Westinghouse Non-Proprietary Class 3

WCAP-14535A

# TOPICAL REPORT ON REACTOR COOLANT PUMP FLYWHEEL INSPECTION ELIMINATION

Westinghouse Energy Systems

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# TOPICAL REPORT ON REACTOR COOLANT PUMP FLYWHEEL INSPECTION ELIMINATION

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# EXECUTIVE SUMMARY

This report provides the technical basis for the elimination of inspection requirements for reactor coolant pump (RCP) motor flywheels for all operating domestic Westinghouse plants and several Babcock and Wilcox plants, including Crystal River Unit 3, Oconee Units 1, 2 and 3, Davis Besse and Three Mile Island Unit 1. This report was submitted for review by the United States Nuclear Regulatory Commission (NRC) in January 1996, and after two requests for additional information, the NRC issued a Safety Evaluation Report (SER) in September 1996. This SER accepted the technical arguments presented herein, and provided partial relief from RCP motor flywheel inspection requirements.

At the request of the NRC (see the letter in Appendix G of this report), Westinghouse Report WCAP-14535 has been revised to include the responses to the NRC requests for additional information (Appendices E and F), and the NRC safety evaluation report (Appendix G). Additionally, the key provisions of the SER and followup clarifications are included in Appendix H. This final version of WCAP-14535 includes an "A" following the report number, which designates acceptance by the NRC. The content of this report is identical to WCAP-14535, with the exception of the additional appendices as noted.

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# SECTION 1
# INTRODUCTION

An integral part of the reactor coolant system (RCS) in pressurized water reactor plants is the reactor coolant pump (RCP), a vertical, single stage, single-suction, centrifugal, shaft seal pump. The RCP ensures an adequate cooling flow rate by circulating large volumes of the primary coolant water at high temperature and pressure through the reactor coolant system. Following an assumed loss of power to the RCP motor, the flywheel, in conjunction with the impeller and motor assembly, provide sufficient rotational inertia to assure adequate cooling flow during RCP coastdown, thus resulting in adequate core cooling.

During normal power operation, the RCP flywheel possesses sufficient kinetic energy to produce high energy missiles in the event of failure. Conditions which may result in overspeed of the RCP increase both the potential for failure and the kinetic energy of the flywheel. This led to the issuance of Regulatory Guide 1.14 in 1971 (Reference 1), which describes a range of actions to ensure flywheel integrity.

One of the recommendations of Regulatory Guide 1.14 (a portion of which is shown in Appendix A) is regular inservice volumetric inspection of flywheels. Operating power plants have been inspecting their flywheels for over twenty years now, and no flaws have been identified which affect flywheel integrity. Flywheel inspections are expensive, and involve irradiation exposure for personnel, so this study was commissioned to present the safety case for flywheels, and to quantify the effects of elimination of such inspections.

## 1.1 Previous Flywheel Integrity Evaluations

*Westinghouse Plants*

Fracture evaluations were performed in WCAP-8163 (Reference 2) for a postulated rupture of the RCP discharge piping. The RCP flywheel evaluated had an outer radius of 37.5", a bore radius of 4.7" and a keyway with a radial length of 0.9" and a width of 2.0", which are typical dimensions for RCP flywheels. The flywheel material was A533, Grade B, Class 1 steel plate, which is typically used in flywheel construction. The ultimate tensile stress (for ductile failure analysis) was 80,000 psi, and the fracture toughness at 120°F in the weak or transverse direction was 220,000 psi $\sqrt{\text{inch}}$. Detailed finite element analyses were performed to determine the stress intensity factors for cracks emanating radially from the flywheel keyway. These results were compared to closed form solutions for crack tip locations remote from the keyway, with good correlation. The conclusion of the Reference 2 evaluation was that the limiting speed for ductile failure of 3485 rpm (about 290 % of the normal operating speed) is governing for crack lengths less than 1.15 inches, and that the brittle fracture limit is governing for larger crack lengths. Because the 1.15 inch crack is very large in comparison to that detectable under inspection and quality assurance procedures for the flywheel design, it was concluded that 3485 rpm was the limiting speed for design. The failure prediction methodology was verified by scale model testing, which is discussed in detail in Reference 2.

A series of flywheel overspeed studies were carried out for postulated circumferential and longitudinal split pipe breaks. Table 1-1 summarizes the studies performed in Reference 2. The maximum speed of 3321 rpm is less than the original design limiting speed of 3485 rpm.

**Table 1-1: Summary of LOCA Speed Calculations for Westinghouse Plants**

| Case No. | Description | Peak Speed (rpm) |
|---|---|---|
| 1 | 4 Loop plant, double ended break, RCP trip after 30 seconds. | 1248 |
| 2 | Case 1 with instantaneous power loss. | 3321 |
| 3 | Case 1 with instantaneous power loss and break area equal to 60% of double ended break area. | 2609 |
| 4 | Case 3 with break area equal to 3.0 $ft^2$. | 1189 |
| 5 | Case 3 with break area equal to 0.5 $ft^2$. | 1189 |
| 6 | Case 3 for a 3 loop plant | 2330 |
| 7 | Case 2 with moment of inertia increased by 10% | 3200 |
| 8 | Case 1 with moment of inertia increased by 10% | 1248 |
| 9 | Case 1 with loop out of service | 2965 |
| 10 | Case 1 with longitudinal split break areas of 0.5 $ft^2$, 3.0 $ft^2$ and pipe cross sectional area. | 1200 |
| 11 | Case 10 with instantaneous power loss | 1200 |

*Babcock and Wilcox Plants*

Babcock and Wilcox analyzed the RCP for a spectrum of postulated reactor coolant system breaks for a typical Babcock and Wilcox 2568 MWt, 177 fuel assembly, nuclear steam system (Reference 3). A stress analysis of the upper flywheel assembly top flywheel was conducted to determine areas of stress concentration, stress magnitude, and the most likely flawed configurations to consider in the fracture mechanics analysis. The upper assembly top flywheel was considered to be the most critical component, and was the only component modeled for the stress analysis. This spoked flywheel had an outer radius of 36", and an inner radius of 15.2". The flywheel material was ASTM A-516-67 grade 65. The ultimate tensile stress was 76,500 psi, the yield stress was 48,500 psi, and the fracture toughness at 70°F and 120°F was 67,000 and 109,000 psi $\sqrt{\text{inch}}$, respectively. Stresses were calculated using a finite element model.

Three flawed configurations were considered in the linear elastic fracture mechanics analysis. These configurations were through-wall radial cracks perpendicular to the faces of the flywheel, and emanating from the following locations: the inner bore, a bolt hole, and a keyway. Since shrink fit forces would retard the growth of radial cracks in the keyway area, they were omitted from the analysis of the keyway crack. The initial crack length was assumed to be the largest crack that could be missed in nondestructive testing (0.24").

Linear elastic fracture mechanics calculations were performed for flywheel temperatures of 70°F and 120°F. The results of the analysis indicated that the flywheels of the RCPs will not fail under the expected normal operating conditions and that failure conditions are not reached until 220% of the normal operating speed is attained, for the assumed initial crack of 0.24". (The normal operating speed is 1190 rpm, rounded off to 1200 rpm for calculational purposes).

Fatigue crack growth calculations were performed to determine the size of the flaw over the life of the plant. Motor startup is the only plant transient significant to the flywheel. It was assumed that there are 500 starts over the 40 year life of the plant. The applied cycle stress was based on 125% of normal speed. Fatigue crack growth was calculated to be less than 0.0002". Therefore, it was concluded that the assumed initial crack would not grow to critical length during the design life of the flywheel.

LOCA evaluations performed in Reference 3 included eight different cold leg breaks, including the 8.55 $ft^2$ double ended break at the RCP discharge (with and without electrical braking effects), and smaller break sizes. A summary of the results from the eight analyses are provided in Table 1-2.

**Table 1-2: Summary of LOCA Speed Calculations for Babcock and Wilcox Plants**

| Case No. | Description | Pump Trip Time (seconds) | Max Speed (rpm) |
|---|---|---|---|
| 1 | 8.55 $ft^2$ cold leg guillotine break (pump discharge). | 0.1 | 3310 |
| 2 | 8.55 $ft^2$ cold leg guillotine break (pump discharge). | 30.0 | 1700 |
| 3 | 5.00 $ft^2$ cold leg split break (pump discharge). | 30.0 | 1210 |
| 4 | 3.0 $ft^2$ cold leg split break (pump discharge). | 30.0 | 1200 |
| 5 | 1.0 $ft^2$ cold leg split break (pump discharge). | 30.0 | 1190 |
| 6 | 8.55 $ft^2$ cold leg guillotine break with 80% voltage (pump discharge). | 30.0 | 2510 |
| 7 | 8.55 $ft^2$ cold leg guillotine break with 90% pump and motor inertia (pump discharge). | 30.0 | 1750 |
| 8 | 8.55 $ft^2$ cold leg guillotine break (pump suction). | 0.1 | 1190 |

Notes: Maximum speed is for the pump in the broken line.
Pump trip time is seconds after the break.

## 1.2 Leak Before Break (LBB) Considerations

Subsequent to the analyses of References 2 and 3, 10 CFR Part 50 Appendix A General Design Criterion 4 was revised to allow exclusion of dynamic effects associated with postulated pipe ruptures, including the effects of missiles, pipe whip, and discharging fluids from the design basis, when analyses reviewed and approved by the NRC demonstrate that the probability of fluid system rupture is extremely low under conditions consistent with the design basis for the piping. This is commonly referred to as leak-before-break (LBB) licensing. Since that time, all domestic Westinghouse and Babcock and Wilcox designed PWR plants have qualified for LBB exclusion of the primary loop double ended guillotine LOCA.

Given that a plant has LBB exclusion for the main loop LOCA, the largest break required to be postulated under the structural design basis becomes that of the largest branch line. The largest branch lines not covered by the LBB exclusion would be 14" schedule 140 or 160 piping (0.72 $ft^2$ break area, maximum), typically the accumulator line in the cold leg piping. Such a break may be treated as the equivalent of a 0.72 $ft^2$ longitudinal split break in the primary loop piping.

*Westinghouse Plants*

As shown in Table 1-1, the smallest breaks examined were 3.0 $ft^2$ and 0.5 $ft^2$ longitudinal split breaks (Cases 10 and 11). The 3.0 $ft^2$ split break would bound the largest branch line break not covered by the LBB exclusion (0.72 $ft^2$) with respect to the effect on the RCP speed. From Reference 2, it is apparent that with or without RCP power, the RCP speed will not exceed 1200 rpm for 3.0 $ft^2$ or 0.5 $ft^2$ longitudinal split breaks for the model 93A 6000 hp RCP described in Reference 2.

Reference 2 concluded that the increase in RCP speed due to the 3.0 $ft^2$ area split break was less than 11 rpm over the normal operating speed of 1189 rpm, or less than 1%. Given that the Reference 2 analysis shows that the RCP speed increase is less than 1% for the 3.0 $ft^2$ longitudinal breaks area, and that the maximum credible break under LBB is less than 1/4 of that size, it is concluded that any RCP speed increase resulting from a branch line break will be well within the design RCP speed tolerance of 25%, i.e., 1.25 times the design speed of 1200 rpm, or 1500 rpm, with or without the dynamic braking effects from the RCP being energized. No known non-LOCA events which lead to RCP speedup would be more limiting than the above mentioned pipe break with respect to overspeed. (Further studies extended this conclusion to a range of RCP designs including 63A (4000 hp), 93 (6000 hp), 93A (6000 hp), 93A (7000 hp) and 100 (8000 hp). Note that RCP rotational inertia is a plant specific parameter. The above conclusion for RCP applicability is only valid for the range of pump rotational inertias from 45000 to 123000 $lb_m$-$ft^2$. As shown in the next section, all Westinghouse flywheels meet this criterion. Therefore, a peak LOCA speed of 1500 rpm is used in the evaluation of Westinghouse RCP flywheel integrity in this report.

*Babcock and Wilcox Plants*

As shown in Table 1-2, the smallest breaks examined were 5.0 $ft^2$, 3.0 $ft^2$, and 1.0 $ft^2$ split breaks (Cases 3, 4 and 5). The 1.0 $ft^2$ split break would bound the largest branch line break not covered by the LBB exclusion (0.72 $ft^2$) with respect to the effect on the RCP speed. From Reference 3, the RCP speed will not exceed 1200 rpm for 1.0 $ft^2$ split breaks, with the effects of electrical braking. Although calculations were not specifically performed to determine the effect of excluding electrical braking effects, the Babcock and Wilcox pumps are similar in design to Westinghouse pumps, where the effect of electrical braking was found to be very small on the small break sizes of interest. (As noted for typical Westinghouse pressurized water reactors, a loss of RCP drive power due to electrical faults in the 30 second time interval following a large area break LOCA is an event of extremely low probability, in the range of $3.0 \times 10^{-7}$). Therefore, a peak LOCA speed of 1500 rpm is used in the evaluation of Babcock and Wilcox RCP flywheel integrity in this calculation.

### 1.3 Report Purpose

The purpose of this report is to provide an engineering basis for the elimination of RCP flywheel inservice inspection requirements for all operating domestic Westinghouse plants and the following Babcock and Wilcox plants:

- Crystal River Unit 3
- Oconee Units 1, 2 and 3
- Davis Besse
- Three Mile Island Unit 1

Three complimentary approaches will be used to demonstrate that flywheel inspection may be safely eliminated. A study of the inspection techniques and a summary of inspection results to date shows no indications have been found which affect flywheel integrity (see Section 3.) A stress and fracture evaluation has shown that very large flaws are needed to cause a failure under maximum overspeed conditions (Section 4). Finally, a risk assessment has been completed to directly compare the flywheel failure probabilities with and without further inspections (Section 5).

# SECTION 2
# DESIGN AND FABRICATION

Reactor coolant pump flywheels consist of one or more large steel discs which are shrunk fit either directly to the RCP motor shaft or to spokes extending from the motor shaft. In the case of two or more flywheel discs, the individual flywheels are bolted together to form an integral flywheel assembly. Each flywheel is keyed to the motor shaft with one or more vertical keyways.

## 2.1 Flywheel Geometry

The flywheels which are attached directly to the motor shaft typically consist of two flywheel discs which are bolted together and are located above the RCP rotor core. The top and bottom discs typically have the same outer diameter and bore dimensions but different thicknesses. The bottom disc usually has a circumferential notch along the outside diameter bottom surface for placement of antirotation pawls. Typically, each flywheel is keyed to the motor shaft by means of three vertical keyways, positioned at 120° intervals. An example of this type of flywheel is shown in Figure 2-1.

The spoked flywheels consist of an upper and a lower flywheel assembly, above and below the RCP rotor core. The upper flywheel assembly consists of three discs bolted together, with the top disc having a larger outside diameter than the middle and bottom disc. The lower flywheel consists of a single disc, of the same dimensions as the middle and bottom disc of the upper flywheel assembly. There are eight spokes, 2.5 inches thick, extending from and welded to the motor shaft. Each flywheel assembly is keyed to the spokes by means of one keyway. An example of this type of flywheel is shown in Figure 2-2.

For the purpose of the evaluations performed for this report, the larger flywheel outside diameter for a particular flywheel assembly is used, since this is judged to be conservative with respect to stress and fracture. For the flywheels investigated in this report, outer diameters range from 65 to 76.5 inches, bore diameters range from 8.375 to 30.5 inches (the later being the spoked flywheel), and keyway radial lengths range from 0.39 to 1.06 inches.

Most of the flywheels covered by this report are made from A533 Grade B Class 1 or A508 Class 3 steel. Flywheels for the pumps at three plants are made from A516 Grade 70 steel, and those at one plant are made from boiler plate.

A summary of pertinent flywheel parameters is provided in Table 2-1. Plant alpha designations used in Table 2-1 are identified in Table 2-2.

## 2.2 Material Information

The pump motors for all the Westinghouse plants and many of the Babcock and Wilcox plants were manufactured by Westinghouse. All of the Westinghouse flywheels except Haddam Neck are made of A533 Grade B Class 1 steel. The Haddam Neck flywheels were made of boiler plate steel.

It has not been possible to locate each of the certified material test reports for all of the flywheels, but a sample is contained in Appendix D. It will be helpful to examine the ordering specifications for the Westinghouse flywheel materials. The first specification is dated December 1969, and requires that the nil-ductility transition temperature from both longitudinal and transverse Charpy specimens be less than 10°F. This does not guarantee $RT_{NDT}$ is less than 10°F, but it is highly likely that this is the case.

The Westinghouse equipment specification was changed in January of 1973 to require both Charpy and drop weight tests to ensure that $RT_{NDT}$ is no greater than 10°F.

Even though it is likely that most, if not all, of the flywheels in operation have an $RT_{NDT}$ of 10°F or less, a range of $RT_{NDT}$ values from 10°F to 60°F has been assumed in the integrity evaluations to be discussed later.

## Table 2-1: Summary of Westinghouse and Babcock &Wilcox Domestic Flywheel Information

| Group | Outer Diam. (Inches) | Bore (Inches) | Keyway Radial Length (Inches) | Pump & Motor Inertia ($Lb_m$-$ft^2$) | Material Type | Applicable Plants (Plant Alpha Designation) |
|---|---|---|---|---|---|---|
| 1 | 76.50 | 9.375 | 0.937 | 110,000 | SA533B | TGX/THX/Spare |
| 2 | 75.75 | 8.375 | 0.906 | 82,000 | SA533B | PSE[4]/PNJ/Spare |
| 3 | 75.00 | 9.375 | 0.937 | 95,000 | SA533B | CQL; CAE/CBE/CCE/CDE[1]; DAP/DBP/DCP/DDP; GAE/GBE[1]; SAP/Spare; NEU; NAH; CGE/Spare; WAT/Spare; TBX/TCX/Spare; SCP; VRA/VGB/Spare |
| 4 | 75.00 | 9.375 | 0.937 | 83,000 | SA533B | TVA/TEN/Spare |
| 5 | 75.00 | 9.375 | 0.937 | 82,000 | SA533B | ALA/APR/Spare; AEP/AMP/Spare; CWE/COM; DLW/DMW |
| 6 | 75.00 | 9.375 | 0.937 | 80,000 | SA533B | NSP/NRP[3]; WPS[3] |
| 7 | 75.00 | 8.375 | 0.911 | 82,000 | SA533B | INT Spare |
| 8 | 75.00 | 8.375 | 0.906 | 82,000 | SA533B | IPP/INT; PGE/PEG |
| 9 | 75.00 | 8.375 | 0.906 | 80,000 | SA533B | WEP[6]/WIS |
| 10 | 72.00 | 16.125 | 0.906 | 72,000 | SA533B | BOCO/Spare |
| 11 | 72.00 | 9.375 | 0.937 | 72,700 | SA533B | BDAVI[5] |
| 12 | 72.00 | 8.375 | 0.906 | 80,000 | SA533B | RGE[4] |
| 13 | 72.00 | 8.375 | 0.906 | 70,000 | SA533B | CPL/Spare; FPL/FLA/Spare; VPA/VIR[4] |
| 14 | 65.00 | 8.375 | 0.656 | 45,000 | Boiler Plate | CYW[2] |
| 15 | 72.00 | 30.50 | 0.390 | 70,540 | A516 | B3MI1[7] |
| 16 | 65.00 | 13.800 | 1.060 | 70,000 | A516 | BCRY3 |

Notes:
1) Spare has a keyway radial length of 0.885".
2) Haddam Neck spare has a keyway radial length of 0.618", and material is SA533B.
3) Spare has a keyway radial length of 0.883".
4) Spare has a keyway radial length of 0.911".
5) Spares have a keyway radial length of 0.942", one spare is of SA508 material.
6) Spare has a keyway radial length of 0.937".
7) Spoked flywheels.

**Table 2-2: Plant Alpha Designation Listing**

| Plant Alpha Designation | Plant |
|---|---|
| AEP/AMP | D.C. Cook Units 1 and 2 |
| ALA/APR | J.M. Farley Units 1 and 2 |
| CAE/CBE | Byron Units 1 and 2 |
| CCE/CDE | Braidwood Units 1 and 2 |
| CGE | V.C. Summer |
| CWE/COM | Zion Units 1 and 2 |
| CPL | H.B. Robinson Unit 2 |
| CQL | Shearon Harris |
| CYW | Haddam Neck |
| DAP/DBP | McGuire Units 1 and 2 |
| DCP/DDP | Catawba Units 1 and 2 |
| DLW/DMW | Beaver Valley Units 1 and 2 |
| FPL/FLA | Turkey Point Units 3 and 4 |
| GAE/GBE | Vogtle Units 1 and 2 |
| IPP/INT | Indian Point Units 2 and 3 |
| NAH | Seabrook |
| NEU | Millstone Unit 3 |
| NSP/NRP | Prairie Island Units 1 and 2 |
| PGE/PEG | Diablo Canyon Units 1 and 2 |
| PSE/PNJ | Salem Units 1 and 2 |
| RGE | Ginna |
| SAP | Wolf Creek |
| SCP | Callaway |
| TBX/TCX | Comanche Peak Units 1 and 2 |
| TVA/TEN | Sequoyah Units 1 and 2 |
| TGX/THX | South Texas Units 1 and 2 |
| VGB/VRA | North Anna Units 1 and 2 |
| VPA/VIR | Surry Units 1 and 2 |
| WAT | Watts Bar Unit 1 |
| WEP/WIS | Point Beach Units 1 and 2 |
| WPS | Kewaunee |
| BCRY3 | Crystal River Unit 3 |
| BDAV1 | Davis Besse |
| BOCO1/BOCO2/BOCO3 | Oconee Units 1, 2 and 3 |
| B3MI1 | Three Mile Island Unit 1 |

