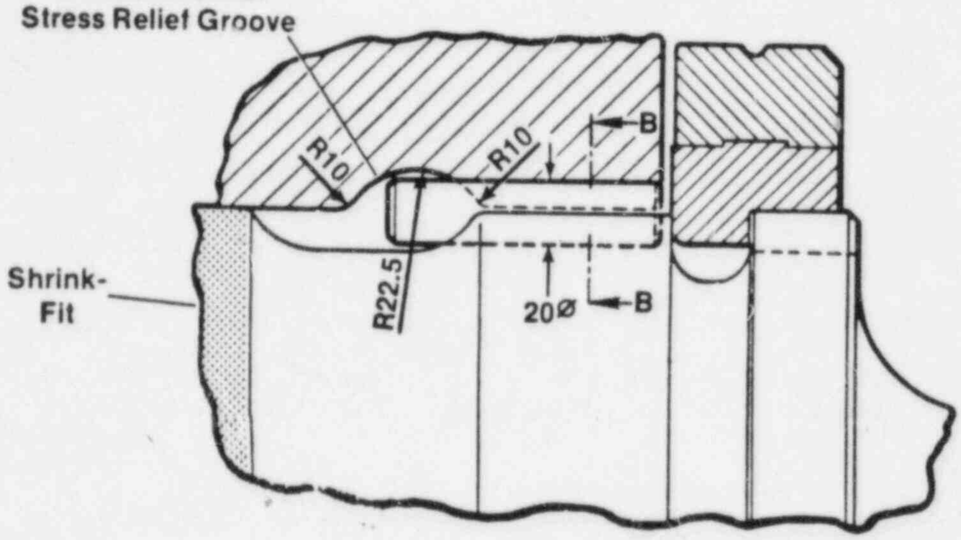
Utility Power Corporation

FIGURE 1/1E84.071

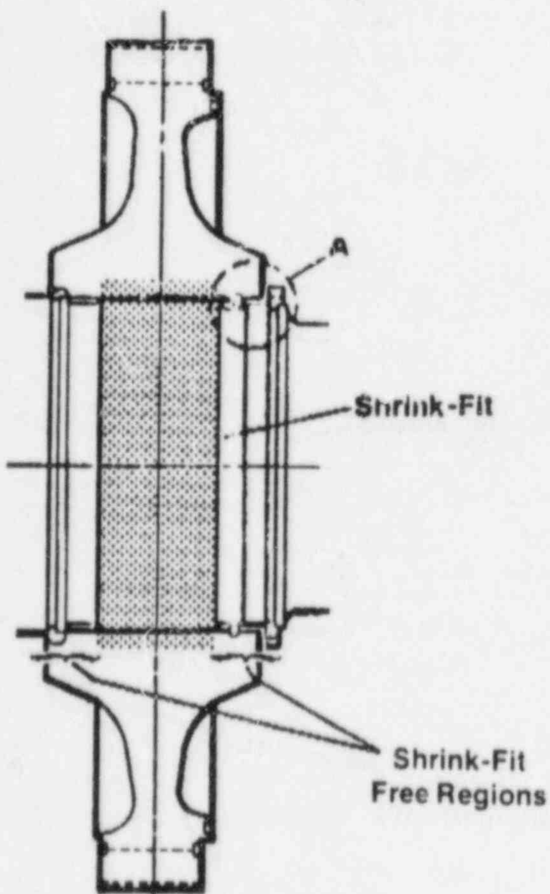
REVISION		
a		
b		
c		
d		
e		

Radius:
R10 = 0.39 in.
R22.5 = 0.89 in.