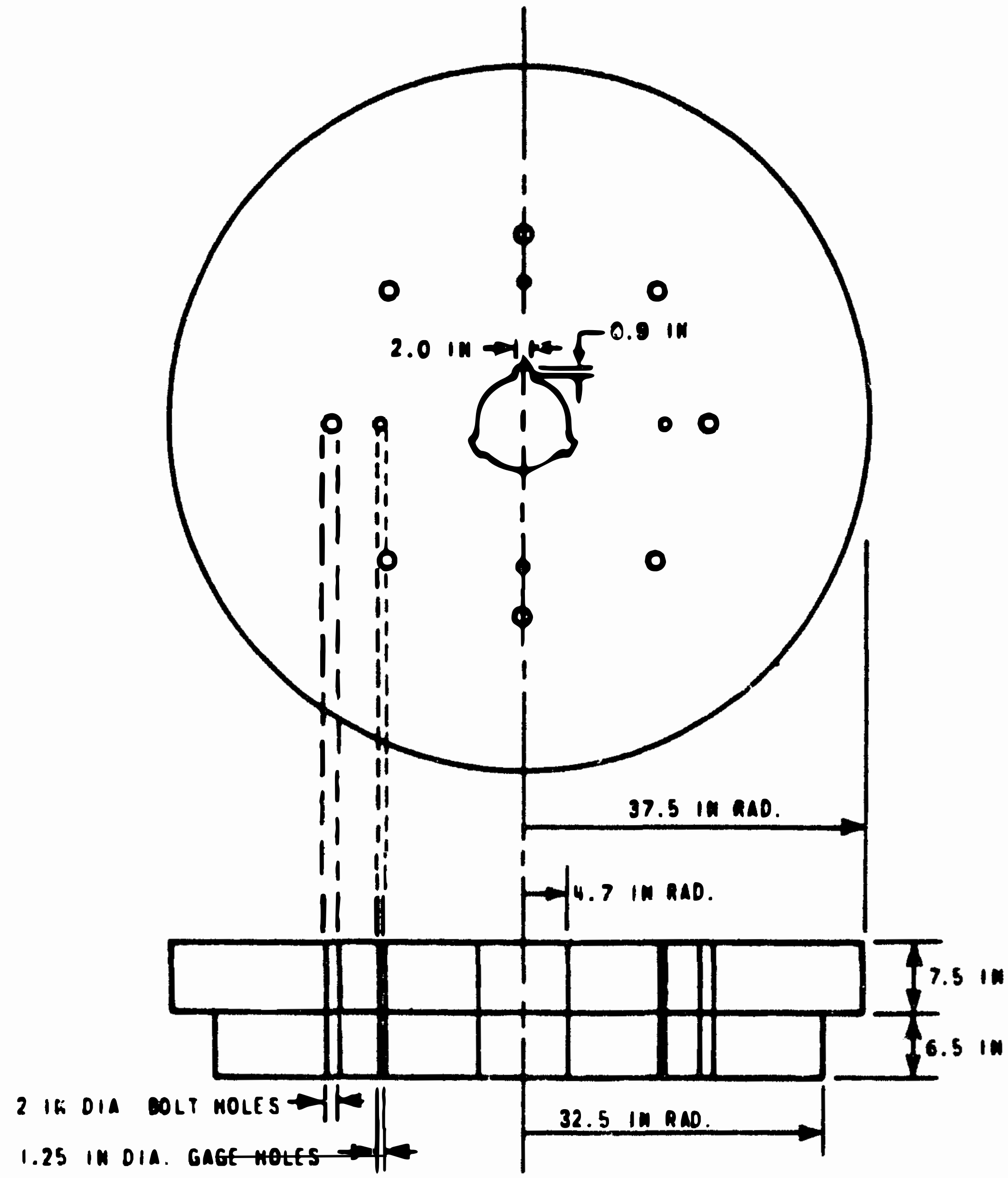



**Figure 2-1: Example of a Flywheel which is Attached Directly to the Motor Shaft**

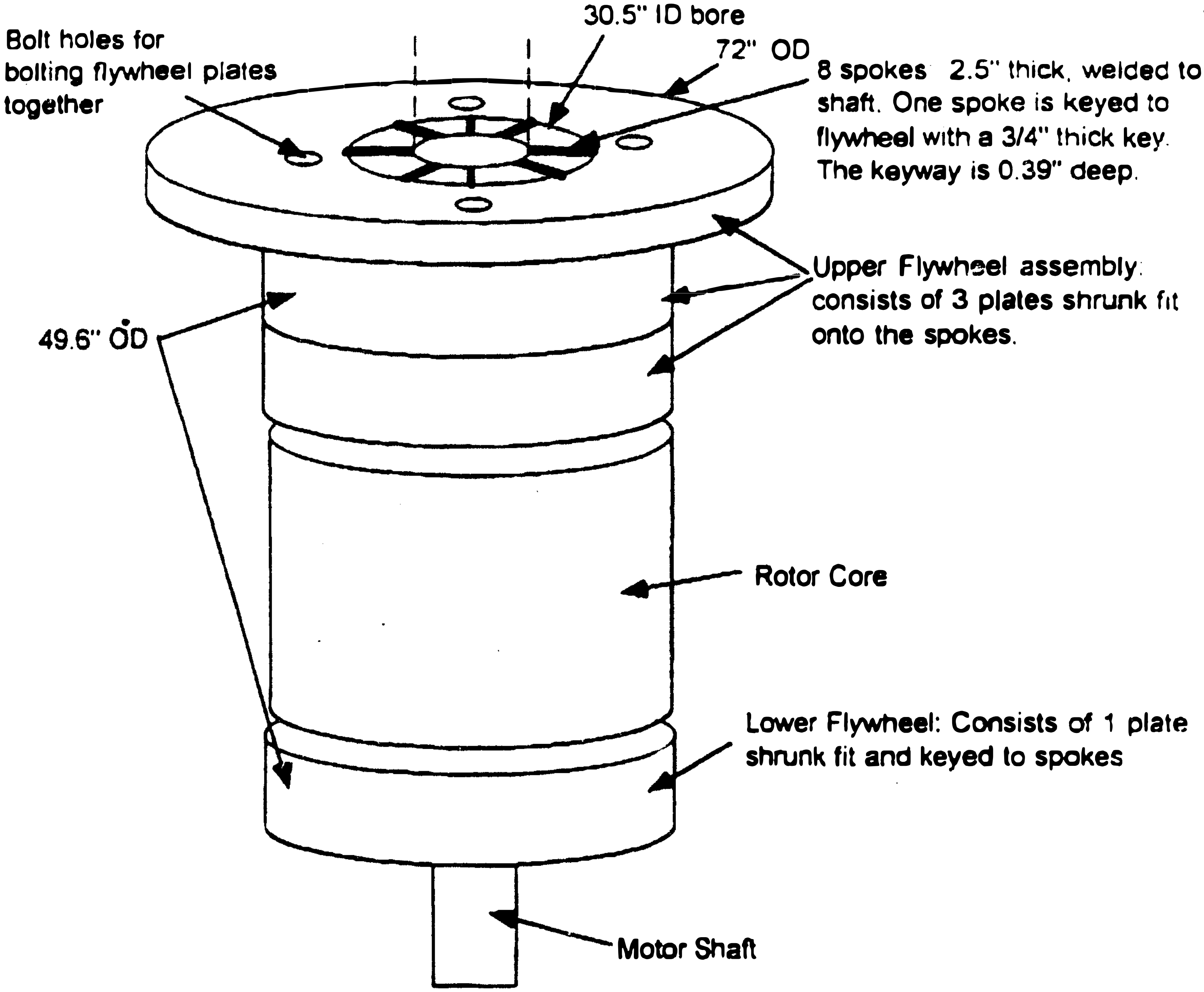



**Figure 2-2: Example of a Spoked Flywheel**

# SECTION 3
# INSPECTION

Flywheels are inspected at the plant or during motor refurbishment. Inspections are conducted under Section XI (Reference 4) standard practice for control of instrumentation and personnel qualification. The inspections are conducted by UT level II and level III examiners.

## 3.1 Examination Volumes

Reactor Coolant pump flywheel examinations are conducted under the control of Utility ISI programs according to surveillance schedules governed by individual Plant Technical Specifications. The volumetric examinations recommended in Regulatory Guide 1.14 have been uniformly applied to the accessible surfaces of the pump flywheel after removal of the shroud cover and gauge hole plugs. The volume of flywheel is inspected generally with straight beam techniques applied laterally, checking the plate material for planar defects emanating from the bore, keyways, and around the gauge holes and ream bolt holes.

## 3.2 Examination Approaches

Generally, three examinations are performed. The keyway corner exam is conducted by inserting specially designed ultrasonic probes into the gauge holes and directing the sound laterally through the plate material so that reflections are obtained from the center bore radius. Normal reflections will then be seen from the corners of the keyways. These reflections are predictable in distance and rate of occurrence, with abnormalities such as cracking branching out from the keyway being detectable as an abnormal response. A second examination is performed when the sound is projected laterally towards the other remaining gauge holes, for evidence of cracking emanating from the bores of the holes and plate material between the holes. The third examination is commonly referred to as the "Periphery" examination. In this test, standard contact transducers are placed on the outer edges of both upper and lower flywheel plates. The sound is directed laterally into the plate material for examination of the material between the peripheral holes and the plate outer edge.

## 3.3 Access and Exposure

Access to the exam surfaces is made possible by permanent walkways or by erecting scaffolding. Radiation exposure depends greatly on the amount of pump motor work being conducted nearby and can range from 20-100 millirem/hour.

### 3.4 Inspection History

A survey was conducted of historical plant inservice inspection results, and all member utilities contributed. The flywheel population surveyed was a total of 217. A total of 729 examination results were reported, and no indications which would affect the integrity of the flywheels were found. These results are summarized on a plant by plant basis in Table 3-1. A summary of recordable indications is provided in Table 3-2. It is interesting to note from Table 3-2 that a number of indications in the form of nicks, gashes, etc. were found at the keyway area, having been created by the act of removing or reassembling the flywheel. These were all dispositioned as not affecting flywheel integrity, but are clear evidence that disassembly for inspection and reassembly actually can produce damage.

Indications were found at the Haddam Neck plant, in the weld used to join the two flywheel plates together. The indications identified were associated with this seal weld and resulted in no radially oriented cracking, and no impact on the integrity of the flywheels. A detailed summary of this finding is given in Appendix B. Sample flywheel inspection procedures are provided in Appendix C.

## Table 3-1: Flywheel Inspection Results

| Plant Alpha Designation | Plant | Number of Flywheels | Total Number of Flywheel Inspections | Total Number of Inspections with No Indications or Nonrecordable Indications | Total Number of Inspections with Recordable Indications | Number of Indications Affecting Flywheel Integrity |
|---|---|---|---|---|---|---|
| AEP | Cook 1 | 4 | 14 | 13 | 1 | 0 |
| AMP | Cook 2 | 4 | 12 | 12 | 0 | 0 |
| ALA | Farley 1 | 3 | 17 | 17 | 0 | 0 |
| APR | Farley 2 | 3 | 19 | 19 | 0 | 0 |
| CAE/CBE | Byron 1 & 2 | 8 | 20 | 19 | 1 | 0 |
| CCE | Braidwood 1 | 4 | 13 | 11 | 2 | 0 |
| CDE | Braidwood 2 | 4 | 9 | 8 | 1 | 0 |
| CGE | Summer | 4 | 10 | 10 | 0 | 0 |
| CWE | Zion 1 | 4 | 10 | 9 | 1 | 0 |
| COM | Zion 2 | 4 | 16 | 16 | 0 | 0 |
| CPL | Robinson 2 | 4 | 22 | 20 | 2 | 0 |
| CQL | Harris | 3 | 17 | 17 | 0 | 0 |
| CYW | Haddam Neck | 4 | 32 | 28 | 4 | 0 |
| DAP | McGuire 1 | 4 | 13 | 13 | 0 | 0 |
| DBP | McGuire 2 | 4 | 8 | 8 | 0 | 0 |
| DCP | Catawba 1 | 4 | 6 | 6 | 0 | 0 |
| DDP | Catawba 2 | 4 | 6 | 6 | 0 | 0 |
| DLW | Beaver Valley 1 | 3 | 15 | 11 | 4 | 0 |
| DMW | Beaver Valley 2 | 3 | 5 | 5 | 0 | 0 |
| FPL/FLA | Turkey Point 3 and 4 | 7 | 36 | 34 | 2 | 0 |
| GAE/GBE | Vogtle 1 and 2 | 9 | 19 | 19 | 0 | 0 |
| IPP | Indian Point 2 | 5 | 21 | 21 | 0 | 0 |
| INT | Indian Point 3 | 5 | 17 | 17 | 0 | 0 |
| NAH | Seabrook | 4 | 8 | 8 | 0 | 0 |
| NEU | Millstone 3 | 5 | 12 | 12 | 0 | 0 |
| NSP | Prairie Island 1 | 2 | 13 | 12 | 1 | 0 |
| NRP | Prairie Island 2 | 2 | 11 | 10 | 1 | 0 |

## Table 3-1: Flywheel Inspection Results (continued)

| Plant Alpha Designation | Plant | Number of Flywheels | Total Number of Flywheel Inspections | Total Number of Inspections with No Indications or Nonrecordable Indications | Total Number of Inspections with Recordable Indications | Number of Indications Affecting Flywheel Integrity |
|---|---|---|---|---|---|---|
| PGE | Diablo Canyon 1 | 4 | 12 | 11 | 1 | 0 |
| PEG | Diablo Canyon 2 | 4 | 11 | 11 | 0 | 0 |
| PSE/PNJ | Salem 1 and 2 | 9 | 24 | 13 | 11 | 0 |
| RGE | Ginna | 3 | 21 | 21 | 0 | 0 |
| SAP | Wolf Creek | 4 | 13 | 12 | 1 | 0 |
| SCP | Callaway | 4 | 11 | 11 | 0 | 0 |
| TBX | Comanche Peak 1 | 4 | 8 | 8 | 0 | 0 |
| TCX | Comanche Peak 2 | 4 | 4 | 4 | 0 | 0 |
| TVA/TEN | Sequoyah 1 and 2 | 9 | 37 | 36 | 1 | 0 |
| TGX | South Texas 1 | 4 | 12 | 12 | 0 | 0 |
| THX | South Texas 2 | 4 | 12 | 12 | 0 | 0 |
| VGB/VRA | North Anna 1 and 2 | 7 | 37 | 33 | 4 | 0 |
| VPA/VIR | Surry 1 and 2 | 7 | 17 | 17 | 0 | 0 |
| WAT | Watts Bar 1 | 4 | 4 | 2 | 2 | 0 |
| WEP | Point Beach 1 | 2 | 12 | 12 | 0 | 0 |
| WIS | Point Beach 2 | 2 | 13 | 13 | 0 | 0 |
| WPS | Kewaunee | 3 | 6 | 5 | 1 | 0 |
| BCRY3 | Crystal River 3 | 4 | 30 | 30 | 0 | 0 |
| BDAV1 | Davis Besse | 5 | 24 | 22 | 2 | 0 |
| BOCO1 | Oconee 1 | 4 | 6 | 6 | 0 | 0 |
| BOCO2 | Oconee 2 | 4 | 2 | 2 | 0 | 0 |
| BOCO3 | Oconee 3 | 4 | 3 | 3 | 0 | 0 |
| B3MI1 | Three Mile Island 1 | 4 | 9 | 9 | 0 | 0 |
| TOTALS | 57 | 217 | 729 | 686 | 43 | 0 |

## Table 3-2: Summary of Recordable Indications

| Plant Alpha Designation | Year | Description of Recordable Indications |
|---|---|---|
| AEP | 1987 | Surface examination on RCP flywheel no. 13 showed two 3/8" long recordable indications. Surface chatter removed by minor surface reconditioning. |
| CAE/CBE | 1993 | 0.45" rounded indication in RCP flywheel 1B keyway area (surface exam) characterized as minor tool mark. |
| CCE | 1991 | PT indications on RCP "A" flywheel were acceptable. |
| | 1994 | Indications noted on RCP "B" flywheel with PT and VT-1 were resurfaced and found to be acceptable. |
| CDE | 1994 | Four 1/16" rounded indications noted in various areas located approximately 0.8" below top surface of RCP "C" flywheel. One linear indication noted (circ. oriented). Indications were acceptable. |
| CWE | 1986 | PT recordable indication in loop 1 RCP flywheel, bleed out from gouges and metal folds in keyways. |
| CPL | 1984 | PT recordable indication on RCP "C" flywheel bore was filed out and reexamined. |
| | 1992 | Gouge on spare flywheel blended out to 3 to 1 taper. |
| DLW | 1980 | PT indication, unsatisfactory mechanical damage from removal of RCP "B" flywheel. Grinding repaired condition. |
| | 1987 | PT recordable indication dispositioned as satisfactory for RCP "A" flywheel. Damage from handling. |
| | 1993 | UT recordable indication in RCP "B" flywheel due to geometry, dispositioned as satisfactory. PT recordable indication due to handling, dispositioned as satisfactory. |
| | 1994 | UT recordable indication in RCP "C" flywheel due to geometry, dispositioned as satisfactory. |
| FPL/FLA | 1974 | Laminations midwall (UT) in motor 1S-76P499 flywheel accepted as-is. |
| | 1993 | Torn metal in keyway (PT) on motor 2S-76P499 flywheel removed by buffing. |
| NSP | 1994 | MT of flywheel no. 11 periphery (0.4 inch) to be re-examined in January 1996 outage. |
| NRP | 1995 | MT indications in periphery of flywheel no. 21 (which were buffed in 1993) were found to be unchanged. |
| PGE | 1995 | Multiple MT linear indications (laminations) on lower periphery of RCP 1-4 flywheel, accept as-is, monitor. |
| PSE/PNJ | 1983-1995 | Eleven recorded indications from surface examinations on seven flywheels were identified as minor chatter marks in keyway from original rough machine cuts due to the arbor tool used during manufacture. Accept as is. |

## Table 3-2: Summary of Recordable Indications (Continued)

| Plant Alpha Designation | Year | Description of Recordable Indications |
|---|---|---|
| SAP | 1995 | Wear marks on bottom surface of RCP 1 flywheel within seal ring (circular like spacer wear) - removed. |
| TVA/TEN | 1993 | Recorded indications (10 year MT) in flywheel 3S-81P352. Laminations in edge, dispositioned as acceptable. |
| VGB/VRA | 1983 | Tool marks noted in keyway of flywheel 2S-81P355. |
| | 1986 | Four PT indications in the keyway of flywheel 3S-81P355 caused by incorrect installation. |
| | 1988 | Six reportable indications from keyway scratches in flywheel 3S-81P777. |
| | 1993 | Three acceptable rounded indications in the keyway of flywheel 2S-81P777. |
| WAT | 1986 | PT recorded indication in keyway area of RCP 1 flywheel resulted from tool chatter which occurred during manufacture of the flywheel. The indications were formed by the tearing and smearing of the raised metal (introduced by the tool chatter) at disassembly and reassembly of the keys. |
| | 1986 | VT recorded indication in keyway area of RCP 4 flywheel. |
| WPS | 1976 | Visual recorded indication in RCP "A" flywheel. Machine chips in five small holes in center of shaft. |
| BDAV1 | 1975 | Volumetric preservice indication in RCP 2 flywheel found to be acceptable. Surface tears in keyway removed by surface conditioning. |
| | 1988 | Surface gouges in bore of RCP 4 flywheel from flywheel removal found to be acceptable. |
| CYW | 1971 | See Appendix B. |

# SECTION 4
# STRESS AND FRACTURE EVALUATION

All of the flywheels were subjected to a detailed stress and fracture evaluation, which is summarized in this section. To avoid repetition, the flywheels were grouped by geometry, and the logic for this grouping is explained in Section 4.1. There are two possible failure mechanisms, ductile and brittle, which must be considered in flywheel evaluation and these are discussed in detail in evaluations reported earlier (References 2 and 3). Figure 4-1 shows the results of a typical flywheel overspeed evaluation, where the flywheel failure speed was calculated for a range of postulated crack depths. Note that the brittle failure limit governs for large flaws. The limiting speed increases for small flaws. Using brittle fracture considerations alone, the limiting speed would approach infinity for vanishingly small flaws. For these situations, the ductile failure limit governs, a finding that has been proven by scale model tests whose results are reported in Reference 2.

Regulatory Guide 1.14, Revision 1, Section C, Subsection 2 (see Appendix A, or Reference 1), provides the following regulatory position for flywheel design:

*a.* *The flywheel assembly, including any speed-limiting and antirotation devices, the shaft, and the bearings, should be designed to withstand normal conditions, anticipated transients, the design basis loss-of-coolant accident, and the Safe Shutdown Earthquake loads without loss of structural integrity.*

*b.* *Design speed should be at least 125% of normal speed but not less than the speed that could be attained during a turbine overspeed transient. Normal speed is defined as synchronous speed of the a.c. drive motor at 60 hertz.*

*c.* *An analysis should be conducted to predict the critical speed for ductile failure of the flywheel. The methods and limits of paragraph F-1323.1(b) in Section III of the ASME Code are acceptable. If another method is used, justification should be provided. The analysis should be submitted to the NRC staff for evaluation.*

*d.* *An analysis should be conducted to predict the critical speed for nonductile failure of the flywheel. Justification should be given for the stress analysis method, the estimate of flaw size and location, which should take into account initial flaw size and flaw growth in service, and the values of fracture toughness assumed for the material. The analysis should be submitted to the NRC staff for evaluation.*

e. *An analysis should be conducted to predict the critical speed for excessive deformation of the flywheel. The analysis should be submitted to the NRC staff for evaluation. (Excessive deformation means any deformation such as an enlargement of the bore that could cause separation directly or could cause an unbalance of the flywheel leading to structural failure or separation of the flywheel from the shaft. The calculation of deformation should employ elastic-plastic methods unless it can be shown that stresses remain within the elastic range).*

f. *The normal speed should be less than one-half of the lowest of the critical speeds calculated in regulatory positions C.2.c, d, and e above.*

g. *The predicted LOCA overspeed should be less than the lowest of the critical speeds calculated in regulatory positions C.2.c, d, and e above.*

These guidelines will be reviewed in this section, for all the flywheels covered by this report, and the results tabulated.

## 4.1 Selection of Flywheel Groups for Evaluation

From the flywheel dimensional information provided in Table 2-1 of this report, six flywheel groups were selected for evaluation, which encompass the range of domestic flywheel dimensions covered by this report. These groups are as follows:

**Table 4-1: Flywheel Groups Evaluated**

| Flywheel Group | Outer Diameter (Inches) | Bore (Inches) | Keyway Radial Length (Inches) | Comments |
|---|---|---|---|---|
| 1 | 76.50 | 9.375 | 0.937 | Maximum flywheel OD. |
| 2 | 75.75 | 8.375 | 0.906 | Large flywheel OD, Minimum flywheel bore. |
| 10 | 72.00 | 16.125 | 0.906 | Large flywheel OD, Large flywheel bore. |
| 14 | 65.00 | 8.375 | 0.656 | Minimum flywheel OD, Minimum flywheel bore. |
| 15 | 72.00 | 30.500 | 0.390 | Maximum flywheel bore (spoked flywheel), Minimum keyway radial length. |
| 16 | 65.00 | 13.800 | 1.060 | Minimum flywheel OD, Maximum keyway radial length. |

### 4.2 Ductile Failure Analysis

The capacity of a structure to resist ductile failure with sufficient margin of safety during faulted conditions can be demonstrated by meeting the faulted condition criteria of Section III of the ASME Boiler and Pressure Vessel Code. The faulted condition stress limits for elastic analysis, $P_m$ and $P_m + P_b$, are taken as 0.7 $S_u$ and 1.05 $S_u$, where $S_u$ is the minimum specified ultimate tensile stress of the material. As in Reference 2, 80 ksi was used for $S_u$, which is the minimum specified value for A-533 Grade B, Class 1 steel. The stresses in the RCP flywheel, neglecting local stress concentrations such as holes and keyways, can be calculated by the following equations (Reference 2):

$$\sigma_r = \frac{(3+\nu)}{8}\,\frac{\rho\omega^2}{386.4}\left(b^2 + a^2 - \frac{a^2b^2}{r^2} - r^2\right)$$

$$\sigma_\theta = \frac{(3+\nu)}{8}\,\frac{\rho\omega^2}{386.4}\left[b^2 + a^2 + \frac{a^2\,b^2}{r^2} - \left(\frac{1+3\nu}{3+\nu}\right)r^2\right]$$

| | | |
|---|---|---|
| where $\sigma_r$ | = | radial stress, psi |
| $\sigma_\theta$ | = | circumferential, or hoop stress, psi |
| $\nu$ | = | Poisson's ratio, 0.3 |
| $\rho$ | = | flywheel material density, 0.283 $lb_m/inch^3$ |
| $\omega$ | = | flywheel angular speed, radians/second |
| b | = | flywheel outer radius, inches |
| a | = | flywheel bore radius, inches |
| r | = | flywheel radial location of interest, inches |

Since the stress in the thickness direction ($\sigma_z$) is assumed to be negligible, and the radial stress ($\sigma_r$) always falls between $\sigma_z$ and $\sigma_\theta$, the maximum stress intensity at any point in the flywheel is equal to the circumferential stress, $\sigma_\theta$. It should be noted that the circumferential stress peaks at the flywheel bore and keyway locations and decreases approximately linearly thereafter in the radial direction. To apply the faulted stress limits to a nonlinear stress distribution, the actual stress distribution must be resolved into its membrane and bending components:

$$P_m = \frac{1}{(b-a)} \int_a^b \sigma_\theta \, dr$$

$$P_b = \frac{6}{(b-a)^2} \int_a^b \sigma_\theta \, (r_m - r) \, dr$$

where $r_m$ is the flywheel mean radius defined as (a + b) / 2. Substituting the circumferential stress term shown above and carrying out the integrations yields

$$P_m = \left(\frac{3+v}{8}\right) \frac{\rho\omega^2}{386.4\ (b-a)} (b^3 - a^3) \left[1 - \frac{1}{3}\left(\frac{1+3v}{3+v}\right)\right]$$

$$P_b = \left(\frac{3+v}{8}\right) \frac{6\ \rho\omega^2}{386.4\ (b-a)^2} \left[\frac{b^4}{12}\left(\frac{1+3v}{3+v}\right) + \frac{b^3 a}{2}\ [1 - \frac{1}{3}\left(\frac{1+3v}{3+v}\right)]\right.$$

$$\left. -a^2 b^2 \ln(\frac{b}{a}) - \frac{b\ a^3}{2}[1 + \frac{1}{3}(\frac{1+3v}{3+v})] - \frac{a^4}{12}(\frac{1+3v}{3+v})\right]$$

As was performed in the Reference 2 evaluation, a ductile failure limiting speed was determined for each flywheel group selected for evaluation, assuming that cracks are not present and neglecting the local stress effects from holes and keyways. Limiting speeds were also calculated considering the reduced cross sectional area resulting from the keyway, and from assuming that cracks may be present. Cracks were assumed to emanate radially from the keyway, through the full thickness of the flywheel. The results of these calculations are provided in the following table.

**Table 4-2: Ductile Failure Limiting Speed (rpm)**

| Flywheel Group | Assuming No Cracks | | Crack Length (from Keyway) | | | |
|---|---|---|---|---|---|---|
| | Neglecting Keyway Radial Length | Considering Keyway Radial Length | 1" Crack | 2" Crack | 5" Crack | 10" Crack |
| 1 | 3487 | 3430 | 3378 | 3333 | 3240 | 3012 |
| 2 | 3553 | 3493 | 3435 | 3386 | 3281 | 3060 |
| 10 | 3503 | 3471 | 3443 | 3398 | 3238 | 2990 |
| 14 | 4086 | 4032 | 3961 | 3903 | 3768 | 3448 |
| 15 | 3175 | 3155 | 3105 | 3056 | 2915 | 2698 |
| 16 | 3900 | 3850 | 3815 | 3760 | 3565 | 3264 |

Per Regulatory Guide 1.14, Revision 1, Section C, item 2f, the normal speed should be less than one-half of the lowest of the critical speeds as calculated for ductile failure, nonductile failure and excessive deformation. At the minimum calculated limiting speed of 3155 rpm (assuming cracks are not present), the normal speed must be less than 1577 rpm. Since the normal operating flywheel speed is 1200 rpm, item 2f of the Regulatory Guide is satisfied for ductile failure with no cracks present. Assuming that a rather large crack of 10" depth is present, item 2f is still satisfied for ductile failure since one-half of the lowest calculated critical speed (2698 rpm) is 1349 rpm, which is higher than the normal operating flywheel speed of 1200 rpm.

Per item 2g of Section C of the Regulatory Guide, the predicted LOCA overspeed should be less than the lowest of the critical speeds calculated for ductile failure, nonductile failure and excessive deformation. Since the predicted LOCA overspeed is in all cases less than 1500 rpm, and the minimum calculated limiting velocity for ductile failure is 3155 rpm, item 2g of the Regulatory Guide is satisfied for ductile failure, assuming no cracks are present. Assuming that a rather large crack of 10" length is present, item 2g is still satisfied for ductile failure since the lowest calculated critical speed (2698 rpm) is higher than the LOCA overspeed of 1500 rpm

Therefore, the Regulatory Guide acceptance criteria for ductile failure of the flywheels are satisfied.

### 4.3 Nonductile Failure Analysis

As provided in Reference 2, an approximate solution for the stress intensity factor for a radial full depth crack emanating from the bore of a rotating disk may be calculated by the following equations (Reference 5):

$$K_I = \frac{\rho\omega^2}{386.4} b^{3/2} \phi \left[ \frac{\pi\left(\frac{c}{b}-\frac{a}{b}\right)}{(1-\nu^2)} \right]^{1/2}$$

$$\phi = \frac{(3+\nu)}{32}\left[3\left(1+\frac{a^2}{b^2}\right)+3\left(\frac{a}{b}\right)\left(\frac{b}{c}\right)+\left(1+\frac{a}{b}+\frac{a^2}{b^2}\right)\frac{\left(1-\frac{a}{b}\right)}{\left(1-\frac{c}{b}\right)}\right]$$

$$-\left(\frac{1+3\nu}{32}\right)\left[\frac{\left(\frac{c}{b}\right)^3-\left(\frac{a}{b}\right)^3}{\left(\frac{c}{b}-\frac{a}{b}\right)}+\frac{1}{3}\frac{\left(1-\frac{a}{b}\right)^3}{\left(1-\frac{c}{b}\right)}\right]$$

| | | |
|---|---|---|
| where $\rho$ | = | flywheel material density ($lb_m$ per cubic inch) |
| $\omega$ | = | flywheel angular speed (radians per second) |
| $b$ | = | flywheel outer radius (inches) |
| $a$ | = | flywheel inner radius (inches) |
| $c$ | = | radial location of crack tip (inches) |
| $\nu$ | = | Poisson's ratio (0.3) |

In the Reference 2 analysis, the keyway radial length was initially assumed to be included as part of the total crack length for conservatism. Using the closed form solution, a nonzero value of stress intensity was obtained for a zero crack length (i.e., c = a + keyway radial length), as would be expected, since the keyway itself was in essence considered to be a crack. To eliminate this undue conservatism for short crack lengths, finite element analysis was performed. It was shown that cracks emanating from the center of the keyway yielded higher stress intensity factors than cracks emanating from the keyway corner, and that a zero length crack resulted in a zero stress intensity factor. The finite element analysis results were in close agreement with the closed form solution for crack lengths larger than about 1.0 inch. It was also shown in the Reference 2 analysis that the ductile failure mode controls for smaller crack lengths (less than 1.15 inches for the particular flywheel evaluated), and that nonductile failure controls for larger crack lengths. Therefore, the closed form solution was used for calculation of the stress intensity factors in this report, keeping in mind that it is overly conservative for small cracks. (However, small cracks are controlled by the ductile failure mode).

To envelope the range of $RT_{NDT}$ values for the flywheel materials, an upper and lower bound value of 0°F and 60°F were used in this report. The lower bound fracture toughness for ferritic steels was calculated by the following equation (Reference 4):

$$K_{IC} = 33.2 + 20.734 \exp[0.02 (T - RT_{NDT})]$$

This resulted in fracture toughness values of 117 ksi $\sqrt{\text{inch}}$ and 58.5 ksi $\sqrt{\text{inch}}$ for $RT_{NDT}$ values of 0°F and 60°F, respectively, at an ambient temperature of 70°F. The ambient temperature used for the fracture evaluation represents a much lower temperature than would be expected in the containment building during normal plant operating conditions (typically 100°F to 120°F), and is therefore conservative with respect to nonductile failure analysis.

At the maximum flywheel overspeed condition of 1500 rpm, the following critical crack lengths were calculated for cracks emanating radially from the keyway. Note that an intermediate $RT_{NDT}$ value of 30°F ($K_{IC}$ = 79.3 ksi $\sqrt{\text{inch}}$) is included in the table.

**Table 4-3: Critical Crack Lengths for Flywheel Overspeed of 1500 rpm**

| Flywheel Group | Critical Crack Length in Inches and % through Flywheel | | |
|---|---|---|---|
| | $RT_{NDT}$ = 0°F | $RT_{NDT}$ = 30°F | $RT_{NDT}$ = 60°F |
| 1 | 16.6" (50%) | 7.7" (24%) | 3.1" (9%) |
| 2 | 17.5" (53%) | 8.5" (26%) | 3.6" (11%) |
| 10 | 15.1" (56%) | 7.5" (27%) | 3.3" (12%) |
| 14 | 20.3" (73%) | 14.4" (52%) | 8.3" (30%) |
| 15 | 10.4" (51%) | 5.3" (26%) | 2.6" (12%) |
| 16 | 17.2" (70%) | 11.4" (46%) | 6.0" (24%) |

Note: Crack length is measured radially from the keyway, and percentage through flywheel is calculated as the crack length divided by the radial length from the keyway to the flywheel outer radius.

As shown in the above table, the critical crack lengths are quite large, even when considering higher values of $RT_{NDT}$ and a lower than expected operating temperature.

### 4.3.1 Fatigue Crack Growth

To estimate the magnitude of fatigue crack growth during plant life, an initial radial crack length of 10% of the way through the flywheel (from the keyway to the flywheel outer radius) was conservatively assumed. The fatigue crack growth rate may be characterized in terms of the range of applied stress intensity factor, and is generally of the form (Reference 4):

$$\frac{da}{dN} = C_0 \, (\Delta K_I)^n$$

where $da/dN$ = crack growth rate (inches/cycle)

$n$ = slope of the log (da/dN) versus log ($\Delta K_I$)

$C_0$ = scaling constant

The fatigue crack growth behavior is affected by the R ratio ($K_{min}/K_{max}$) and the environment. Reference fatigue crack growth behavior of carbon and low alloy ferritic steels exposed to an air environment is provided by the above equation with $n = 3.07$ and $C_0 = 1.99 \times 10^{-10}$ S. (S is a scaling parameter to account for the R ratio and is given by $S = 25.72\,(2.88 - R)^{-3.07}$ where $0 \le R < 1$. Since the maximum stress intensity range occurs between RCP shutdown (zero rpm) and the normal operating speed of approximately 1200 rpm, the R ratio is zero, and S = 1). The fatigue crack growth rate for the flywheels may therefore be estimated by

$$\frac{da}{dN} = 1.99 \times 10^{-10} \, (\Delta K_I)^{3.07}$$

Assuming 6000 cycles of RCP starts and stops for a 60 year plant life (typical for RCP design including the potential for extended plant life, and conservative for actual operation), the estimated radial crack growth is as shown below:

**Table 4-4: Fatigue Crack Growth Assuming 6000 RCP Starts and Stops**

| FLY-WHEEL GROUP | FLY-WHEEL OD (INCHES) | FLY-WHEEL BORE (INCHES) | KEY-WAY RADIAL LENGTH (INCH) | LENGTH FROM KEYWAY TO OD (INCHES) | ASSUMED INITIAL CRACK LENGTH (INCHES) | $\Delta K_I$ (KSI $\sqrt{INCH}$) | CRACK GROWTH AFTER 6000 CYCLES (INCH) |
|---|---|---|---|---|---|---|---|
| 1 | 76.50 | 9.375 | 0.937 | 32.63 | 3.26 | 38 | 0.08 |
| 2 | 75.75 | 8.375 | 0.906 | 32.78 | 3.28 | 37 | 0.08 |
| 10 | 72.00 | 16.125 | 0.906 | 27.03 | 2.70 | 35 | 0.07 |
| 14 | 65.00 | 8.375 | 0.656 | 27.66 | 2.77 | 25 | 0.02 |
| 15 | 72.00 | 30.500 | 0.390 | 20.36 | 2.04 | 33 | 0.05 |
| 16 | 65.00 | 13.800 | 1.060 | 24.54 | 2.45 | 28 | 0.03 |

As shown in the above table, crack growth is negligible over a 60 year life of the flywheel, even when assuming a large initial crack length.

### 4.4 Excessive Deformation Analysis

The change in the bore radius (a) and the outer radius (b) of the flywheel at the overspeed condition may be estimated by the following equations (Reference 6):

$$\Delta a = \frac{1}{4}\,\frac{\rho\omega^2}{386.4}\,\frac{a}{E}\,[(3+\nu)\,b^2 + (1-\nu)\,a^2]$$

$$\Delta b = \frac{1}{4}\,\frac{\rho\omega^2}{386.4}\,\frac{b}{E}\,[(1-\nu)\,b^2 + (3+\nu)\,a^2]$$

where $a$ = bore radius (inches)
$b$ = outer radius (inches)
$\rho$ = flywheel material density (0.283 $lb_m$/cubic inch)
$\omega$ = flywheel angular speed (radians per second)
$E$ = Young's modulus (30 x $10^6$ psi)
$\nu$ = Poisson's ratio (0.3)

At the flywheel overspeed condition of 1500 rpm (157.08 radians/second), the change in the bore radius and the outer radius is calculated as shown below:

**Table 4-5: Flywheel Deformation at 1500 rpm**

| FLYWHEEL GROUP | CHANGE IN BORE RADIUS (INCH) | CHANGE IN OUTER RADIUS (INCH) |
|---|---|---|
| 1 | 0.003 | 0.006 |
| 2 | 0.003 | 0.006 |
| 10 | 0.005 | 0.006 |
| 14 | 0.002 | 0.004 |
| 15 | 0.010 | 0.009 |
| 16 | 0.004 | 0.004 |

As shown in the table above, a maximum flywheel deformation of only 0.010 inches is anticipated for the flywheel overspeed condition. As deformation is proportional to $\omega^2$, this represents an increase of 56% over the normal operating deformation. This increase would not result in any adverse conditions, such as excessive vibrational stresses leading to crack propagation, since the flywheel assemblies are typically shrunk fit to the flywheel shaft, and the deformations are negligible.

### 4.5 Summary of Stress and Fracture Results

The integrity evaluations presented in this section have shown that the reactor coolant pump flywheels have a very high tolerance for the presence of flaws. The results obtained here are even better than those obtained in earlier evaluations, because the application of leak before break has demonstrated that flywheel overspeed events are limited to less than 1500 rpm.

There are no significant mechanisms for inservice degradation of the flywheels, since they are isolated from the primary coolant environment. Analyses presented in this section have shown there is no significant deformation of the flywheels even at maximum overspeed conditions. Fatigue crack growth calculations have shown that for 60 years of operation, crack growth from large postulated flaws in each of the flywheel groups is only a few mils. Therefore the flywheel inspections completed prior to service are sufficient to ensure their integrity during service. In fact, the most likely source of inservice degradation is damage to the keyway region which could occur during disassembly or reassembly for inspection.

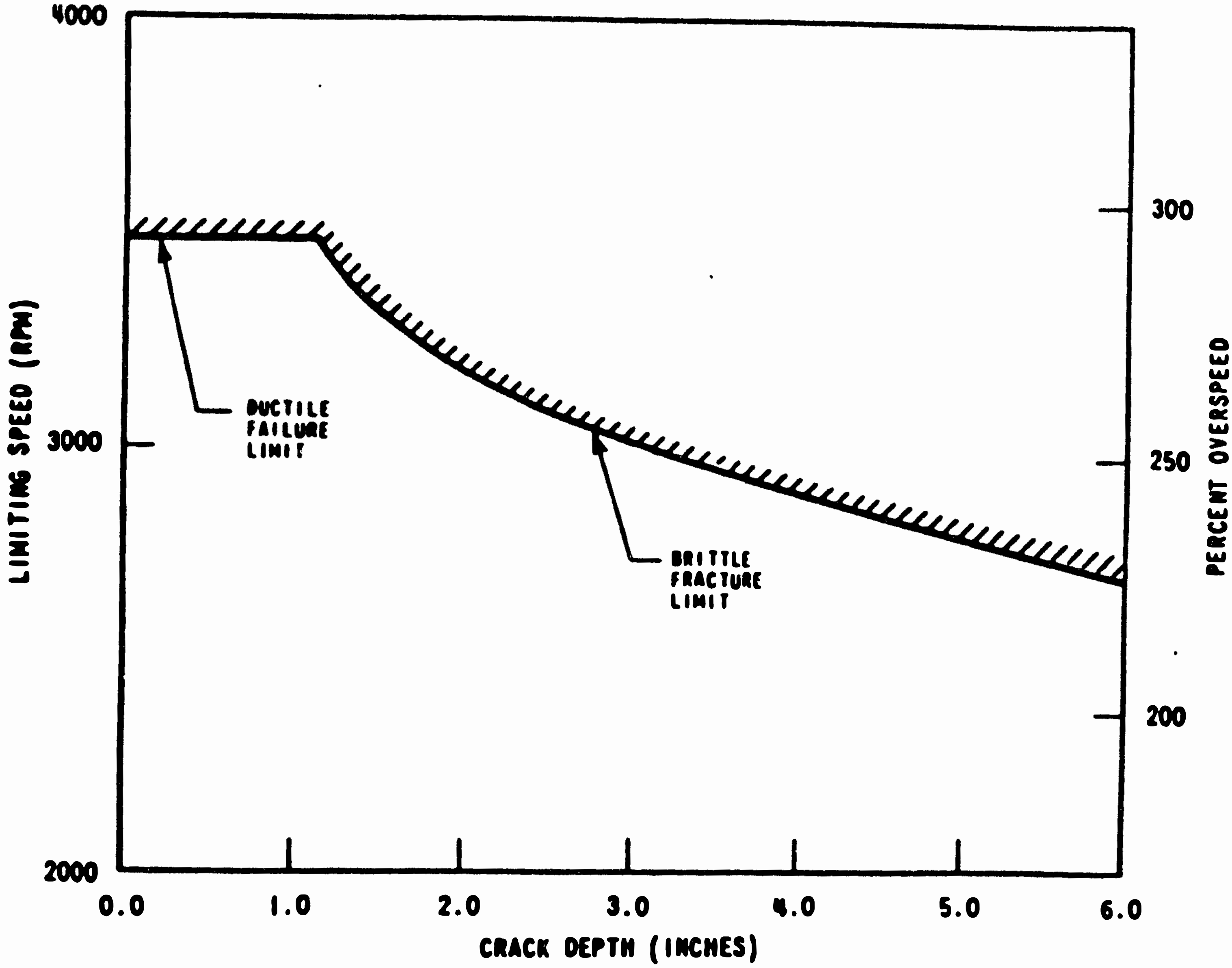



**Figure 4-1: Results of a Typical Reactor Coolant Pump Flywheel Overspeed Evaluation**

# SECTION 5
# RISK ASSESSMENT: EFFECT OF INSPECTIONS

To investigate the effect of flywheel inspections on the risk of failure, a structural reliability and risk assessment was performed for each of the flywheel groups selected for evaluation in Section 4. A 40 year plant life including the potential for an extended plant life of 60 years, and 12 month operating cycles were assumed for the evaluation. The following subsections describe the methodology used and the results of this assessment.

## 5.1 Method of Calculating Failure Probabilities

The probability of failure of the RCP flywheel as a function of operating time t, $Pr(t \leq t_f)$, is calculated directly for each set of input values using Monte-Carlo simulation with importance sampling. The Monte-Carlo simulation does not force the calculated distribution of time to failure to be of a fixed type (e.g. Weibull, Log-normal or Extreme Value). The actual failure distribution is estimated based upon the distributions of the uncertainties in the key structural reliability model parameters and plant specific input parameters. Importance sampling, as described by Witt (Reference 7), is a variance reduction technique to greatly reduce the number of trials required for calculating small failure probabilities. In this very effective technique, random values are selected from the more severe high or low regions of their distributions so as to promote failure. However, when failure is calculated, the count is corrected to account for the lower probability of simultaneously obtaining all of the more severe random values.

To apply this simulation method to reactor pump flywheel (RPFW) failure, the existing Westinghouse PROF (probability of failure) Software System (object library) is combined with the problem-specific structural analysis models described in Section 4.3. The PROF library provides standard input and output, including plotting, and probabilistic analysis capabilities (e.g. random number generation, importance sampling). The result is the executable program RPFWPROF.EXE for calculation of pump flywheel failure probability with time. The failure mode being simulated by the program is an initial flaw, undetected during pre-service inspection, growing by fatigue crack growth due to pump startup and shutdown until a critical length is obtained. The critical length is that which causes the flaw stress intensity factor due to pump overspeed during the design limiting event to exceed the fracture toughness of the flywheel material.

The Westinghouse PROF Software Library, which was used to generate the RPFWPROF program, has been verified and benchmarked in a number of ways. Table 5-1 provides a comparison of probabilities from hand calculation for simple models where the only random variables are the initial and limiting crack depths. The crack growth due to two independent mechanisms is deterministic (variables are constant). As can be seen, the W-PROF calculated values agree very well (less than 4% error) for a number of different distributions and with the effects of importance sampling.

**Table 5-1: Simple Verification of Results for Westinghouse PROF Methods**

| Type of Distribution on Crack Depths (1) | Import. Sampling Shift (2) | Hand Calculated Prob. (3) | W-PROF Calculated Probability | Percent Error |
|---|---|---|---|---|
| Normal | 0.0 | 0.1003 | 0.10004 | -0.26 |
| Normal | ± 1.0 | 0.1003 | 0.09889 | -1.41 |
| Log-Normal | 0.0 | 0.1003 | 0.09880 | -1.50 |
| Log-Normal | ± 1.0 | 0.1003 | 0.09652 | -3.77 |
| Uniform | 0.0 | 0.1003 | 0.10393 | +3.62 |
| Log-Uniform | 0.0 | 0.1003 | 0.10018 | -0.12 |
| Weibull | 0.0 | 0.0950 | 0.0934 | -1.68 |

(1) Same type of distribution on the random values of initial crack depth and limiting crack depth.
(2) Median value of initial depth shifted +1 standard deviation and median value of limiting depth shifted -1 standard deviation when importance sampling (Reference 7) is used with less than half the number of trials.
(3) Calculated using stress-strength overlap techniques on crack depth.

The calculation of failure probability using the W-PROF methods and importance sampling was also compared to that calculated by an alternative method for more complex models. The more complex model also included the uncertainties in growth rate, which were also a function of the crack depth. The alternative method was the @RISK add-in for Lotus 1-2-3 spreadsheets (Reference 8). As seen in Figure 5-1, the comparison of calculated probabilities is excellent at the low probability values, where importance sampling is normally used.

In the verification of the simplified piping fracture mechanics (SPFM) structural reliability programs for risk based inspection (Reference 9), the calculated probabilities for thermal transient induced fatigue crack growth were compared with results from the pc-PRAISE program (Reference 10). PRAISE, which was developed by Lawrence Livermore National Laboratory for the NRC, is the nuclear industry's standard for calculating the structural reliability of piping. As shown in Figure 5-2, the comparison of calculated leak probabilities with the number of operating cycles, without the effects of inspection, is excellent for both the SPFMPROF and SPFMSRRA programs. The SPFMSRRA program uses Westinghouse developed approximations to estimate the changes in probability with time due to changes in the input variables relative to a reference case. The reference case is initially calculated using the SPFMPROF Program, which is the same type of program as RPFWPROF.