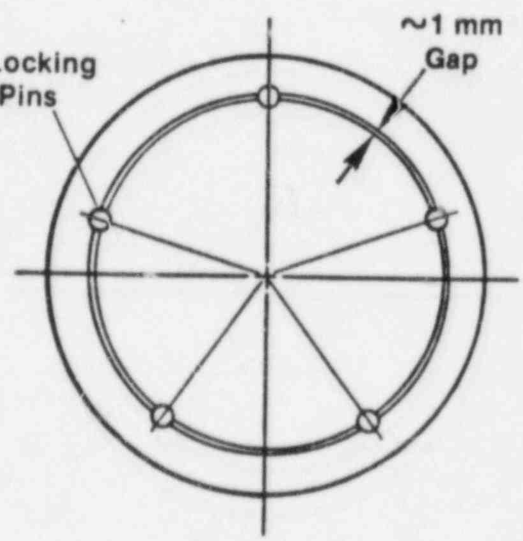
Diameter:
20Ø = 0.79 in.



Detail A



Disk #5



Section B-B

SHRINK-FIT AND
KEYWAY CONFIGURATION
OF LP TURBINE DISK #5

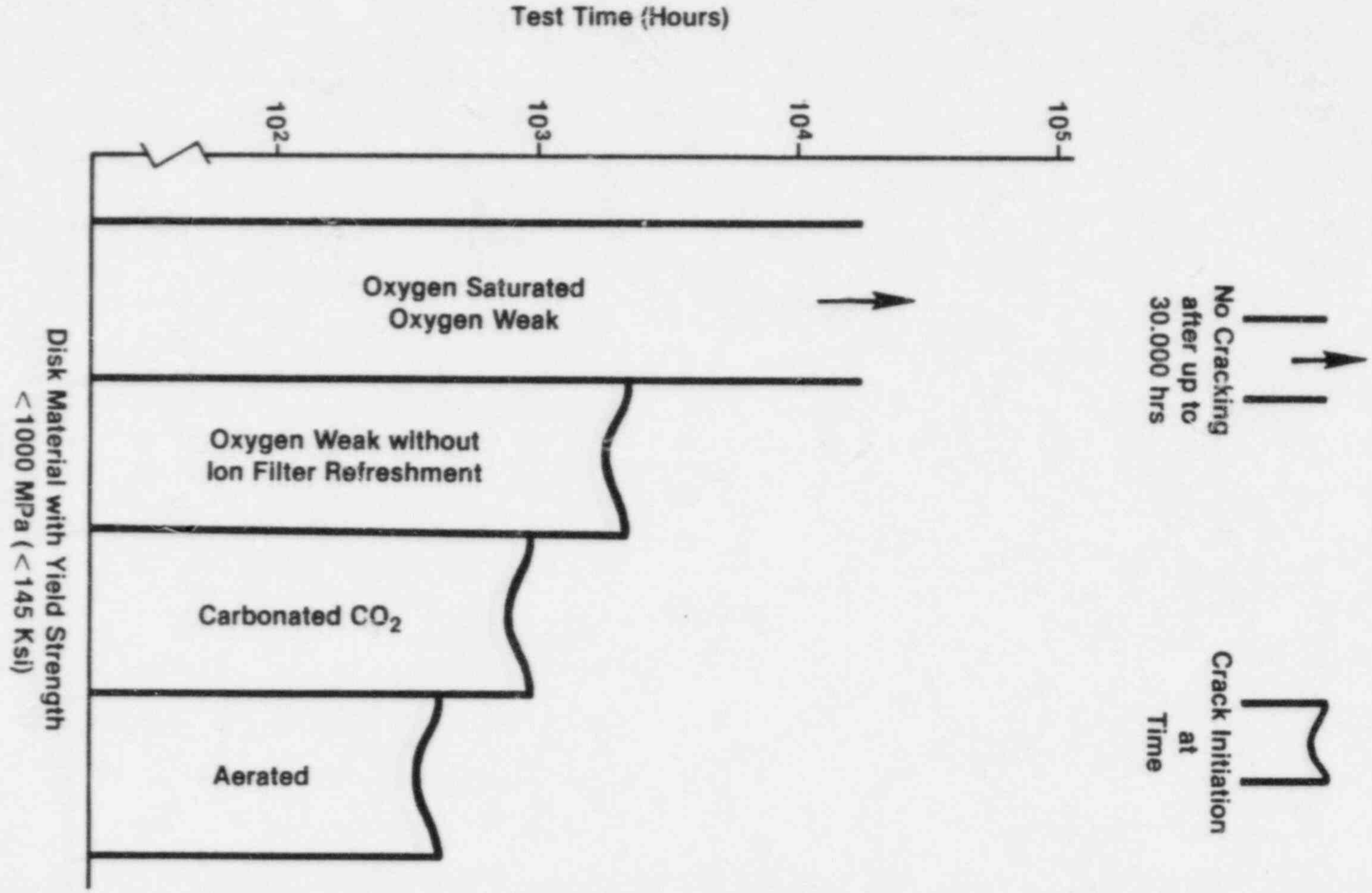
Utility Power
Corporation

FIGURE 2/1E84.072

PROPRIETARY INFORMATION OF
UTILITY POWER CORPORATION

Not to be reproduced, copied or disseminated without the express prior written consent of Utility Power Corporation.