When the same inservice inspection frequency and accuracy are used, Figure 5-3 shows that essentially the same failure probabilities are calculated by pc-PRAISE, SPFMPROF and SPFMSRRA. Therefore, it is concluded that the Westinghouse methods employed in calculating probabilities with the RPFWPROF.EXE program have been sufficiently verified and benchmarked for the assessment of pump flywheel failure risk and the effects of inspection.

The input parameters to the RPFWPROF program are described in Table 5-2. Variables 1 to 4 and 9 to 17 are the key input parameters needed for failure probability calculation, as identified in Section 4 3. Their usage in the program is specified as shown in the last column of Table 5-2 and schematically in the flow chart of Figure 5-4. "Initial" conditions do not change with time, "Steady-State" is not needed for RPFWPROF, "Transient" calculates fatigue crack growth and "Failure" checks to see if the accumulated crack length exceeds the critical length.

**Table 5-2: Variables for Structural Reliability Model of RCP Flywheel Failure**

| No. | Name | Description of Input Variable | Usage Type |
|---|---|---|---|
| 1 | ORADIUS | Outer Flywheel Radius (Inch) | Initial |
| 2 | IRADIUS | Inner Flywheel Radius (Inch) | Initial |
| 3 | PFE-PSI | Probability of Flaw Existing After Preservice Inspection | Initial |
| 4 | ILENGTH | Initial Radial Flaw Length (Inch) | Initial |
| 5 | CY1-ISI | Operating Cycle for First Inservice Inspection | Inspection |
| 6 | DCY-ISI | Operating Cycles Between Inservice Inspections | Inspection |
| 7 | POD-ISI | Flaw Detection Probability per Inservice Inspection | Inspection |
| 8 | DFP-ISI | Fraction PFE Increases per Inservice Inspection | Inspection |
| 9 | NOTR/CY | Number of Transients per Operating Cycle | Transient |
| 10 | DRPM-TR | Speed Change per Transient (RPM) | Transient |
| 11 | RATE-FCG | Fatigue Crack Growth Rate (Inch/Transient) | Transient |
| 12 | KEXP-FCG | Fatigue Crack Growth Rate SIF Exponent | Transient |
| 13 | RPM-DLE | Speed for Design Limiting Event (RPM) | Failure |
| 14 | TEMP-F | Temperature for Design Limiting Event (F) | Failure |
| 15 | RT-NDT | Reference Nil Ductility Transition Temperature (F) | Failure |
| 16 | F-KIC | Crack Initiation Toughness Factor | Failure |
| 17 | DLENGTH | Flywheel Keyway Radial Length (Inch) | Failure |

Variables 5 to 8 are available to calculate the effects of an inservice inspection (ISI) in the RPFWPROF program. In a Monte-Carlo type simulation, the failure probability at a given time is approximated as the ratio of the number of failures at that time to the total number of trials. For inservice inspections, this ratio is modified to reflect the fact that only those cracks that are not detected will remain to possibly cause failure. That is, a component with a detected crack is assumed to be repaired or replaced, returning it to a good-as-new condition. This modified ratio for ISI is expressed by the following equation:

$$Pr_f = \sum_{n=1}^{N} \left[ Pr_{ND}(n)\, F(n) \right] / N$$

Where:

$Pr_f$ = the approximate probability of failure,

$Pr_{ND}(n)$ = the ISI non-detection probability for the nth trial,

$F(n)$ = the failure weight for the nth trial
(e.g. 1 if failure occurs and 0 otherwise for no importance sampling), and

N = the total number of trials (simulations).

The non-detection probability normally varies as a function of time since it depends upon the size of the crack at the time the ISI is performed. That is, the larger the crack size, the lower the probability of not detecting it. This is also expressed in equation form for the Ith inservice inspection as:

$$Pr_{ND}(n) = \prod_{i=1}^{I} \left[ Pr_{ND}(n,t_i) \right]$$

Where:

$Pr_{ND}(n,t_i)$ = the probability of non-detection for the inservice inspection of weld n at time $t_i$.

These equations, which are used in the simplified model for the effect of ISI, are consistent with those described in the pc-PRAISE Code User's Manual (Reference 10). They are somewhat optimistic since there is no correlation between successive inspections of the same material, which may systematically occur in actual practice. The parameters needed to describe the selected ISI program are the time of the first inspection, the frequency of subsequent inspections (expressed as the number of fuel or operating cycles between inspections) and the probability of non-detection as a function of crack length. For the reactor pump flywheel, the non-detection probability, which is independent of crack length, is simply one minus a constant value of detection probability, variable 7 in Table 5-2. An increase in failure probability due to pump inspection (chance of incorrect disassembly and reassembly) was included in the ISI model but not used (variable 8 set to zero).

The median input values and their uncertainties for each of the parameters of Table 5-2 are shown in Table 5-3. The median is the value at 50% probability (half above and half below this value); it is also the mean (average) value for symmetric distributions, like the normal (bell-shaped curve) distribution. Uncertainties are based upon expert engineering judgement and previous structural reliability modeling experience. For example, the fracture toughness for initiation as a function of the reference nil-ductility transition temperature and the uncertainties on these parameters are based upon prior probabilistic fracture mechanics analyses of the pressure vessel (Reference 11). Also note that the stress intensity factor calculation for crack growth and failure used the flywheel keyway radial length (variable 17) in addition to the calculated flaw length. This allowed the probabilistic models to be checked using the results of the conservative deterministic evaluations of Tables 4-3 and 4-4.

**Table 5-3: Input Values for Structural Reliability Model of RCP Flywheel Failure**

| No. | Name | Median | Distribution | Uncertainty* |
|---|---|---|---|---|
| 1 | ORADIUS | Per Flywheel Group | Constant | |
| 2 | IRADIUS | Per Flywheel Group | Constant | |
| 3 | PFE-PSI | 1.000E-01 | Constant | |
| 4 | ILENGTH | 1.000E-01 | Log-Normal | 2.153E+00 |
| 5 | CY1-ISI | 3.000E+00 | Constant | |
| 6 | DCY-ISI | 4.000E+00 | Constant | |
| 7 | POD-ISI | 5.000E-01 | Constant | |
| 8 | DFP-ISI | 0.000E+00 | Constant | |
| 9 | NOTR/CY | 1.000E+02 | Normal | 1.000E+01 |
| 10 | DRPM-TR | 1.200E+03 | Normal | 1.200E+02 |
| 11 | RATE-FCG | 9.950E-11 | Log-Normal | 1.414E+00 |
| 12 | KEXP-FCG | 3.070E+00 | Constant | |
| 13 | RPM-DLE | 1.500E+03 | Normal | 1.500E+02 |
| 14 | TEMP-F | 9.500E+01 | Normal | 1.250E+01 |
| 15 | RT-NDT | 3.000E+01 | Normal | 1.700E+01 |
| 16 | F-KIC | 1.000E+00 | Normal | 1.000E-01 |
| 17 | DLENGTH | Per Flywheel Group | Constant | |

* Note: Uncertainty is either the normal standard deviation, the range (median to maximum) for uniform distributions or the corresponding factor for logarithmic distributions.

Table 5-4 provides sample output from the RPFWPROF Program for the values of the input variables in Table 5-3. The first page of the output describes the input that is used for the calculations. The "SHIFT MV/SD" column indicates how many standard deviations (SD) the median value (MV) is shifted for importance sampling (Reference 7). The second page of the output provides the change in failure probability per fuel (operating) cycle and the cumulative probability. The deviation on the cumulative total that is output is the deviation due to the Monte-Carlo simulation only. Figure 5-5 shows the computer generated plot comparing the calculated reactor pump failure probabilities with and without the effects of inservice inspection. As can be seen, the effect of ISI, even with a 50% probability of detection, is very small. This is because the failure probability is not changing much with time; therefore, the rate of increase cannot be significantly reduced even for a perfect inspection with 100% probability detection.

**Table 5-4: Example Output from the RPFWPROF Program**

STRUCTURAL RELIABILITY AND RISK ASSESSMENT (SRRA)
WESTINGHOUSE PROBABILITY OF FAILURE PROGRAM RPFWPROF ESBU-NTD

INPUT VARIABLES FOR CASE 1: REACTOR COOLANT PUMP FLYWHEEL FAILURE

| | | | | | |
|---|---|---|---|---|---|
| NCYCLE = | 60 | NFAILS = | 1000 | NTRIAL = | 9999 |
| NOVARS = | 17 | NUMSET = | 4 | NUMISI = | 4 |
| NUMSSC = | 0 | NUMTRC = | 4 | NUMFMD = | 5 |

| VARIABLE NO. | NAME | DISTRIBUTION TYPE | LOG | MEDIAN VALUE | DEVIATION OR FACTOR | SHIFT MV/SD | USAGE NO. | SUB |
|---|---|---|---|---|---|---|---|---|
| 1 | ORADIUS | - CONSTANT - | | 3.6000D+01 | | | 1 | SET |
| 2 | IRADIUS | - CONSTANT - | | 8.0625D+00 | | | 2 | SET |
| 3 | PFE-PSI | - CONSTANT - | | 1.0000D-01 | | | 3 | SET |
| 4 | ILENGTH | NORMAL | YES | 1.0000D-01 | 2.1528D+00 | 1.00 | 4 | SET |
| 5 | CY1-ISI | - CONSTANT - | | 3.0000D+00 | | | 1 | ISI |
| 6 | DCY-ISI | - CONSTANT - | | 4.0000D+00 | | | 2 | ISI |
| 7 | POD-ISI | - CONSTANT - | | 5.0000D-01 | | | 3 | ISI |
| 8 | DFP-ISI | - CONSTANT - | | 0.0000D+00 | | | 4 | ISI |
| 9 | NOTR/CY | NORMAL | NO | 1.0000D+02 | 1.0000D+01 | .00 | 1 | TRC |
| 10 | DRPM-TR | NORMAL | NO | 1.2000D+03 | 1.2000D+02 | 1.00 | 2 | TRC |
| 11 | RATE-FCG | NORMAL | YES | 9.9499D-11 | 1.4142D+00 | 1.00 | 3 | TRC |
| 12 | KEXP-FCG | - CONSTANT - | | 3.0700D+00 | | | 4 | TRC |
| 13 | RPM-DLE | NORMAL | NO | 1.5000D+03 | 1.5000D+02 | 1.00 | 1 | FMD |
| 14 | TEMP-F | NORMAL | NO | 9.5000D+01 | 1.2500D+01 | -2.00 | 2 | FMD |
| 15 | RT-NDT | NORMAL | NO | 3.0000D+01 | 1.7000D+01 | 2.00 | 3 | FMD |
| 16 | F-KIC | NORMAL | NO | 1.0000D+00 | 1.0000D-01 | -1.00 | 4 | FMD |
| 17 | DLENGTH | - CONSTANT - | | 9.0600D-01 | | | 5 | FMD |

## Table 5-4: Example Output from the RPFWPROF Program (Cont'd.)

PROBABILITIES OF FAILURE MODE: FATIGUE CRACK GROWTH SIF > TOUGHNESS

NUMBER FAILED = 470 NUMBER OF TRIALS = 9999

| END OF CYCLE | FAILURE PROBABILITY WITHOUT FOR PERIOD | AND CUM. TOTAL | WITH IN-SERVICE INSPECTION FOR PERIOD | CUM. TOTAL |
|---|---|---|---|---|
| 1.0 | 9.00777D-08 | 9.00777D-08 | 9.00777D-08 | 9.00777D-08 |
| 2.0 | 1.00713D-08 | 1.00149D-07 | 1.00713D-08 | 1.00149D-07 |
| 3.0 | 8.70982D-11 | 1.00236D-07 | 8.70982D-11 | 1.00236D-07 |
| 11.0 | 3.56616D-11 | 1.00272D-07 | 8.91540D-12 | 1.00245D-07 |
| 12.0 | 9.40206D-13 | 1.00273D-07 | 1.17526D-13 | 1.00245D-07 |
| 13.0 | 2.17369D-11 | 1.00294D-07 | 2.71711D-12 | 1.00248D-07 |
| 14.0 | 4.71179D-10 | 1.00766D-07 | 5.88974D-11 | 1.00307D-07 |
| 18.0 | 2.91939D-10 | 1.01058D-07 | 1.82462D-11 | 1.00325D-07 |
| 19.0 | 1.59524D-09 | 1.02653D-07 | 9.97024D-11 | 1.00425D-07 |
| 24.0 | 6.00973D-12 | 1.02659D-07 | 9.39020D-14 | 1.00425D-07 |
| 26.0 | 2.07667D-11 | 1.02680D-07 | 3.24480D-13 | 1.00425D-07 |
| 31.0 | 1.30332D-09 | 1.03983D-07 | 1.01822D-11 | 1.00435D-07 |
| 32.0 | 2.87692D-11 | 1.04012D-07 | 1.12380D-13 | 1.00435D-07 |
| 34.0 | 1.81125D-11 | 1.04030D-07 | 7.07521D-14 | 1.00435D-07 |
| 35.0 | 1.30472D-10 | 1.04160D-07 | 5.09655D-13 | 1.00436D-07 |
| 38.0 | 1.12340D-10 | 1.04273D-07 | 2.19414D-13 | 1.00436D-07 |
| 40.0 | 2.93218D-11 | 1.04302D-07 | 2.86346D-14 | 1.00436D-07 |
| 46.0 | 8.71264D-11 | 1.04389D-07 | 4.25422D-14 | 1.00436D-07 |
| 47.0 | 1.12251D-10 | 1.04501D-07 | 5.48099D-14 | 1.00436D-07 |
| 50.0 | 7.94921D-11 | 1.04581D-07 | 1.94[illegible]72D-14 | 1.00436D-07 |
| 51.0 | 5.07795D 12 | 1.04586D-07 | 1.239[illegible]3D-15 | 1.00436D-07 |
| 52.0 | 2.88193D-12 | 1.04589D-07 | 3.51798D-16 | 1.00436D-07 |
| 54.0 | 4.48702D-10 | 1.05037D-07 | 5.47732D-14 | 1.00436D-07 |
| 55.0 | 1.17426D-11 | 1.05049D-07 | 1.43343D-15 | 1.00436D-07 |
| 58.0 | 9.35600D-11 | 1.05143D-07 | 5.71045D-15 | 1.00436D-07 |
| 59.0 | 2.43375D-11 | 1.05167D-07 | 1.48544D-15 | 1.00436D-07 |
| 60.0 | 0.00000D+00 | 1.05167D-07 | 0.00000D+00 | 1.00436D-07 |

DEVIATION ON CUMULATIVE TOTALS = 4.73585D-09 4.63324D-09

Note: Failure probabilities are provided in double precision format (e.g. 4.28172D-08 is $4.28172 \times 10^{-8}$)

## 5.2 Evaluation of Risk for RCP Flywheels

Evaluations were performed to determine the effect on the probability of flywheel failure for continuing the current inservice inspections over the life of the plant and for discontinuing the inspections. Since most plants have been in operation for at least ten years, the evaluation calculated the effects of the inspections being discontinued after ten years.

It is important to keep in mind that the probability of failure determined by these evaluations is only a calculated parameter. The reason for this is that the evaluation conservatively assumes that the probability of a flaw existing after preservice inspection is 10%, and that the ISI flaw detection probability is only 50%. In reality, most preservice and ISI flaws would be detected, especially for the larger flaw depths which may lead to failure. Therefore, the calculated values are very conservative. (The effects of some important parameters on the calculated probability of failure are discussed later in Section 5.3). The most important result of the evaluation is the change in calculated probability of failure from continuing to discontinuing the inspections after ten years (cycles) of plant life.

As shown in Figures 5-6 through 5-11, the effect of inservice inspection on failure probability has little effect on minimizing the potential for failure of the flywheel. The results of this assessment are summarized as follows for a plant life of 40 and 60 years:

**Table 5-5: Probability of Failure after 40 and 60 Years with and without Inservice Inspection**

| Flywheel Group | Probability of flywheel failure with ISI prior to and after 10 years | Probability of flywheel failure with ISI prior to 10 years and without ISI after 10 years | | % Increase in failure probability for eliminating inspections | |
|---|---|---|---|---|---|
| | | At 40 years | At 60 years | At 40 years | At 60 Years |
| 1 | 2.45E-7 | 2.50E-7 | 2.57E-7 | 2 | 5 |
| 2 | 1.43E-7 | 1.45E-7 | 1.47E-7 | 1 | 3 |
| 10 | 1.00E-7 | 1.04E-7 | 1.05E-7 | 4 | 5 |
| 14 | 2.98E-10 | 2.98E-10 | 2.98E-10 | 0 | 0 |
| 15 | 1.15E-8 | 1.18E-8 | 1.22E-8 | 3 | 6 |
| 16 | 6.92E-9 | 7.02E-9 | 7.02E-9 | 1 | 1 |

It can be seen above that continuing inspection after 10 years has essentially no impact on the failure probabilities.

## 5.3 Sensitivity Study

A sensitivity study was performed to determine the effect of some important flywheel risk assessment parameters on the probability of failure. Flywheel group 10 was arbitrarily chosen for the study. The parameters evaluated included the probability of detection, the initial flaw length, and the initial flaw length uncertainty. The results of this study are summarized in the table below. Note that this study was performed for a flywheel design life of 40 years.

**Table 5-6: Effect of Flywheel Risk Parameters on Failure Probability**

| Description of flywheel risk parameter varied | Probability of flywheel failure after 40 years with ISI prior to and after 10 years | Probability of flywheel failure after 40 years with ISI prior to 10 years and without ISI after 10 years |
|---|---|---|
| Base Case | 1.00E-7 | 1.04E-7 |
| Probability of Detection of 10% | 1.03E-7 | 1.04E-7 |
| Probability of Detection of 80% | 1.00E-7 | 1.04E-7 |
| Initial flaw length of 0.05 inches | 4.57E-8 | 4.74E-8 |
| Initial flaw length of 0.20 inches | 2.97E-7 | 3.01E-7 |
| Ilength 3 Sigma Bound Factor of 3 | 6.40E-8 | 6.46E-8 |
| Ilength 3 Sigma Bound Factor of 20 | 1.94E-7 | 1.95E-7 |

The values for the base case, shown in Table 5-6 above are for a 10% probability of a flaw existing after preservice inspection, an initial flaw length of 0.10 inch (1.006 inch with keyway), an initial flaw length (Ilength) 3-sigma bound factor of 10, an initial inservice inspection at three years of plant life and subsequent inspections at four year intervals, and a probability of detection of 50% per inservice inspection (see Table 5-5, flywheel group 10).

The flaw detection probability was varied from 50% to 10% and 80%. Failure probability increased approximately 3% for a decrease in flaw detection probability from 50% to 10%. Failure probability did not change for an increase in flaw detection probability from 50% to 80%. Therefore, flaw detection probability, which is a measure of how well the inspections are performed, has essentially no effect on flywheel failure probability.

The initial flaw length was varied from 0.10 inch to 0.05 inch and 0.20 inches. Failure probability decreased by 54% for a decrease in initial flaw length from 0.10 inch to 0.05 inch. Failure probability tripled for an increase in initial flaw length from 0.10 inch to 0.20 inches. Therefore, initial flaw length does affect flywheel failure probability, but the failure probability is small, even for larger initial flaw lengths. Moreover, the probability of the larger flaw being missed during preservice inspection would be even smaller than the assumed 10 percent.

The initial flaw length 3-sigma bound factor was varied from 10 to 3 and 20. Failure probability decreased about 38% for a decrease in the 3-sigma bound factor from 10 to 3. Failure probability increased about 90% for an increase in the factor from 10 to 20. Therefore, the uncertainty in the deviation factor does affect flywheel failure probability, but failure probability is still small, even for a higher 3-sigma bound factor of 20.

### 5.4 Risk Assessment Conclusions

An evaluation of flywheel structural reliability was performed for each of the flywheel groups selected for evaluation in Section 4, using methods which have been sufficiently verified and benchmarked.

Using conservative input values for preservice flaw existence, initial flaw length, inservice flaw detection capability and RCP start/stop transients, it was shown that flywheel inspections beyond ten years of plant life have no significant benefit on the risk of flywheel failure. The reasons for this are that most flaws which could lead to failure would be detected during preservice inspection or at worst early in the plant life, and crack growth is negligible over the plant life. It should be noted that the effect on potential flywheel failure from damage through disassembly and reassembly for inspection has not been evaluated. It is believed that this effect could demonstrate that the risk of failure by continuing flywheel inspections is the same as or greater than the risk by eliminating the inspections.

Sensitivity studies showed that improved flaw detection capability and more inspections result in a small relative change in calculated failure probability. Failure probability was most affected by the initial flaw length and its uncertainty. These parameters are determined by the accuracy of the preservice inspection. The uncertainty could be reduced using the results from the first inservice inspection but would probably not change much during subsequent inspections.

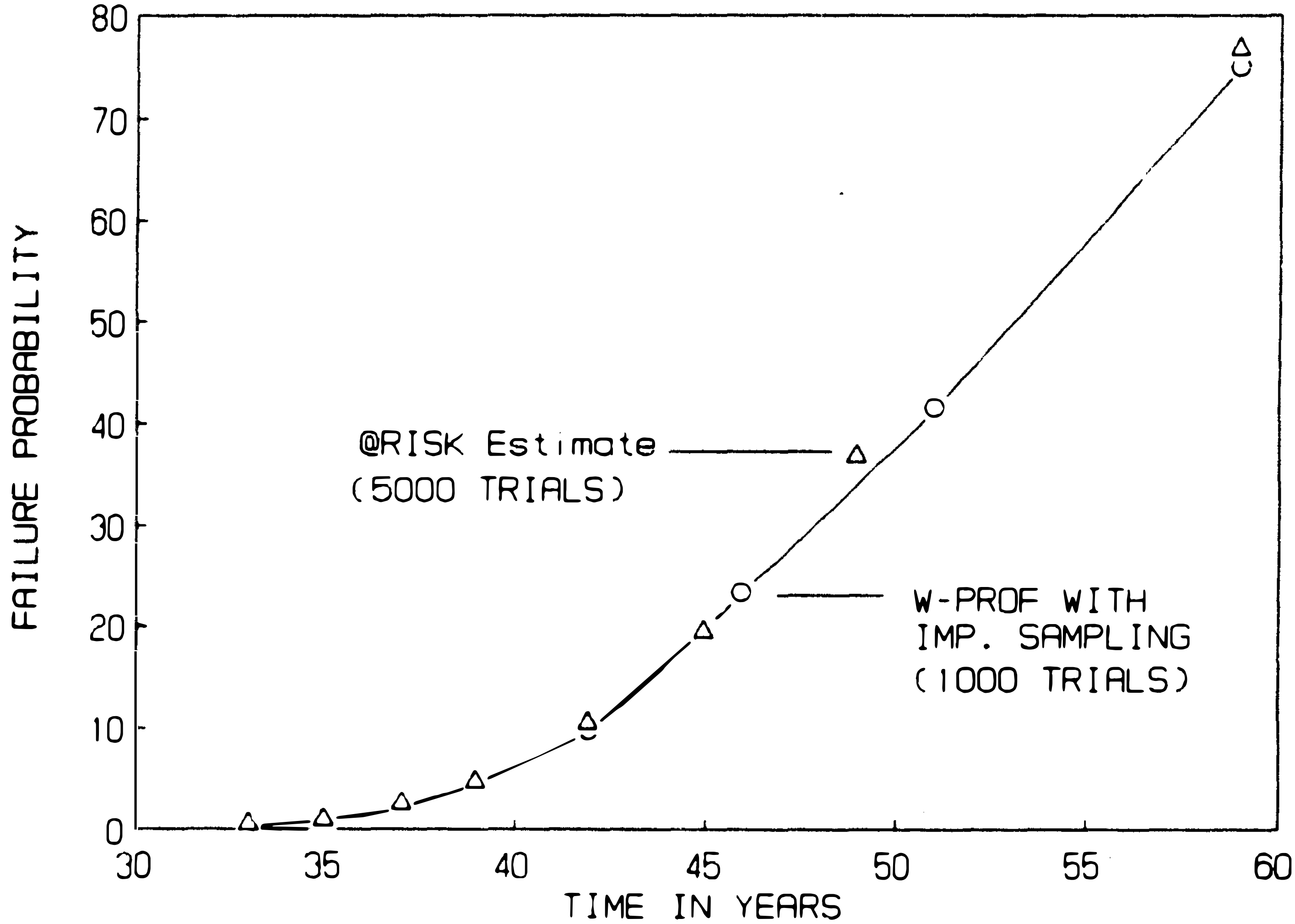



**Figure 5-1: Importance Sampling Check of Westinghouse PROF Methods**

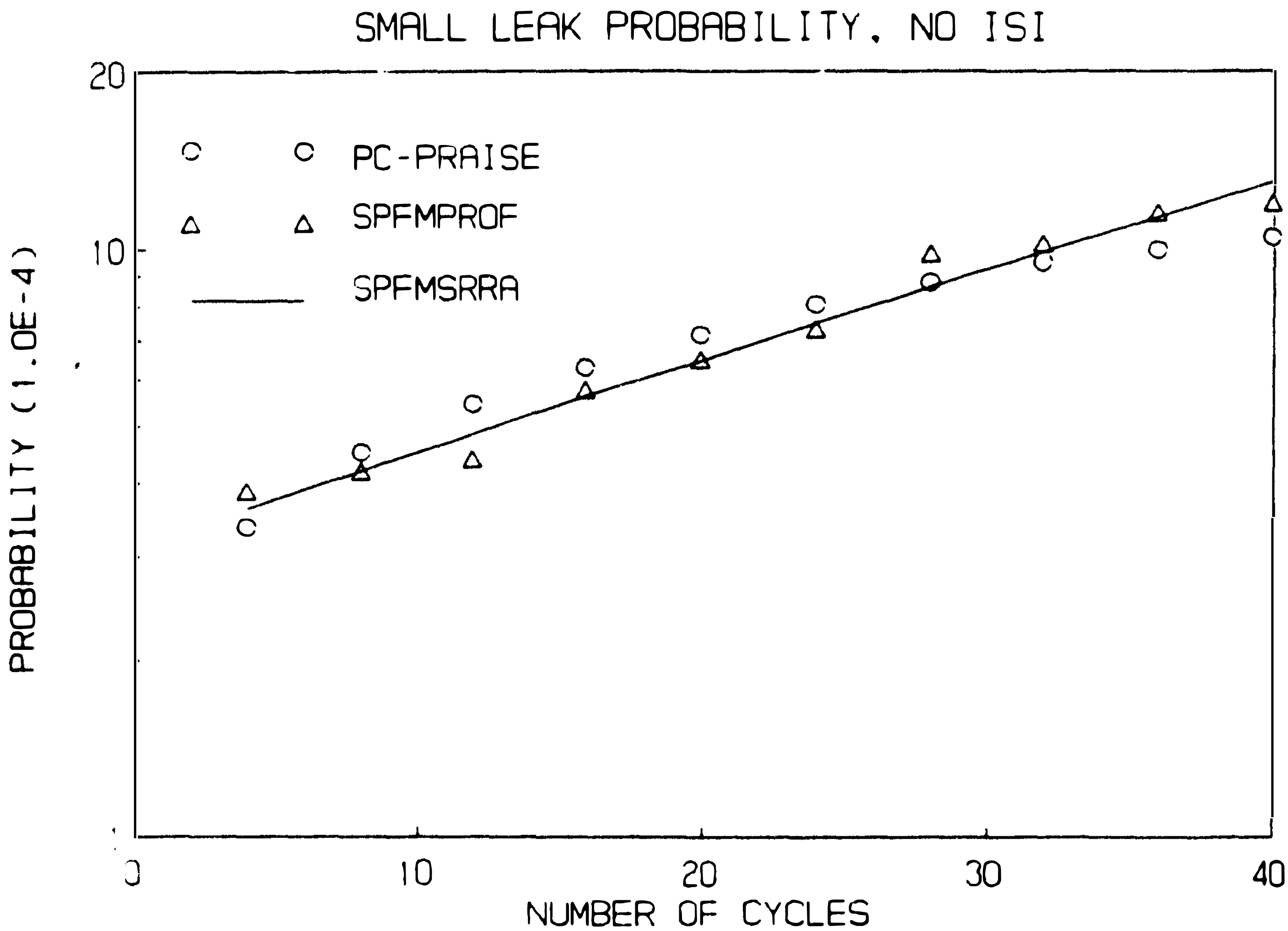



**Figure 5-2: Comparison of Leak Probabilities without Inspection**

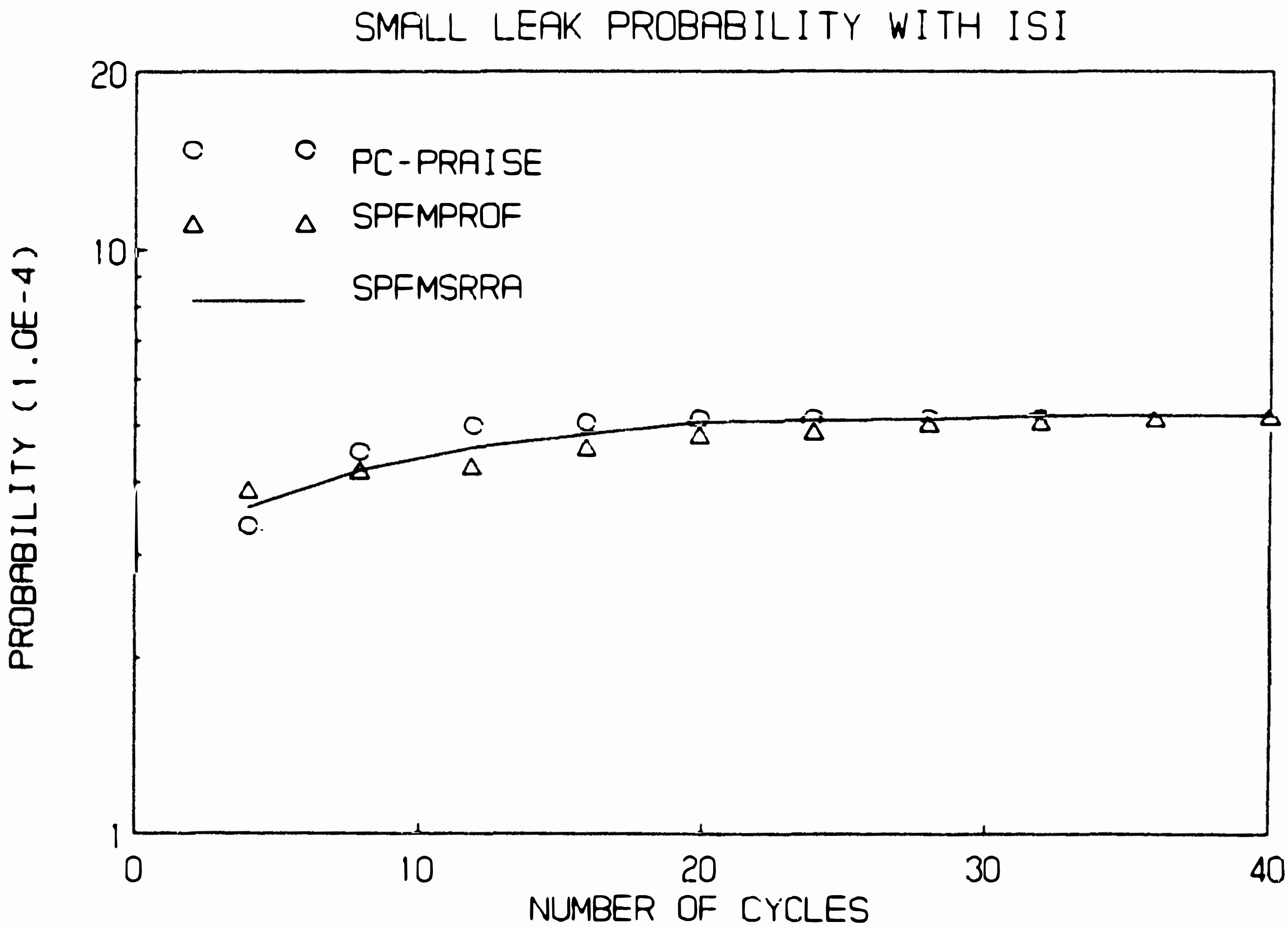



**Figure 5-3: Comparison of Leak Probabilities with Inservice Inspection**

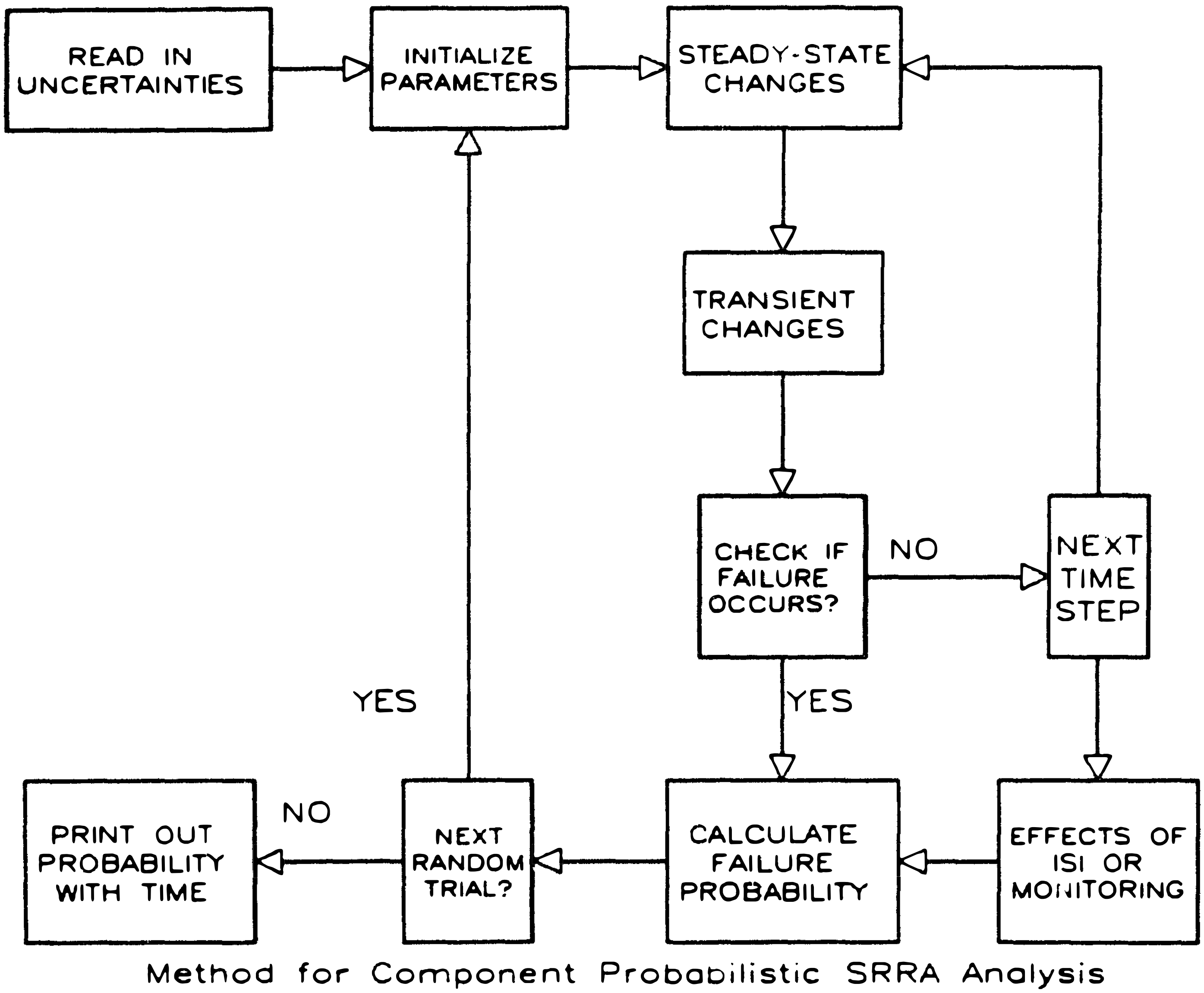



**Figure 5-4:** **Westinghouse PROF Program Flow Chart for Calculating Failure Probability**

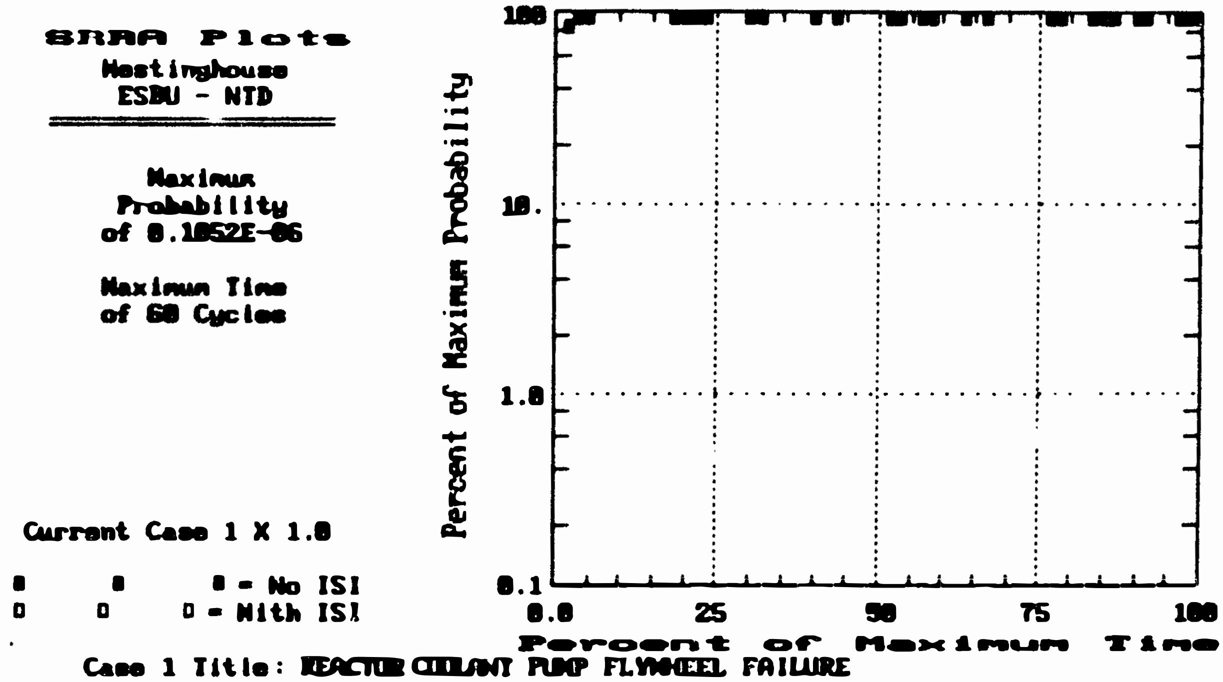



Figure 5-5: Computer SRRA Plot for RCP Flywheel Failure Probability

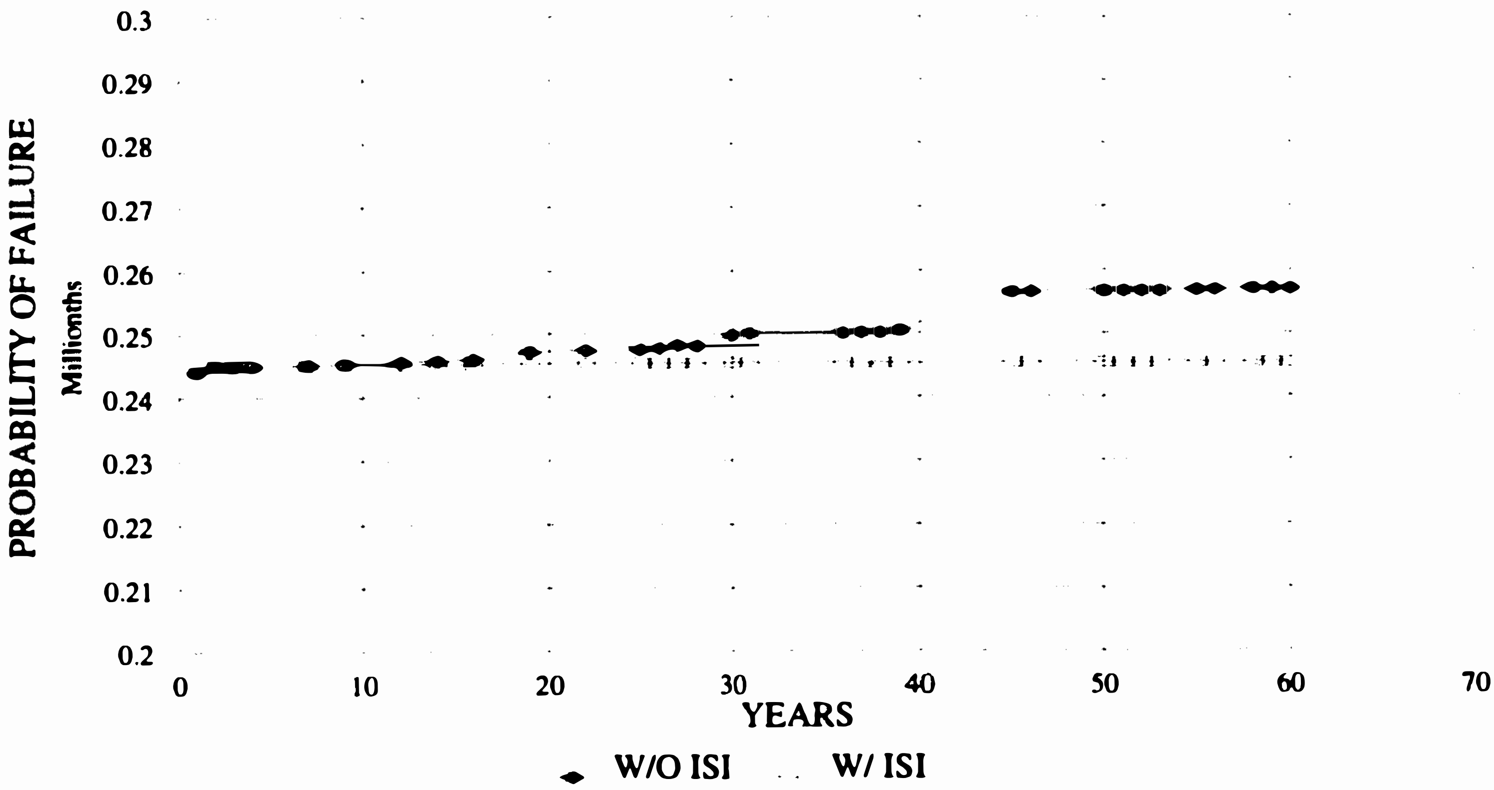



**Figure 5-6: Probability of Failure for Flywheel Evaluation Group 1**

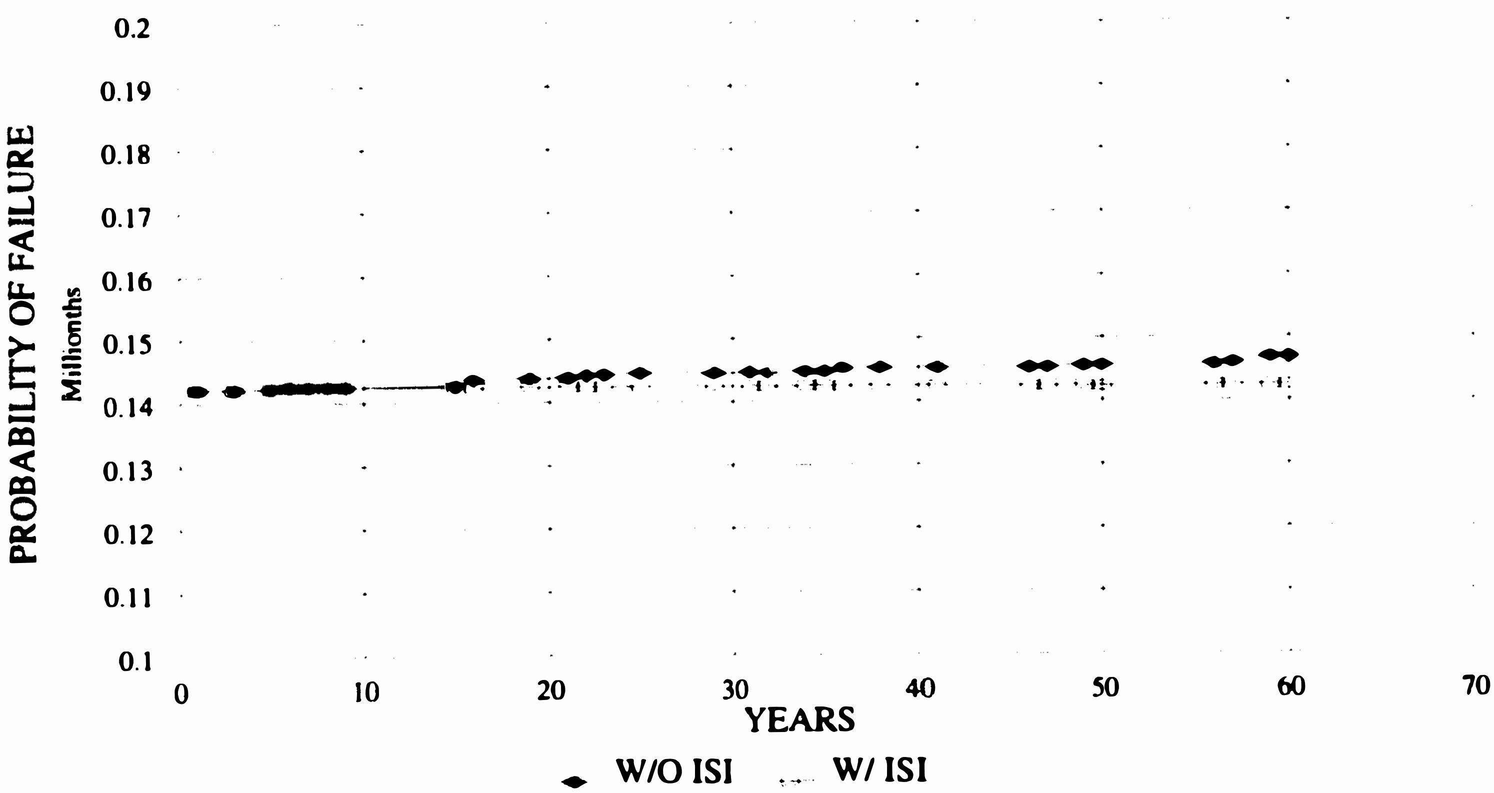



**Figure 5-7: Probability of Failure for Flywheel Evaluation Group 2**

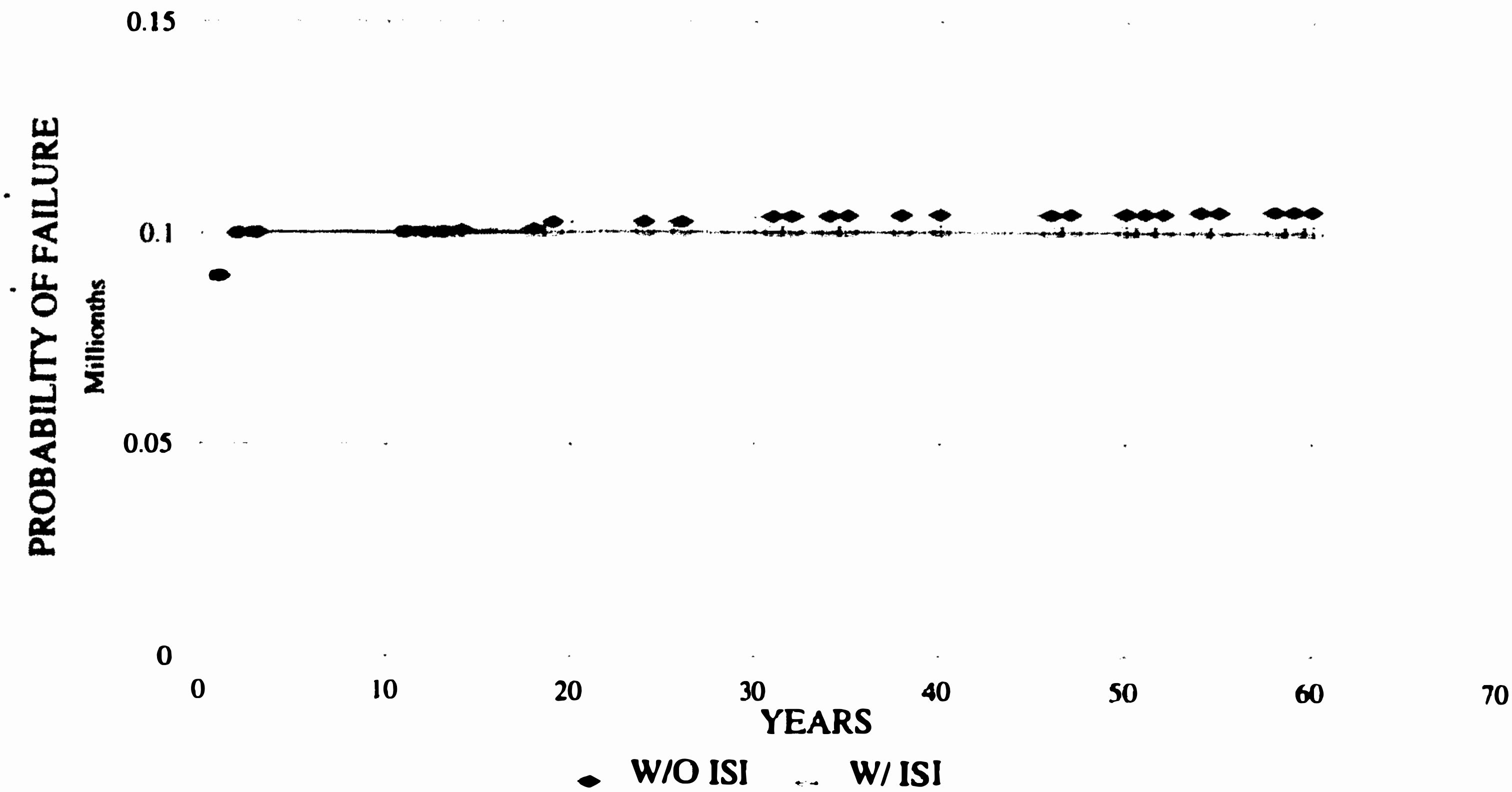



**Figure 5-8: Probability of Failure for Flywheel Evaluation Group 10**

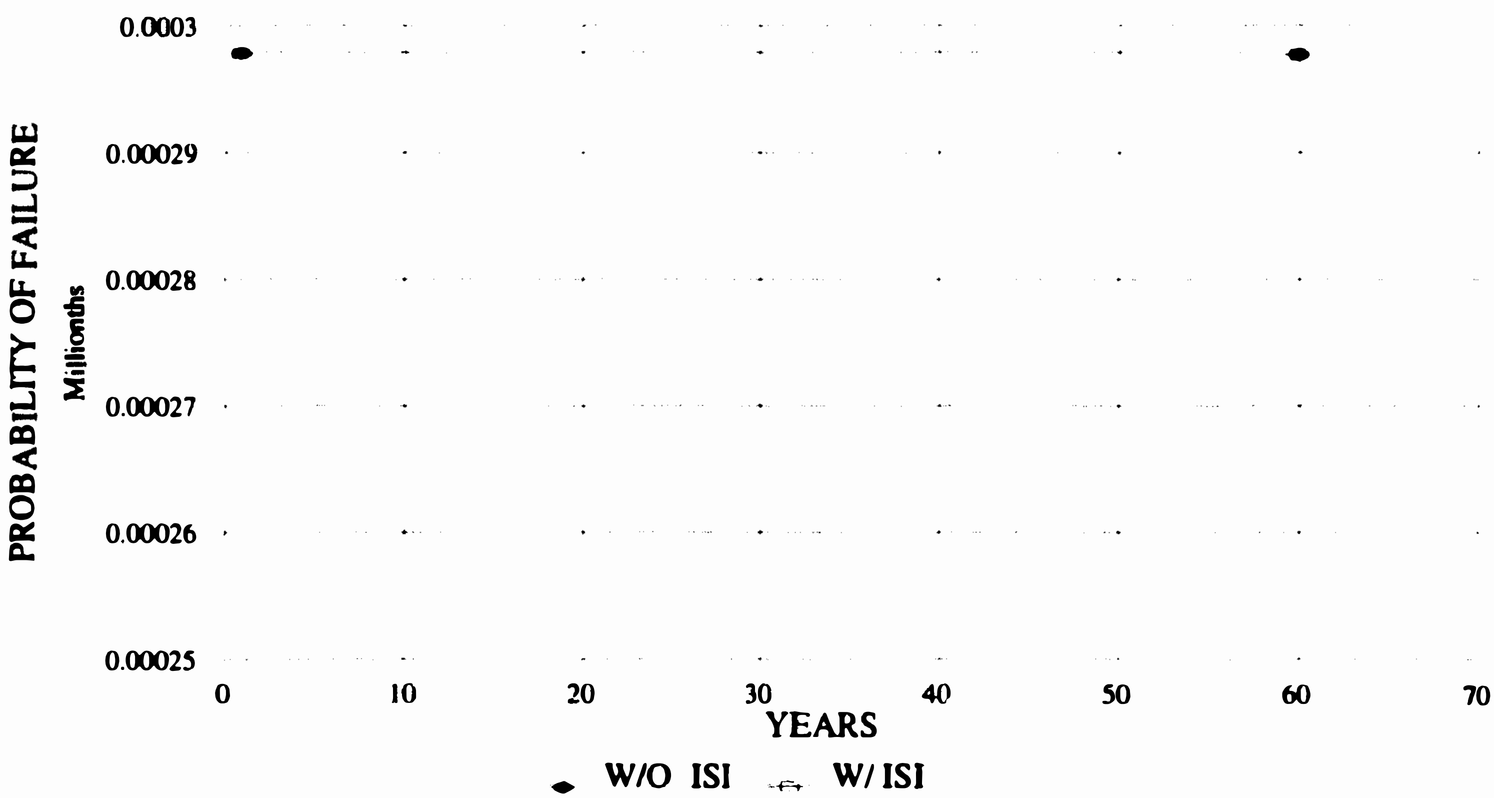



**Figure 5-9: Probability of Failure for Flywheel Evaluation Group 14**

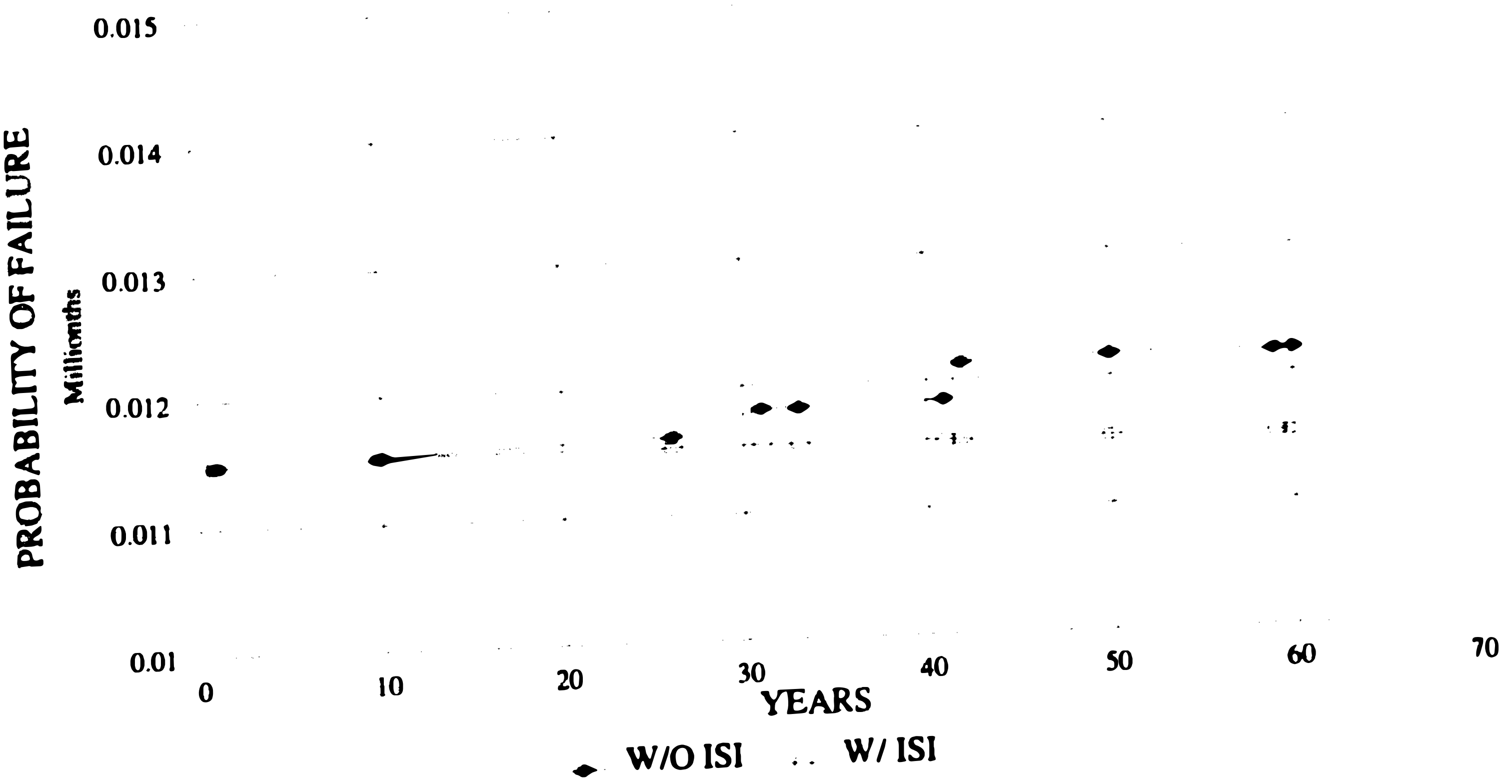



**Figure 5-10: Probability of Failure for Flywheel Evaluation Group 15**

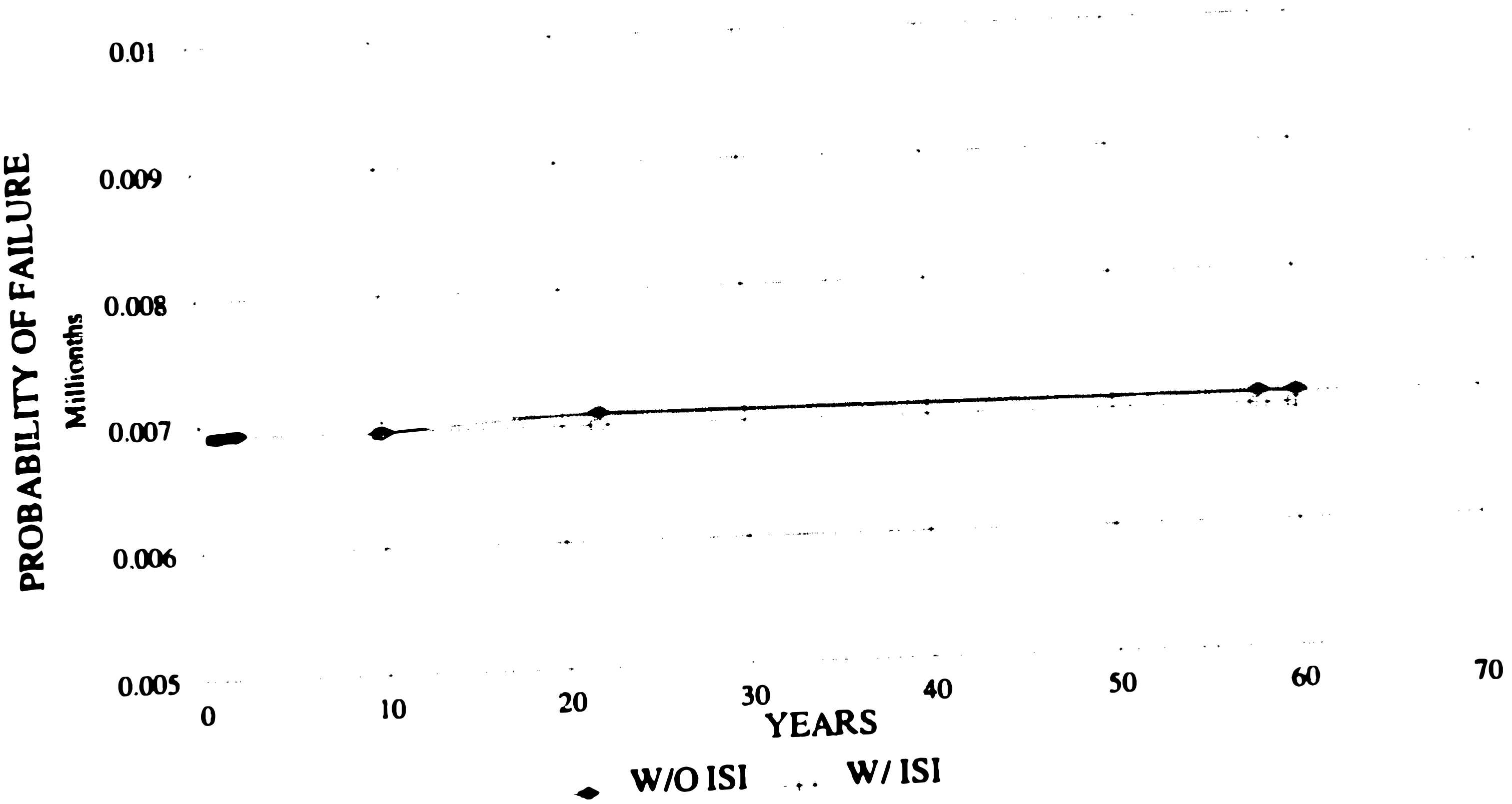



**Figure 5-11: Probability of Failure for Flywheel Evaluation Group 16**

## SECTION 6
## SUMMARY AND CONCLUSIONS

Reactor coolant pump flywheel inspections were implemented as a result of United States Nuclear Regulatory Commission Regulatory Guide 1.14, which was published in 1971 and revised in 1975.

- Flywheels are carefully designed and manufactured from excellent quality steel, which has a high fracture toughness.
- Flywheel overspeed is the critical loading, but leak-before-break has limited the maximum speed to less than 1500 rpm.
- Flywheel inspections have been performed for 20 years, with no indications of service induced flaws.
- Flywheel integrity evaluations show a very high flaw tolerance for the flywheels.
- Crack extension over a 60 year service life is negligible.
- Structural reliability studies have shown that eliminating inspections after 10 years of plant life will not significantly change the probability of failure.
- Inspections result in man-rem exposure and the potential for flywheel damage during assembly and reassembly.

Based on the above conclusions, continued inspections of reactor coolant pump flywheels are not necessary. Furthermore, overall plant safety could be increased by eliminating these inspections, because man rem doses would be lowered, and the potential for flywheel damage during disassembly and reassembly for inspection would be eliminated.

## SECTION 7
## REFERENCES


1) United States Nuclear Regulatory Commission, Office of Standards Development, Regulatory Guide 1.14, "Reactor Coolant Pump Flywheel Integrity," 1971; Revision 1, August 1975.

2) Westinghouse report WCAP-8163, "Topical Report Reactor Coolant Pump Integrity in LOCA," September 1973, WNES Class 3.

3) Babcock and Wilcox Power Generation Group, Nuclear Power Generation Division Topical Report BAW-10040, December 1973, "Reactor Coolant Pump Assembly Overspeed Analysis."

4) ASME Boiler and Pressure Vessel Code, Section XI, 1995 Edition.

5) J. G. Williams and D. P. Isherwood, "Calculation of the Strain-Energy Release Rates of Cracked Plates by an Approximate Method," Journal of Strain Analysis, Vol. 3, No. 1, 17-22 (1968).

6) Formulas for Stress and Strain, Fifth Edition, R. J. Roark and W. C. Young, McGraw-Hill Book Company, 1975.

7) "Development and Applications of Probabilistic Fracture Mechanics for Critical Nuclear Reactor Components," pp 55-70, *Advances in Probabilistic Fracture Mechanics*, ASME PVP-Vol. 92, F. J. Witt, 1984

8) *@RISK, Risk Analysis and Simulation add-In for Lotus 1-2-3, Version 2.01 Users Guide*, Palisade Corporation, Newfield, NY, February 6, 1992

9) *Final Report Documenting the Development of Piping Simplified Probabilistic Fracture Mechanics (SPFM) Models for EG&G Idaho, Inc.*, B. A. Bishop, October 1993, transmitted by Westinghouse Letter FDRT/SRPLO-027(94), February 17, 1994

10) NUREG/CR-5864, *Theoretical and User's Manual for pc-PRAISE, A Probabilistic Fracture Mechanics Computer Code for Piping Reliability Analysis*, Harris and Dedhia, July 1992

11) EPRI TR-105001, *Documentation of Probabilistic Fracture Mechanics Codes Used for Reactor Pressure Vessels Subjected to Pressurized Thermal Shock Loading*, K. R. Balkey and F. J. Witt (Part 1) and B. A. Bishop (Part 2), June 1995

# APPENDIX A

## REGULATORY POSITION

The United States Nuclear Regulatory Commission (NRC) issued Regulatory Guide 1.14, (Reference 1) to describe acceptable methods to ensure RCP flywheel integrity. Under Section C of the regulatory guide, the NRC Regulatory position is defined. This portion of the regulatory guide is provided below.

*1. Material and Fabrication*

*a. The flywheel material should be of closely controlled quality. Plates should conform to ASTM A20 and should be produced by the vacuum-melting and degassing process or the electroslag remelting process. Plate material should be cross-rolled to a ratio of at least 1 to 3.*

*b. Fracture toughness and tensile properties of each plate of a flywheel material should be checked by tests that yield results suitable to confirm the applicability to that flywheel of the properties used in the fracture analyses called for in regulatory positions C.2.c, d, and e.*