REVISION	
a	
b	
c	
d	
e	



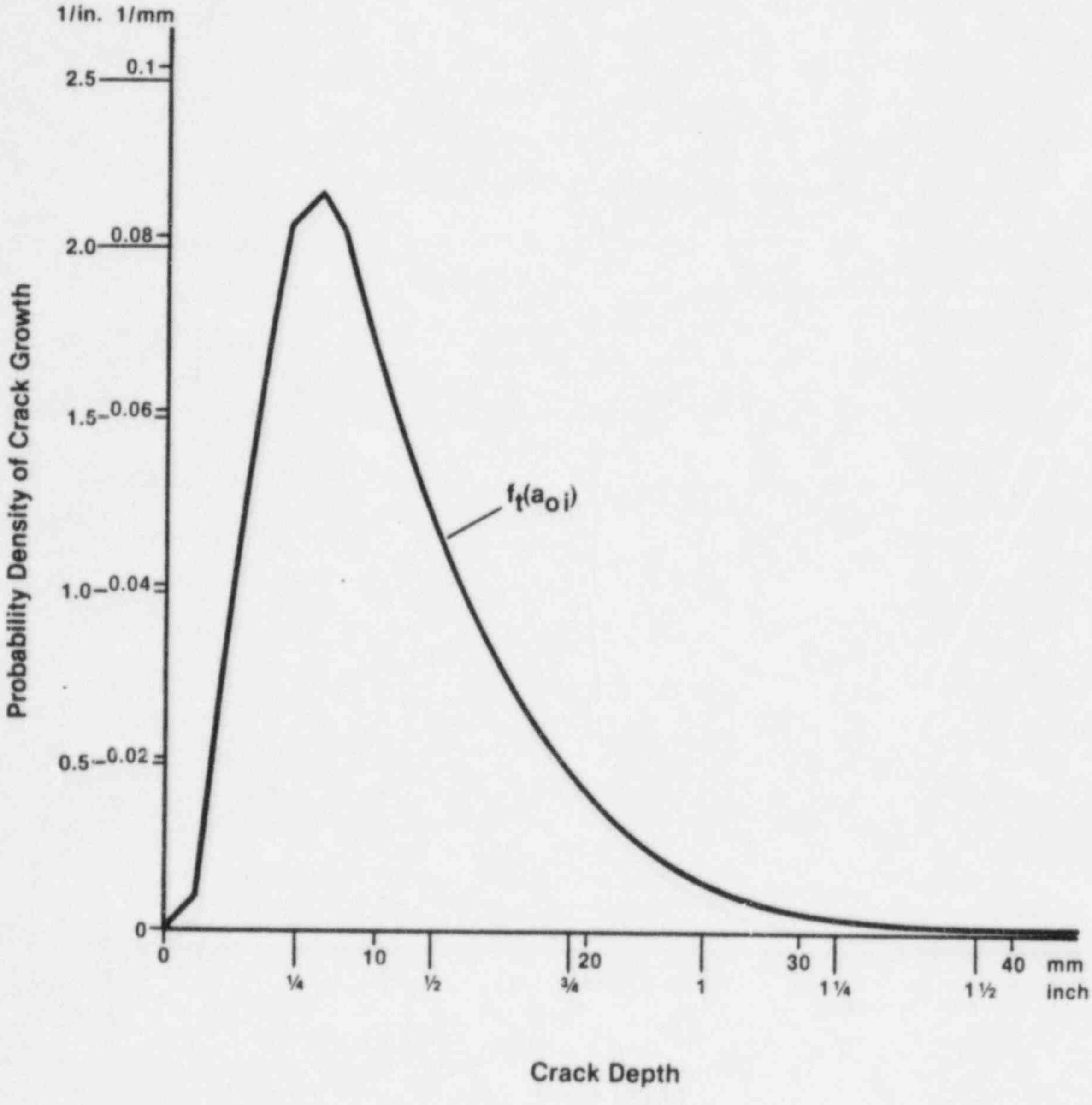
CRACK INITIATION TESTS
AT 90% of $R_{p0.2}$ YIELD
STRENGTH IN HIGH PURITY WATER

Utility Power