*c. All flame-cut surfaces should be removed by machining to a depth of at least 12 mm (1/2 inch) below the flame cut surface.*

*d. Welding, including tack welding and repair welding, should not be permitted in the finished flywheel unless the welds are inspectable and considered as potential sources of flaws in the fracture analysis.*

*2. Design*

*a. The flywheel assembly, including any speed-limiting and antirotation devices, the shaft, and the bearings, should be designed to withstand normal conditions, anticipated transients, the design basis loss-of-coolant accident, and the Safe Shutdown Earthquake loads without loss of structural integrity.*

*b. Design speed should be at least 125% of normal speed but not less than the speed that could be attained during a turbine overspeed transient. Normal speed is defined as synchronous speed of the a.c. drive motor at 60 hertz.*

*c. An analysis should be conducted to predict the critical speed for ductile failure of the flywheel. The methods and limits of paragraph F-1323.1(b) in Section III of the ASME Code are acceptable. If another method is used, justification should be provided. The analysis should be submitted to the NRC staff for evaluation.*

d. *An analysis should be conducted to predict the critical speed for nonductile failure of the flywheel. Justification should be given for the stress analysis method, the estimate of flaw size and location, which should take into account initial flaw size and flaw growth in service, and the values of fracture toughness assumed for the material. The analysis should be submitted to the NRC staff for evaluation.*

e. *An analysis should be conducted to predict the critical speed for excessive deformation of the flywheel. The analysis should be submitted to the NRC staff for evaluation. (Excessive deformation means any deformation such as an enlargement of the bore that could cause separation directly or could cause an unbalance of the flywheel leading to structural failure or separation of the flywheel from the shaft. The calculation of deformation should employ elastic-plastic methods unless it can be shown that stresses remain within the elastic range).*

f. *The normal speed should be less than one-half of the lowest of the critical speeds calculated in regulatory positions C.2.c, d, and e above.*

g. *The predicted LOCA overspeed should be less than the lowest of the critical speeds calculated in regulatory positions C.2.c, d, and e above.*

3. *Testing*

*Each flywheel assembly should be spin tested at the design speed of the flywheel.*

4. *Inspection*

a. *Following the spin test described in regulatory position C.3, each finished flywheel should receive a check of critical dimensions and a nondestructive examination as follows:*

(1) *Areas of higher stress concentrations, e.g. bores, keyways, splines, and drilled holes, and surfaces adjacent to these areas on the finished flywheel should be examined for surface defects in accordance with paragraph NB-2545 or NB-2546 of Section III of the ASME Code using the procedures of paragraph NB-2540. No linear indications more than 1.6 mm (1/16 inch) long, other than laminations, should be permitted.*

(2) *Each finished flywheel should be subjected to a 100% volumetric examination by ultrasonic methods using procedures and acceptance criteria specified in paragraph NB-2530 (for plates) or paragraph NB-2540 (for forgings) of Section III of the ASME Code.*

*b. Inservice inspection should be performed for each flywheel as follows:*

*(1) An in-place ultrasonic volumetric examination of the areas of higher stress concentration at the bore and keyway at approximately 3 year intervals during the refueling or maintenance shutdown coinciding with the inservice inspection schedule as required by Section XI of the ASME Code.*

*(2) A surface examination of all exposed surfaces and complete ultrasonic volumetric examination at approximately 10 year intervals, during the plant shutdown coinciding with the inservice inspection schedule as required by Section XI of the ASME Code.*

*(3) Examination procedures should be in accordance with the requirements of Subarticle IWA-2200 of Section XI of the ASME Code.*

*(4) Acceptance criteria should conform to the recommendations of regulatory position C.2.f.*

*(5) If the examination and evaluation indicate an increase in flaw size or growth rate greater than predicted for the service life of the flywheel, the results of the examination and evaluation should be submitted to the staff for evaluation.*

# APPENDIX B

## HISTORICAL INSPECTION INFORMATION: HADDAM NECK

The following chronological listing shows the results of reactor coolant pump flywheel inspections at the Haddam Neck Plant:

**1970** - Prior to the April 1970 refueling outage, **Westinghouse** and the AEC, became concerned about the possibility of cracks being initiated at or propagating from the interior corners of the keyway areas in RCP flywheels. **Ultrasonic examinations** were performed during the refueling outage on all four RCP flywheels and **revealed a <5% amplitude indication on RCP flywheel #4 in the bore keyway area** and it was not recordable. The indication was recorded by Westinghouse personnel purely for future reference purposes.

**RCP flywheel #1 was liquid penetrant inspected** in the bore area after it had been removed from the shaft and **no indications were observed**.

**Total radiation exposure for** these **first inspections was 1.038 Person REM and** included examination technicians, and engineering and maintenance personnel. This amount of **personnel radiation exposure has continued to be expended to complete these inspections** when they were required **during the last 25 years**.

**1971** - In April 1971, the Inservice **Inspection** Program Requirements of ASME Section XI, were put into the Plant Technical Specifications. **Requirements were** additionally **added for RCP flywheels,** outside of Section XI Requirements, based on AEC request.

Technical Specification Requirement - One different flywheel shall be examined visually and 100% volumetrically at every other refueling shutdown.

The AEC requested that **all four flywheels** be **examined at** the next **refueling outage** before this inspection sampling program could be put into effect.

During the **May 1971** refueling outage, all four flywheels were inspected. The **bore seal weld area of RCP flywheel #4 was found to be cracked**. The cracks were identified in the bore seal weld and it's associated heat affected zone. Cracked areas were **removed by grinding and weld repaired**.

Review of the inspection data shows that these **cracks may have been identified** by the ultrasonic examination indication reported **in 1970,** but the data is not conclusive. One point that does stand out is that the **material of** the **RCP flywheel #4 is** Grade T-1 Boiler Plate and is **different** than the other three flywheels which were fabricated to a Westinghouse specification.

**1973** - During the 1973 refueling outage, the **inspection sampling program** now required by Plant Technical Specifications **began**. RCP flywheels #1 and #4 were examined. Both flywheels were removed from their shafts. **Cracks** were **discovered in the RCP flywheel #4** bore seal weld area **emanating from** the **weld repairs and** in the **existing seal weld areas.**

Westinghouse was contacted and recommended that the **bore seal weld and** associated **heat affected zone** be **removed by grinding**. Ultrasonic and liquid penetrant examinations were performed following the grinding repair and no indications were identified. Additionally, liquid penetrant examinations were performed in the bore pawl areas of both RCP flywheels. Liquid penetrant **indications** were **identified in RCP flywheel #1** at two **bore pawl areas**. These indications were determined to be from mechanical surface marks and were dispositioned as acceptable.

**1980 to 1986** - During this time frame **inspections continued** under the sampling program provided in Plant Technical Specifications with continuing efforts by CYAPCO **to meet a request by** the **NRC to comply with** the inspection requirements specified in **Regulatory Guide 1.14.** **No further flaws/cracks** were **identified** in any of the flywheels. In 1980, one of the flywheels had liquid penetrant indications in the bore keyway areas, but were once again determined to be from mechanical surface marks and dispositioned as acceptable.

**1986** - **Plant Technical Specifications** were **changed** under Amendment No. 87 **to** specifically **include** reference to **Regulatory Guide 1.14 inspection requirements.**

**1987** - During this refueling outage **all four** of the **RCP flywheels** were completely removed from the motors and **sent to Westinghouse for a 10-year refurbishment**. RCP flywheel #1 and #2 were examined to the requirements of Regulatory Guide 1.14 and magnetic particle **indications** were **found in** the **seal baffle surface fillet weld area** of **RCP flywheel #2**. These indications/flaws/cracks were **removed by grinding, weld repaired** and **reinspected** until **no indications** were found. RCP flywheel #3 was not required to be inspected per Regulatory Guide 1.14 requirements. The **RCP flywheel #4 bore seal weld area** that had been ground out in 1973 was **machined smooth,** liquid penetrant inspected, and no indications were observed.

**1988 to Present** - **No cracks** have been **identified** on any of the RCP flywheels **in** the **critical areas** of the bore and keyways **since 1973.**

**No cracks have exceeded the critical flaw size** needed **to cause a** catastrophic **failure** of our flywheels in a normal operating overspeed condition.

**All** of the **1973 RCP flywheel #4 cracks were of a limited depth** approximately 1/2" deep **and the bore seal weld and heat affected zone is now totally removed.**

Note: Additional details are available in Docket No. 50-213, B15320, dated August 10, 1995.

# APPENDIX C

## SAMPLE FLYWHEEL INSPECTION PROCEDURES

NORTHEAST UTILITIES

NUCLEAR QUALITY-RELATED
NONDESTRUCTIVE EXAMINATION PROCEDURES

NU-UT-24

Ultrasonic Examination
Reactor Coolant Pump Flywheel
Connecticut Yankee

| Rev | Issue Date | NUSCO Level III Approval/Date | Director QSD Approval/Date | Auth. Insp. Agency Approval/Date |
|---|---|---|---|---|
| 5 | 11/29/88 | R. J. Fuller-10/12/88 | B. Kaufman-10/18/88 | R. L. Zoner-10/28/88 |
| 6 | 1-4-91 | R J Fuller 6/4/90 | B. Kaufman 6/14/90 | [illegible] 11/8/90 |
| 7 | 4-20-93 | [illegible] 4/5/93 | B. Kaufman 4/12/93 | [illegible] 4.15.93 |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

Always verify with the procedure Status Log before using this procedure.

ULTRASONIC EXAMINATION
REACTOR COOLANT PUMP FLYWHEEL
CONNECTICUT YANKEE

# 1. SCOPE

## 1.1 INTENT

This procedure shall be used in conjunction with Procedure NU-UT-1 unless otherwise specified. NU-UT-1 contains all the general requirements applicable to this examination procedure. This procedure contains all the specific application requirements for the examination of areas specified in paragraph 1.2.

## 1.2 AREAS OF EXAMINATION

This document covers the ultrasonic examination procedure for the bore and keyway areas and the remaining volume of the Connecticut Yankee reactor coolant pump (RCP) flywheels.

## 1.3 TYPE OF EXAMINATION

1. Volumetric examination shall be performed using ultrasonic pulse echo 0° and 3½° beam technique applied to the gage holes in the flywheel.

2. The examinations shall be performed manually using contact search units.

# 2. REFERENCES

1. NU-UT-1 Ultrasonic Examination General Requirements.

2. Calibration block CYW-47. 7

3. Nuclear Regulatory Commission Guide 1.14.

4. ASME Section XI Code - IWA 2240.

# 3. PROCEDURE CERTIFICATION

The examination procedure described in this document is in conjunction with Procedure NU-UT-1 and complies with Section XI of the ASME Boiler and Pressure Code, 1983 Edition, Summer of 1983 Addenda, except where examination coverage is limited by part geometry or access.

# 4. PERSONNEL CERTIFICATION

1. Each person performing ultrasonic examination governed by this procedure shall be certified in accordance with Procedure NU-UT-1.

## 5. EXAMINATION REQUIREMENTS

### 5.1 EXAMINATION FREQUENCY

The nominal examination frequency shall be 5 MHz. Other frequencies may be used if such variables as materials, attenuation, grain structure, etc., necessitates their use to achieve penetration or resolution.

### 5.2 EXAMINATION ANGLES AND COVERAGE

1. The bore and keyways and the remaining accessible volume of the RCP flywheel shall be examined using special design 0° and 3½° azimuth probes. Coverage will be limited to those areas of the flywheel that can be scanned from the four gage hole probes in each flywheel.

2. Other angles and techniques may be used if required for aid in evaluating indications.

## 6. EQUIPMENT REQUIREMENTS

### 6.1 EXAMINATION EQUIPMENT

The following test equipment or its equivalent shall be provided for examinations specified in this procedure.

1. Special design azimuth probes

2. Couplant

## 7. EXAMINATION SYSTEM CALIBRATION

7.1 Calibration using the .920" diameter azimuth probe shall be performed as follows:

1. Fully insert the .920" diameter transducer and set the 0° on the azimuth to coincide with the axial centerline and facing the bore of the flywheel calibration block.

2. Inject couplant and establish acoustic contact.

3. Set the amplitude of the reflection from the bore to 100% full screen height.

4. Rotate transducer counterclockwise, CCW, through 90° and locate the ¼" diameter through drilled hole. Adjust gain if necessary.

5. Using the sweep control, establish a 20" sweep on the display by placing the signal from the sidewall at 5.75" along the timebase. Return to the bore signal and place this at 10" on the timebase.

Through the use of the sweep control and delay control, repeat the above procedure until the display is as described above.

6. <u>Sensitivity:</u> Rotate the transducer to locate the signal from the number one ¼" diameter thru hole, see Figure 1, and adjust signal amplitude from this reflector to 80% FSH. Rotate transducer to locate signal from the number two ¼" diameter thru hole and record % FSH. Draw DAC curve between two points obtained from holes #1 and #2. Rotate transducer to notch in flywheel keyway and record % FSH. If the CRT is saturated, record the dB difference to bring notch signal to 80% FSH.

7. <u>Attenuation:</u> Locate the signal from the bore of the CYW-47 and adjust the amplitude to 80% FSH and note the gain setting. Locate the signal from the bore of the flywheel and set the signal to 80% FSH and record the gain setting. The difference between the gain setting on the calibration block and flywheel must be added or subtracted to the instrument settings for calibration to account for any attenuation differences between the calibration block and the flywheel.

8. Repeat the above calibration steps for the .721" diameter and 3¼° aziumth probe.

9. Upon completion of the calibration, ensure that all data and instrument settings are recorded on the appropriate calibration data sheet (NU-UT-1, Figure 6).

## 7.2 <u>CALIBRATION CHECKS</u>

Calibration checks shall be performed in accordance with Procedure NU-UT-1.

## 8. EXAMINATION PROCEDURES

1. Insert .920" diameter azimuth probe into gage holes on the RCP flywheel and examine bore and keyway to maximum extent possible.

2. Insert .721" diameter azimuth probe into gage holes on the RCP flywheel and examine bore and keyway to the maximum extent possible.

3. Insert the 3¼° angle beam azimuth probe so that the transducer just clears the threaded portion of the gage hole. Examine the bore and keyway to maximum extent possible.

## 9. RECORDING CRITERIA

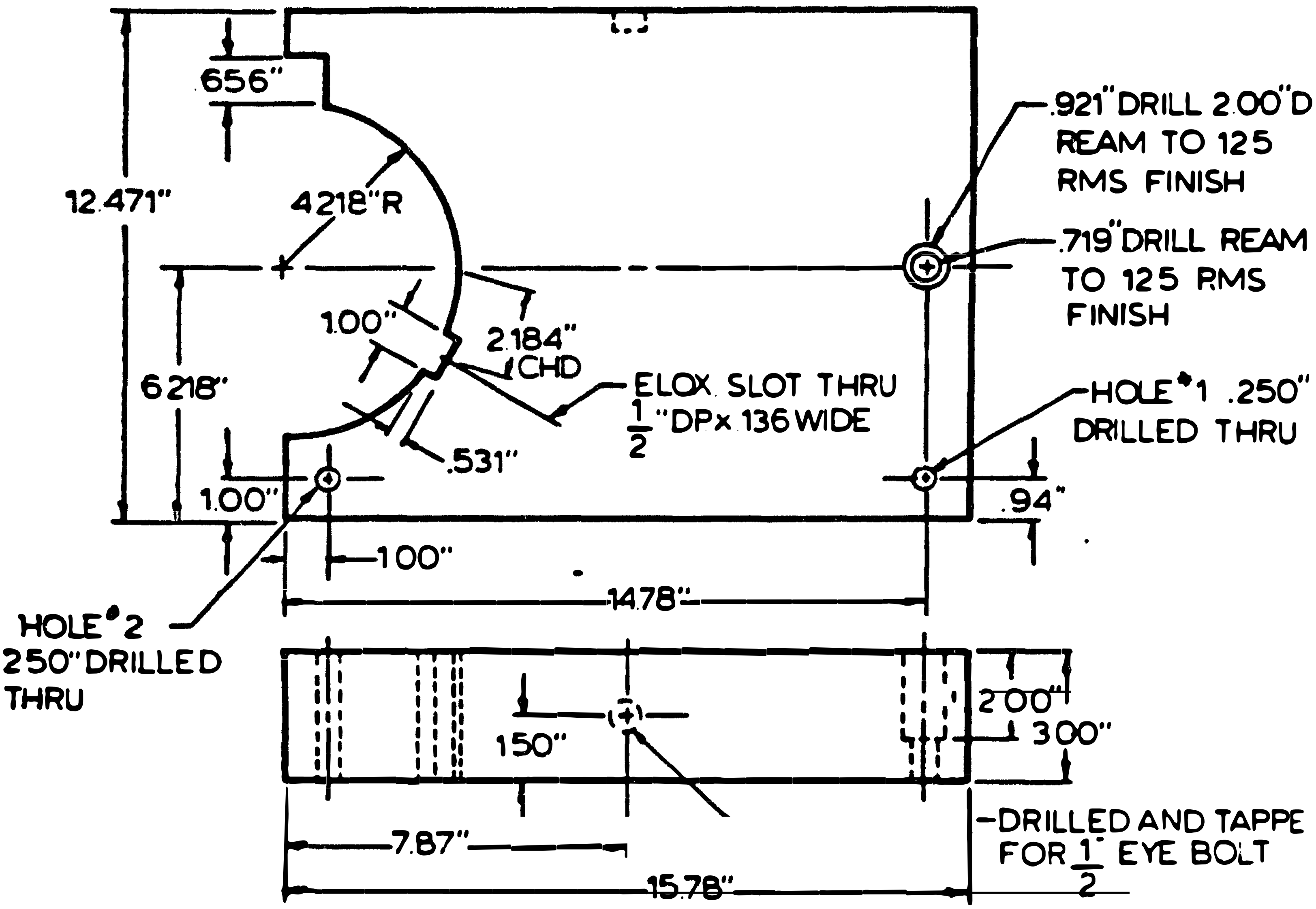
1. All indications with a signal amplitude >100% DAC at reference level shall be recorded and investigated to ensure proper evaluation.

2. The reference point for recording all indications shall be as follows: Looking down at the top surface of the flywheel, locate all indications clockwise, CW, from the gage hole in line with the largest keyway in the flywheel. All radial and angular measurements to recordable indications shall be taken from the exit point of the

probe. A sketch of all recordable indications shall be attached to the RCP flywheel data sheet.

FIGURE 1

# CALIBRATION BLOCK
# CYW-47



REVISION/CHANGE ATTACHMENT SHEET

| Revision | Section | Change |
|---|---|---|
| 5 | All | Major Rewrite |
| 6 | All | Major Rewrite |
| 7 | Para. 2.2 | Change Blocks to Read "Block" |
| | Para. 7.1.6 | Correct Typo |
| | Para. 7.1.7 | Reword 1st Sentence |
| | Para. 7.1.8 | Change 7.6.1 to Read "7.2.1" |

SOUTHERN NUCLEAR OPERATING COMPANY

INSPECTION AND TESTING SERVICES

# MANUAL ULTRASONIC EXAMINATION OF REACTOR COOLANT PUMP MOTOR FLYWHEELS

UT-V-417

REVISION 3

PREPARED BY

SUPERVISOR, NDE PROJECTS APPROVAL

NDE LEVEL III APPROVAL

MANAGER ITS APPROVAL

PLANT VOGTLE APPROVAL

1/11/95

DATE

# TABLE OF CONTENTS

## .0 PURPOSE

This procedure provides the ultrasonic examination requirements for reactor coolant pump flywheel in accordance with the applicable American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code.

## 2.0 SCOPE

This procedure defines the method for ultrasonic examination reactor coolant pump flywheel to facilitate preservice and inservice inspection all high-stress regions (bore, keyways and bolt hole regions) with or without the removal of the flywheel from its shaft.

Note: Applications in this procedure are not covered in Section XI and are based on special techniques as allowed in IWA-2240.

## 3.0 APPLICABLE DOCUMENTS

This procedure is written to comply with the requirements of the following documents to the extent specified within this procedure.

3.1 ASME Boiler and Pressure Vessel Code, Section XI, 1983 Edition with Addenda through Summer 1983, "Rules for Inservice Inspection of Nuclear Power Plant Components."

3.2 ASME Boiler and Pressure Vessel Code, Section V, 1983 Edition with Addenda through Summer 1983, "Nondestructive Examination."

3.3 U. S. Nuclear Regulatory Commission Regulatory Guide 1.14 "Reactor Coolant Pump Flywheel Integrity" Revision 1 dated August 1975.

## 4.0 RESPONSIBILITIES

4.1 The Manager- Inspection and Testing Services shall be responsible for the approval and control of this procedure.

4.2 An ITS NDE Level III individual certified in ultrasonic examination is responsible for having ultrasonic procedures and techniques developed, approved, and for assuring that this procedure, when correctly followed, will detect discontinuities which do not meet the applicable acceptance standards.

## 5.0 QUALIFICATION OF ULTRASONIC EXAMINATION PERSONNEL

5.1 All personnel performing ultrasonic examinations in accordance with this procedure shall be qualified and certified to the requirements of a procedure (written practice) written and approved by ITS in accordance with the "American Society of Nondestructive Testing" (ASME) SNT-TC-1A.

5.2 The ultrasonic examination may be performed by a Level I Examiner under the direct supervision of a certified Level II or Level III individual in ultrasonic examination; however, all interpretation of the results shall be performed by a Level II or Level III examiner certified in ultrasonic examination.

## 6.0 ULTRASONIC EQUIPMENT

6.1 The Ultrasonic Instrument

6.1.1 A pulse-echo type ultrasonic instrument with an A-Scan presentation and operating frequencies of one to ten MHz shall be used to perform examination in accordance with this procedure.

6.2 The Ultrasonic Transducer Search Unit

6.2.1 Search units with a nominal frequency of 2.25 MHz shall be used for examination in accordance with this procedure.

6.2.2 Search unit size for the "periphery" scan shall be .750" to 1.00" diameter straight beam.

6.2.3 Search unit size and configuration for "radial gauge hole" and "keyway corner" examination will be a special design internal probe from the gauge hole.

6.2.4 Upon ITS NDE Level III concurrence, other frequencies and sizes of search units may be used if product grain structure precludes achieving the necessary penetration or sensitivity required.

6.3 Couplant

Any commercially available ultrasonic couplant may be used and shall be certified for total sulfur and halogen content in accordance with the American Society for Testing and Materials (ASTM) D-129 and D0808. The total residual amount of sulfur and halogen shall not exceed one percent by weight.

6.4 Reference Block

Reference blocks (e.g., IIW, ROMPAS, DSC) if used, shall be of the same material as the component to be examined.

6.5 Calibration Block

The flywheel to be examined shall be used for calibration.

6.6 CABLES

Coaxial type cables shall be used and may be of any convenient length not to exceed 50 feet (unless permitted by qualification). The type and length shall be recorded on the Reactor Coolant Pump Flywheel Report, (Figure 417-1), or equivalent form.

## 7.0 SURFACE PREPARATION

The finished contact surface shall be free from any roughness that would interfere with free movement of the search unit. This examination and calibration may be performed through tightly adhered paint.

## 8.0 EQUIPMENT CALIBRATION

8.1 A daily linearity, as a minimum, shall be performed to verify the instrument to linearity requirements of Procedure UT-V-455.

8.2 The reject control shall be placed and remain in the "0" (off or minimum) position during calibration and examination.

8.3 Temperature of the flywheel shall be recorded on the Data Report.

8.4 The equipment calibration shall be performed in accordance with the following and the results documented on the Reactor Coolant Pump Flywheel Report, (Figure 417-1), or equivalent form.

8.4.1 Keyway Corner Examination

8.4.1.1 Reflections from the bore of the flywheel shall be used for calibration.

8.4.1.2 From the gauge hole, obtain the maximum reflection from the bore of the flywheel using the special gauge hole probe.

8.4.1.3 Establish a horizontal screen range by setting the response from the flywheel bore at a maximum of 60 percent of the instruments screen range.

8.4.1.4 Bring the bore reflection to 80% FSH. This shall be the primary reference level.

8.4.2 Radial Gauge Hole Examinations

8.4.2.1 Reflections from any two holes shall be used for calibration. The hole selected for the longest metal path shall be a maximum of 25 inches.

8.4.2.2 From the hole, obtain the maximum response from the nearer of the two holes. Set this response at 80% FSH.

8.4.2.3 Without changing the gain setting, obtain the maximum response from the remaining hole.

8.4.2.4 Mark these amplitudes on the CRT. Connect the two points with a smooth line. Extend the DAC to cover the maximum calibrated screen width. This shall be the primary reference level.

8.4.3 Periphery Examination

8.4.3.1 From the edge of the flywheel, obtain the maximum response from any two holes with a minimum of 10 inches metal path separation.

8.4.3.2 Establish the horizontal screen range to coincide with the hole location from the edge of the plate. The response obtained from the hole with the greatest metal path shall be set between 50-80 percent of screen range.

8.4.3.3 Construct a DAC curve by setting the maximum response from the hole with the shortest metal path at 80% FSH.

8.4.3.4 Without changing the gain setting, obtain the maximum response from the hole with the greatest metal path. Mark these points on the CRT and connect them with a smooth line to cover the examination area. This shall be the primary reference level.

8.5 Calibration Checks

8.5.1 A calibration check shall be performed at the beginning and end of each examination or every 12 hours, whichever is less.

8.5.2 If, in the opinion of the examiner, the validity of the calibration is in doubt, a calibration check shall be performed.

8.5.3 If any point of the calibration check has moved on the sweep line by more than 10 percent of the sweep division reading, correct the sweep range calibration and note the correction on the applicable calibration sheet. If recordable indications are noted, the examination is voided, and a new calibration Section 8.0) shall be recorded and the voided examination shall be reexamined.

8.5.4 If any point of the calibration check has decreased 20 percent or 2 dB of its amplitude, all data and/or calibration sheets since the last calibration or calibration check shall be recorded and the voided examinations shall be reexamined.

8.5.5 If any points of the calibration check was increased more than 20 percent or 2 dB of its amplitude, all recorded indications since the last valid calibration or calibration check may be reexamined with the corrected calibration and their value shall be recorded on the applicable calibration and data sheet.