Corporation

FIGURE 3/1E84.073

REVISION		
a		
b		
c		
d		
e		

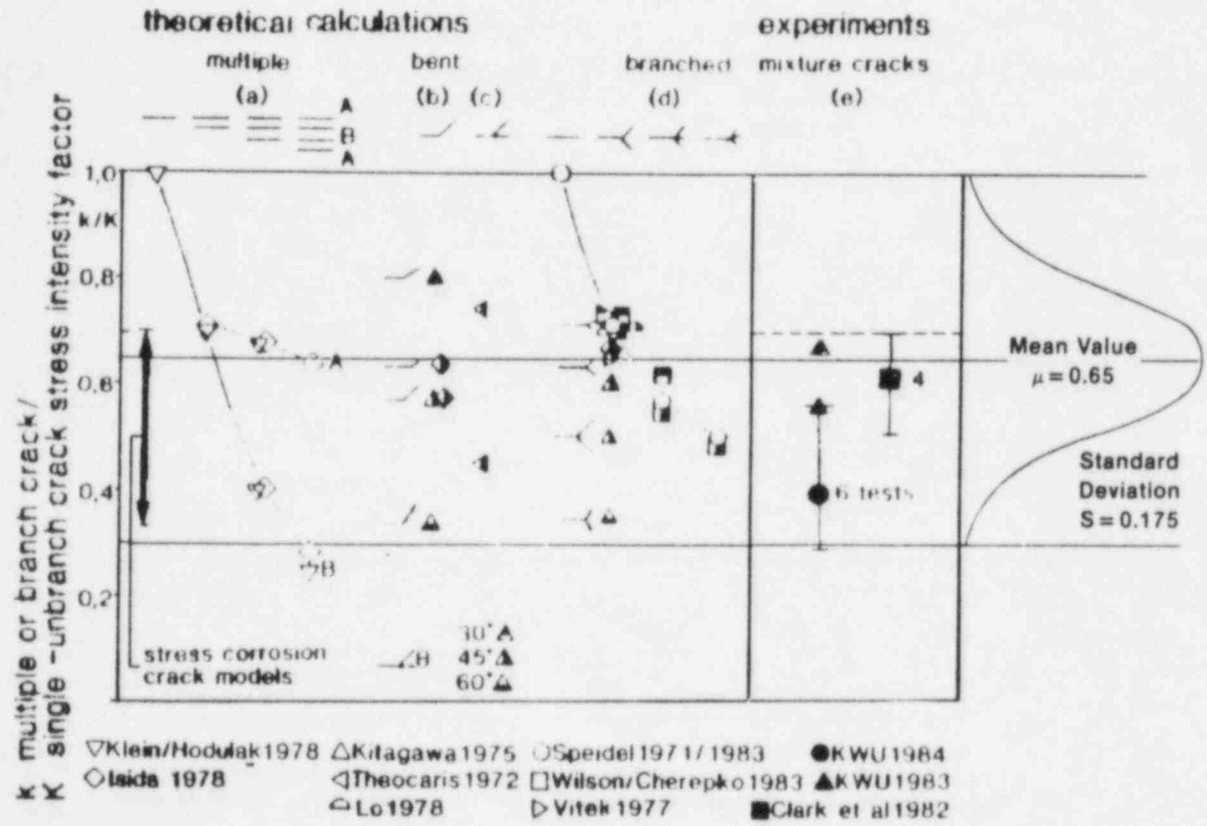
Operating Temperature 235°F
Disk Yield Strength 133 Ksi



COMANCHE PEAK UNIT #1
CRACK GROWTH OF DISK #2
TURBINE SIDE OF LP ROTOR #1

Utility Power Corporation

FIGURE 4/1E84.074



REVISION		
a		
b		
c		
d		
e		

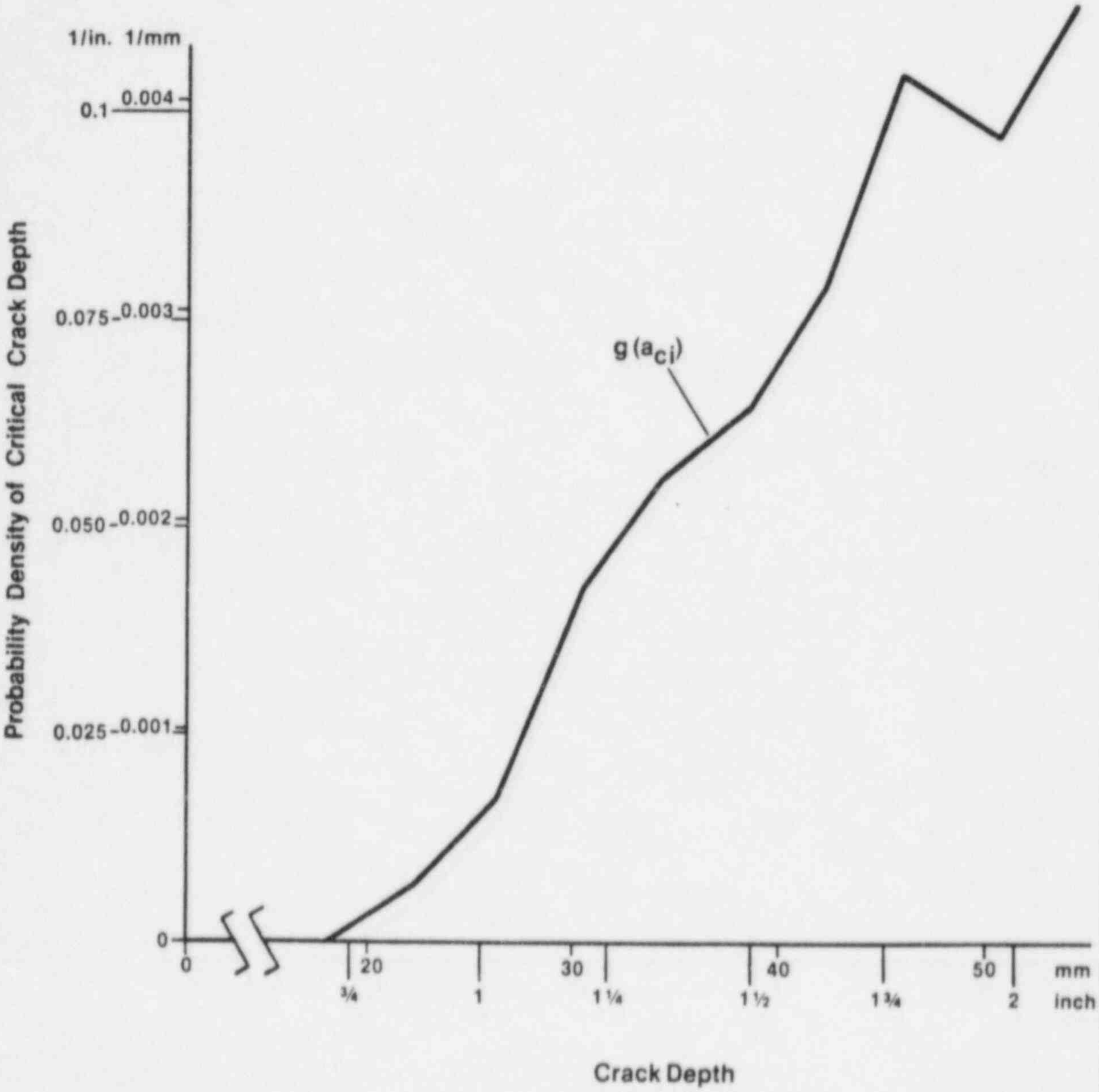
INFLUENCE OF CRACK CONFIGURATION ON STRESS INTENSITY FACTOR

Utility Power Corporation

FIGURE 5/1E84.075

REVISION		
a		
b		
c		
d		
e		

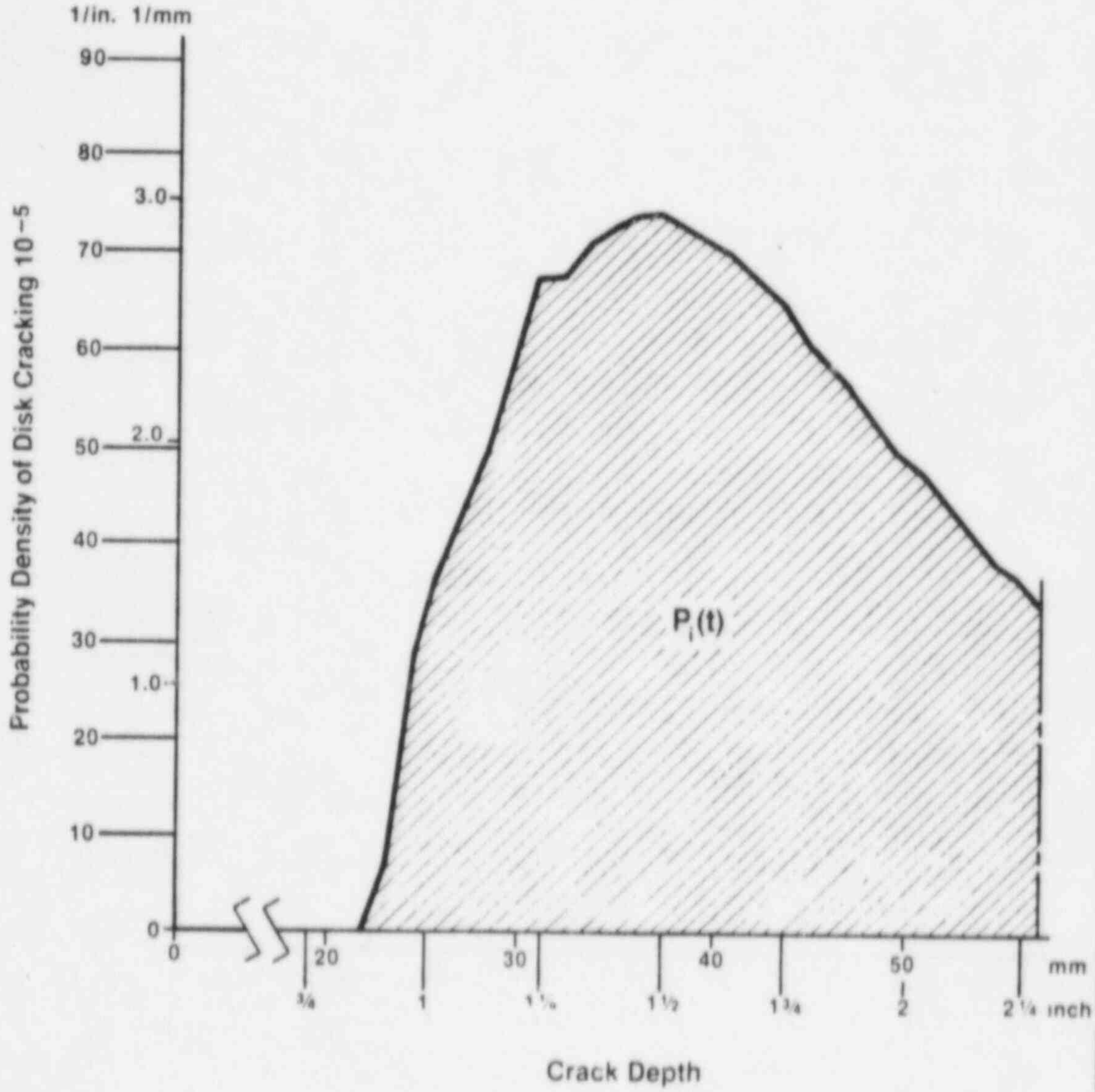
Fracture Toughness 202 Ksi $\sqrt{in}$
Tangential Stress at 110% of Rated Speed 84 Ksi



COMANCHE PEAK UNIT #1 CRITICAL CRACK DEPTH OF DISK #2 TURBINE SIDE OF LP ROTOR #1	Utility Power Corporation FIGURE 6/1E84.076

REVISION		
a		
b		
c		
d		
e		

50000 Service Hours
Probability $P_i(t) = 7.6 \times 10^{-4}$



COMANCHE PEAK UNIT #1
CRACKING OF DISK #2
TURBINE SIDE LP ROTOR #1

Utility Power Corporation

FIGURE 7/1E84.077

REVISION		
a		
b		
c		
d		
e		

Turbine Disk # and Turbine/Gen. Side	1TS	1GS	2TS	2GS	3TS	3GS	4TS	4GS	5TS	5GS
Tangential Stress at 110% Speed Ksi	80	80	84	84	75	75	83	83	81	81
Fracture Toughness Ksi $\sqrt{in}$	203	206	202	212	210	208	214	215	181	176
Operating Temp. °F	287	287	235	235	196	196	170	170	167	167
Yield Strength Ksi	131	131	133	129	117	114	131	127	129	127
Probabilities $P_i(t)$	7.4×10^{-3}	6.9×10^{-3}	7.6×10^{-4}	2.0×10^{-4}	0	0	0	0	0	0
q_i	6.7×10^{-5}	6.7×10^{-5}	1.3×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	2×10^{-3}	2×10^{-3}	2×10^{-3}	2×10^{-3}
$P_i(t) \cdot q_i$	4.9×10^{-7}	4.6×10^{-7}	9.9×10^{-6}	2.6×10^{-6}	0	0	0	0	0	0

Probability P(t) for Rotor #1:
1.34×10^{-5}

COMANCHE PEAK UNIT #1
PROBABILITY OF DISK
CRACKING OF LP ROTOR #1

Utility Power Corporation

TABLE I/1E84.078

REVISION		
a		
b		
c		
d		
e		

Turbine Disk # and Turbine/Gen. Side		1TS	1GS	2TS	2GS	3TS	3GS	4TS	4GS	5TS	5GS
Tangential Stress at 110% Speed Ksi		80	80	84	84	75	75	83	83	81	81
Fracture Toughness Ksi $\sqrt{in}$		207	224	207	224	209	213	197	201	187	183
Operating Temp. °F		287	287	235	235	196	196	170	170	167	167
Yield Strength Ksi		134	129	134	132	111	112	121	129	132	133
Probabilities	$P_i(t)$	8.2×10^{-3}	2.3×10^{-3}	6.0×10^{-4}	1.5×10^{-4}	0	0	0	0	0	0
	q_i	6.7×10^{-5}	6.7×10^{-5}	1.3×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	2×10^{-3}	2×10^{-3}	2×10^{-3}	2×10^{-3}
	$P_i(t) \cdot q_i$	5.4×10^{-7}	1.5×10^{-7}	7.8×10^{-6}	2.0×10^{-6}	0	0	0	0	0	0

Probability P(t) for Rotor #2:
1.04×10^{-5}

Probability P(t) for Rotor #1 and #2:
2.38×10^{-5}

COMANCHE PEAK UNIT #1
PROBABILITY OF DISK
CRACKING OF LP ROTOR #2

Utility Power Corporation

TABLE II/1E84.079