## 9.0 EXAMINATION PROCEDURE

### 9.1 Keyway Corner Examination

9.1.1 Scanning of the keyway corners shall be accomplished starting at the top of the gauge hole and rolling the sound beam from the bore over to examine the keyway and back. Insert the probe with a minimum of 25% overlap and repeat until the entire length of the keyway has been examined.

9.1.2 Each gauge hole shall be used to examine the keyway corners for indications propagating from the keyway.

### 9.2 Radial Gauge Hole Examination

9.2.1 Scanning shall be accomplished by inserting and retracting the probe the full length of the gauge hole and overlapping a minimum of 25% for each insertion.

9.2.2 Each gauge hole shall be used to scan the complete available portion of the flywheel cross-section.

9.3 Periphery Examination

9.3.1 Scanning from the edge shall include the area from the edge up to and including the gauge holes.

9.3.2 The transducer shall be moved across and along the flywheel edge so as to scan the entire edge overlapping each scan by a minimum of 25% of the transducer diameter.

9.4 Scanning speed shall not exceed six inches/second.

9.5 Scanning shall be performed at a minimum gain setting of two times the primary reference level sensitivity (6 dB).

NOTE:

If conditions such as material properties produce noise levels which preclude a meaningful examination, then scanning shall be performed at the highest possible sensitivity level above the primary reference level. The examiner shall note the dB and the reason on the applicable data sheet and notify the site NDE coordinator to proceed per the applicable ITS PM Procedure 2-1.

9.6 Upon completion of the ultrasonic examination, the couplant shall be removed from the area of examination to the extent practical.

## 10.0 INVESTIGATION OF INDICATIONS

10.1 All indications shall be investigated to the extent that the examiner can determine the size, identify and location of the reflectors.

10.2 Previous data, when applicable, shall be made available to the technicians to provide previous examination information.

## 11.0 RECORDING OF INDICATIONS

11.1 For the keyway corner examination, all indication which exceed 10% of the primary reference level shall be recorded.

11.2 For the radial gauge hole or periphery examinations, all indications which exceed 50% DAC shall be recorded.

NOTE:

Geometric reflectors in the flywheel shall be verified by physical measurements and need not be recorded.

## 12.0 REPORTING INDICATIONS

12.1 It shall be the responsibility of the Level II or level III individual certified in ultrasonic examination re review, evaluate the disposition all recordable indications to determine their reportability requirements. Previous data shall be made available to the reviewer/evaluator for appropriate indication disposition.

12.2 Reportable indications or other indications determined to be significant by the ITS Level II or level III individual shall be reported to the operating company in accordance with ITS PM Procedure 3-4.

| VOGTLE ELECTRIC GENERATING PLANT<br>Reactor Coolant Pump Flywheel Report | Southern Nuclear Operating Company<br>UT-V-Form 015 |
|---|---|
| Plant/Unit: | RCP Flywheel No: |
| Isometric Drawing No: | Procedure/Revision/Deviation: |
| Couplant Batch No: | Sheet No: |

**Transducer** | **Periphery Exam** | **Gauge Hole & Keyway Exam**

| Transducer | Periphery Exam | Gauge Hole & Keyway Exam |
|---|---|---|
| Serial No: | ____ | ____ |
| Size: | ____ | ____ |
| Frequency: | ____ | ____ |

Equipment

Instrument: ____ Frequency: ____ Damping: ____

Serial No: ____ Rep. Rate: ____ Reject: ____

Cable Type: ____ Cable Length: ____

Calibration/Examination

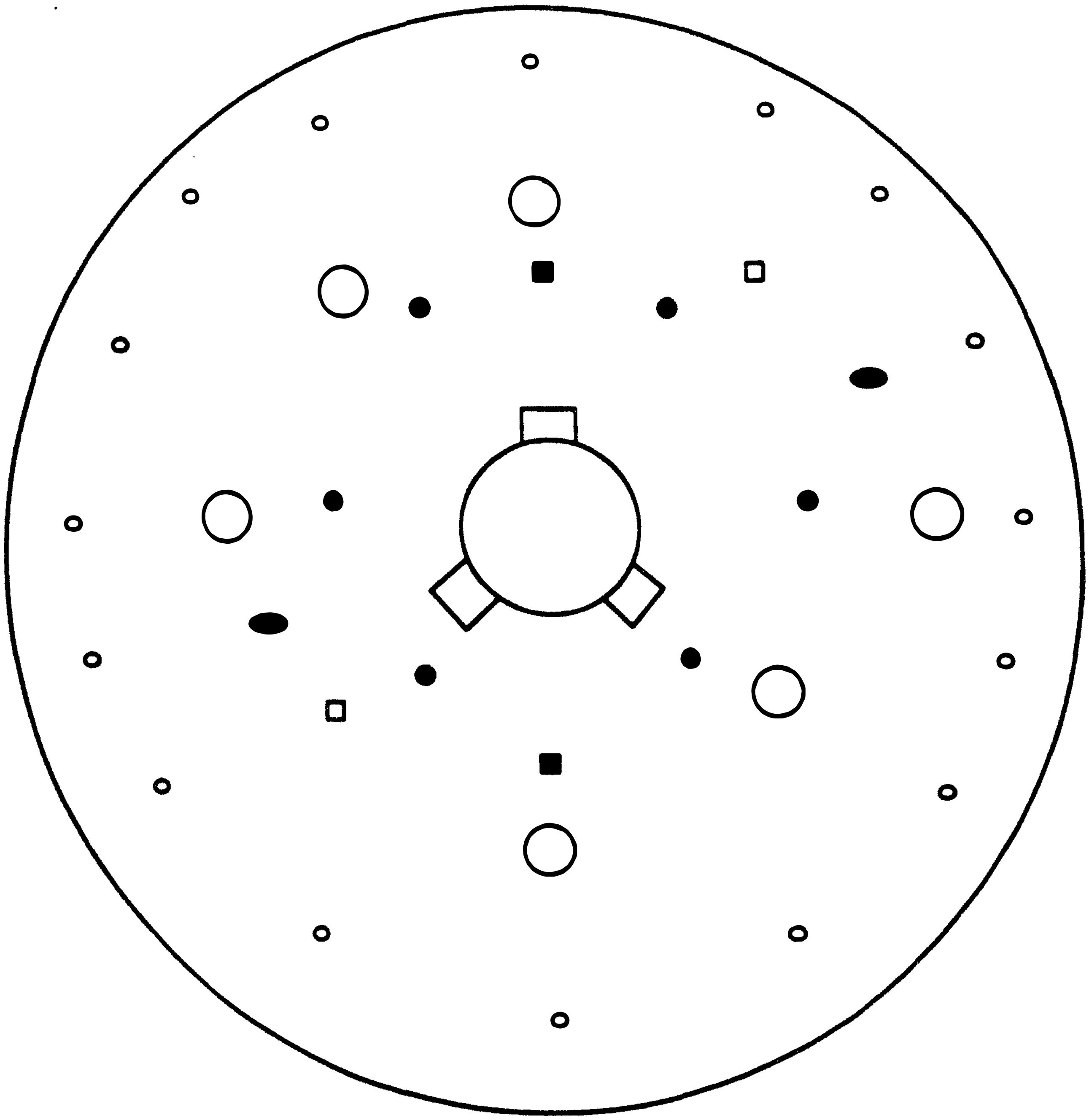
| Region | | | |
|---|---|---|---|
| Keyway Corner | Screen Range: | ____ | % FSH |
| | dB: | ____ | |
| | Screen Div: | ____ | NI __ NRI __ RI __ |
| Bolt Hole Region | Screen Range: | ____ | |
| | dB: | ____ | |
| | Screen Div: | ____ | NI __ NRI __ RI __ |
| Periphery | Screen Range: | ____ | |
| | dB: | ____ | |
| | Screen Div: | ____ | NI __ NRI __ RI __ |

Remarks: ____

| Examiner/SNT Level: | Examiner/SNT Level: |
|---|---|
| Technical Review: | Non Technical Review: |

Figure 417-1

Vogtle Reactor Coolant
Pump Flywheel



3/4" x 3-3/4"

1-3/8" x 5"

1-1/2" x 3-3/4"

1" x 10"

2" x 1-7/8"

3" x 10"

Figure 417-2

| GPU Nuclear | GPU NUCLEAR<br>ISI/NDE MANUAL | Number<br>5361-NDE-7209.24. |
|---|---|---|
| Title<br>ULTRASONIC EXAMINATION OF REACTOR COOLANT PUMP FLYWHEELS | | Revision No.<br>0 |
| Applicability/Scope<br>This procedure is applicable a[illegible]y site | | Responsible Office<br>5361 |
| This document is within QA Plan Scope X Yes __ No<br>Safety Reviews Required X Yes __ No | | Effective Date<br>08-15-95 |

List of Effective Pages

| Page | Revision | Page | Revision |
|---|---|---|---|
| 1.0 | 0 | E1-1 | 0 |
| 2.0 | 0 | E2-1 | 0 |
| 3.0 | 0 | E3-1 | 0 |
| 4.0 | 0 | E4-1 | 0 |
| 5.0 | 0 | E5-1 | 0 |
| 6.0 | 0 | E6-1 | 0 |
| 7.0 | 0 | E7-1 | 0 |
| 8.0 | 0 | | |
| 9.0 | 0 | | |
| 10.0 | 0 | | |
| 11.0 | 0 | | |
| 12.0 | 0 | | |
| 13.0 | 0 | | |

TMI-1

GPU N DOCUMENT CONTROL COPY #10

This procedure replaces 6100-QAP-7209.24.

| | Signature | Concurring Organizational Element | Date |
|---|---|---|---|
| Originator | [signature] | NDE/ISI Specialist | 7-25-95 |
| Concurred By | [signature] | Level III | 7-28-95 |
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| Approved By | [signature] | Chemistry/Materials Director | 8/1/95 |
| | | | |

| GPU Nuclear | GPU NUCLEAR ISI/NDE MANUAL | Number 5361-NDE-7209.24 |
|---|---|---|
| Title Ultrasonic Examination of Reactor Coolant Pump Flywheels | | Revision No. 0 |

## DOCUMENT HISTORY

| Revision | Summary of Change | Date |
|---|---|---|
| 0 | Original Revision. This procedure replaces 6100-QAP-7209.24. | 08-15-95 |

TABLE OF CONTENTS

1.0 **PURPOSE**

1.1 The purpose of this procedure is to describe the techniques for manual ultrasonic examination of TMI-1 Reactor Coolant pump motor assembly flywheels.

2.0 **APPLICABILITY/SCOPE**

2.1 This procedure is applicable to all certified GPUN and contractor personnel assigned by GPUN to perform manual ultrasonic examination of reactor coolant pump flywheels.

2.2 The requirements of this procedure delineate the manual ultrasonic techniques to detect. locate and dimension indications in the reactor coolant pump motor assembly flywheels in accordance with Reference 6.2

3.0 **DEFINITIONS**

3.1 None.

4.0 **PROCEDURE**

4.1 Personnel Qualification and Certification

4.1.1 GPUN personnel performing examinations to this procedure shall be certified in accordance with Reference 6.3.

4.1.2 Contractor personnel performing examinations to this procedure shall be qualified and certified in accordance with the Contractor's written practice which has been approved by GPUN or they may be certified in accordance with Reference 6.3.

4.1.3 At least one member of the examination crew shall be certified Level II UT inspector or higher.

4.1.4 The examination crew should demonstrate practical proficiency in applying the technical requirements of this standard to a GPUN UT Level III.

4.2 Material/Equipment

4.2.1 Flaw detector

4.2.1.1 A pulse echo ultrasonic flaw detection instrument capable of generating frequencies from 1.0 to 5.0 MHZ shall be utilized. The instrument shall contain a stepped gain control, calibrated in units of 2db or less, and shall be accurate over its useful range to ±0% of the nominal amplitude ratio which will allow comparison of indications beyond the viewable portion of the CRT.

4.2.2 Search units

4.2.2.1 Angle beam and straight beam search units shall be single element with a nominal frequency of 2.25 MHZ. Other frequencies may be used to overcome variables caused by material properties and for purposes of evaluation of indications. Use of other frequencies shall be approved by a GPUN UT Level III and recorded on Exhibit 1.

4.2.2.2 Examinations shall be performed utilizing a 45° beam angle for flywheels #1 and #4 from the top and bottom surfaces respectively.

4.2.3 Angle beam exit point/angle verification

4.2.3.1 Prior to performance of examinations the exit point of the search unit wedge (angle beam) shall be verified utilizing a standard IIW block or mini-IIW block. This verification shall be performed daily prior to any examinations being performed.

4.2.3.2 Prior to performance of examinations, the actual beam angle shall be determined utilizing a carbon steel IIW block or mini-IIW block. This shall be done to verify that the beam angle is within the required range of ±° of the nominal angle of the search unit wedge. This verification shall be performed daily prior to any examinations being performed. The actual angle and nominal angle of the search unit wedge shall be recorded on Exhibit 1.

4.2.4 Coaxial cables

4.2.4.1 Coaxial cable assembly shall be of any convenient length not to exceed 50 feet.

4.2.5 Couplant

4.2.5.1 Any GPUN approved couplant, such as Ultragel II, which provides intimate contact required for the transmission of high frequency ultrasound shall be acceptable for use. Use of couplant shall be as required by reference 6.8.

4.2.5.2 The minimum amount of couplant should be utilized to prevent damage to the motor windings.

4.2.5.3 Couplant shall be removed from the flywheels after completion of the examinations.

4.2.6 Calibration standard

4.2.6.1 The pump motor assembly flywheels have calibration holes as shown in Exhibits 3 and 4. These holes may be utilized for the initial calibration if directed by a GPUN UT Level III. Flywheel Calibration Standards TMI 370 (Flywheel #1) and TMI 371 (Flywheel #4) shall be used to establish the sweep range of the instrument and DAC curve. To establish the primary sensitivity level for examination, the transfer method, which is outlined in paragraph 4.4.3.6, shall be performed when using calibration standards.

4.3 Prerequisites

4.3.1 Surface preparation

4.3.1.1 Surfaces to be examined shall be clean and free of foreign material which could interfere with the performance of the examination or conduction of sound energy into the part.

> **NOTE**
> Precautions shall be taken to prevent loose parts from falling into motor flywheel assemblies whenever access is gained to the flywheels.

4.3.2 Examination records

4.3.2.1 Baseline and subsequent examination records should be available for review.

4.3.3 Maintenance and Operation Preparation

4.3.3.1 Operation of the flywheel motor lift pumps shall be coordinated with the control room. The motor lift pumps must be energized before the flywheels can be rotated.

4.3.3.2 The oil drip pan should be removed for access to the lower flywheel.

4.4 Calibration

4.4.1 Instrument calibration

4.4.1.1 Instrument calibration for screen height, horizontal and amplitude control linearity shall be in accordance with References 6.4.

4.4.1.2 For instruments and search units, maintenance, calibration and performance characteristics shall be as required by reference 6.9.

4.4.2 System calibration

4.4.2.1 Calibration shall include the complete ultrasonic examination system. Any change in search units, shoes, couplants, cables, ultrasonic instruments, recording devices or any part of the examination system shall be cause for a calibration check. The calibration shall be performed on flywheel calibration standards and the transfer method identified in paragraph 4.4.3.6 shall be performed.

4.4.2.2 The maximum reflector response, during calibration, shall be obtained with the sound beam oriented essentially perpendicular to the axis of the calibration reflector. The centerline of the search unit shall be a minimum of 3/4" from the nearest edge of the calibration standard. Rotation of the sound beam into a corner formed by the reflector and the side of the block may produce a higher amplitude signal at a longer beam path; this beam path shall not be used for calibration.

4.4.2.3 The temperature difference between component to be examined and the basic calibration block shall not exceed 25°F.

4.4.2.4 The transfer method as described elsewhere in this procedure may be omitted by a GPUN Level III if there is reason to question the reliability of the results or if unobtainable.

4.4.3 45° angle beam calibration

4.4.3.1 Calibration shall be performed on Calibration Standard TMI-370 for flywheel #1 and TMI-371 for flywheel #4. Side drilled holes (SDH) are present in each flywheel as identified in Exhibits 3 and 4, however, only the 1/2T SDHs shall be utilized for the transfer method.

> **NOTE**
> Calibration may be performed directly on the flywheel but only as directed by a GPUN UT Level III.

4.4.3.2 To determine the 45° angle beam sweep calibration on flywheel #1, utilize Calibration Standard TMI-370 and place the bottom notch at the 4.2 screen position and the top notch at 8.4. The instrument sweep is now calibrated to represent 10" of metal path.

4.4.3.3 On Calibration Standard TMI-370 for Flywheel #1, establish a DAC curve by adjusting the gain to set the bottom notch signal at 80% ± % FSH at screen position 4.2. Without changing gain, peak the top notch signal at screen position 8.4 and mark the location on the screen. Plot a DAC curve by connecting the peak signal locations (marked on the CRT screen) with a straight line and extrapolate through the full examination range. Note the gain setting (db) on Exhibit 1.

4.4.3.4 On Calibration Standard TMI-370, locate the 1/2T SDH and establish a signal between 50% and 80% FSH and note the signal height and gain setting (db) on Exhibit 1.

4.4.3.5 On flywheel #1, locate the 1/2T SDH by scanning adjacent to the edge of the flywheel (i.e. 1 to 3 inches) as the flywheel is being slowly rotated or by visually locating the holes between the flywheel face and the motor housing or both.

4.4.3.6 The transfer method shall be used to note the difference in gain (db) between the response received from the 1/2T signal in the calibration standard and the 1/2T signal in the flywheel and add or subtract the difference to the reference level established by the bottom notch. This level shall be primary reference level and the difference shall be noted on Exhibit 1.

**NOTE**

Other transfer methods may be utilized such as the two search unit techniques with the sound opposing each other, but only as directed and approved by GPUN UT Level III.

4.4.3.7 To determine the 45° angle beam sweep calibration on Flywheel #4, utilize Calibration Standard TMI-371 and place the 1/2T signal at screen division 3, the 3/4T at 4.5 the bottom notch at 6 and the 1 1/4T at 7.5. The instrument sweep is now calibrated to represent 20" of metal path.

4.4.3.8 On Calibration Standard TMI-371 for flywheel #4, establish a DAC curve by adjusting the gain to set the 1/2T signal at 80% ±5% FSH at screen position 3 and mark its position on the CRT. Maximize the response from the 3/4T and 1 1/4T SDHs and mark their positions on the CRT. Note the gain setting (db) on Exhibit 1, since this reference level will be utilized for the transfer method on the flywheel. Connect the marks with a straight line and extrapolate through the thickness being examined.

4.4.3.9 Locate the bottom notch signal on Calibration Standard TMI-371 at screen division 6. Increase or decrease the gain to set the peak of this signal to the DAC curve line. Note this gain setting (db) on Exhibit 1.

4.4.3.10 On flywheel #4, locate the 1/2T SDH as identified in paragraph 4.4.3.5 for flywheel #1. With the gain setting and signal height from the 1/2T SDH in paragraph 4.4.3.8, utilize the transfer method as outlined in paragraph 4.4.3.6 to determine the db difference between the 1/2T SDH in flywheel #4 and the 1/2T SDH response on Calibration Standard TMI-371.

4.4.3.11 Add or subtract the db difference established in paragraph 4.4.3.10 to the gain setting established in paragraph 4.4.3.9. This gain setting shall be primary reference level.

4.4.4 System calibration confirmation

4.4.4.1 The sweep range and primary DAC curve shall be checked and verified:

- At the beginning of each day of examination.
- At least every four (4) hours during performance of examinations.
- If any component of the test system is changed (i.e., instrument, transducer, coaxial cable, etc.).
- After any change in personnel.
- At the completion of the examination to which the calibration applies.
- If the operator suspects any malfunction of the UT system.
- In the event of a power loss.

4.4.5 Calibration changes

4.4.5.1 If any point on the DAC curve has decreased 20% of its amplitude, all data sheets since the last calibration check shall be marked void. A new calibration shall be performed and recorded and the voided examination area(s) shall be re-examined.

4.4.5.2 If any point on the DAC curve has increased more than 20% of its amplitude, recordable indications taken since the last valid calibration or calibration check may be re-examined with the current calibration and their values changed on the data sheets.

4.4.5.3 If any point on the DAC curve has moved on the sweep line more than 10% of the sweep division reading, correct the sweep range calibration and note the correction on the appropriate data sheets. If recordable indications are noted on the data sheets, those data sheets shall be voided and a new calibration shall be recorded and the examination areas shall be re-examined.

4.5 Examination procedures

4.5.1 Examination of base material for laminar type reflectors.

4.5.1.1 Base material adjacent to the inner bore region on flywheels #1 and #4 and the bolt holes on flywheel #1 shall be scanned with a longitudinal (0 degree) search unit to detect discontinuities which may interfere with the transmission of shear waves during angle beam examination. (See Exhibit 7)

> **NOTE**
> The requirements of paragraph 4.5.1.1 apply only when there is a reason to question sound penetration such as excessive loss of back reflection or existence of abnormal geometric reflectors which dampen.

4.5.2 General requirements

4.5.2.1 All angle beam examinations shall be performed at a scanning sensitivity level at 2x (+6 db) greater than the calibrated reference sensitivity level.

4.5.2.2 Scan speeds shall not exceed six (6) inches per second. Scan the exposed areas within each access port prior to moving the flywheel to the next adjacent area for each system calibration.

4.5.2.3 All angle beam examinations shall be performed in two directions (i.e. beam directed essentially clockwise and counter clockwise around the flywheel bore regions and bolt holes as depicted on Exhibits 5 and 6).

4.5.2.4 Beam angles other than 45° may be utilized as directed and approved by a GPUN UT Level III.

4.5.3 45° Angle Beam Examination

4.5.3.1 On flywheel #1, the top surface is accessible through access ports 1 through 3. The area of interest for the top flywheel is the inside bore region which includes the keyway and all accessible areas surrounding the four (4) bolt holes (Reference Exhibits 5 and 6).

4.5.3.2 On flywheel #4, the bottom surface is accessible through one access port. The area of interest for the bottom flywheel is the inside bore region which includes the keyway.

4.5.3.3 For both Flywheels #1 and #4, the examination requirements for the inside bore region and keyway are identified on Exhibit 5. Exhibit 6 delineates the requirements on flywheel #1 for examination of the areas surrounding each bolt hole.

4.5.3.4 For the inside bore region, Keyway and the areas surrounding the bolt holes, scanning shall be performed on a tangential line or on a line perpendicular to the flywheel and bolt hole radii. The scan width (w) shall be as identified in Exhibits 5 and 6. The minimum overlap of the search unit shall be 25% of the search unit width. The search unit shall be oscillated a minimum of 15° in each direction for each parallel path.

> **NOTE**
> Due to access restrictions and surface area limitations, the scanning distances and patterns will be a best effort activity. Limitations and restrictions shall be documented on the UT Examination Data Sheet, Exhibit 2, or a Limited Examination Sheet.

4.5.3.5 45° angle beam examination of flywheels #2 and #3 is not possible unless the flywheels are disassembled.

4.5.4 Evaluation/Interpretation

4.5.4.1 Indications showing a signal amplitude response equal to or greater than 20% of the reference response shall be investigated to determine their origin (geometric or non-geometric). If an indication is determined geometric, it need not be recorded.

4.5.4.2 Evaluation of indications shall be made at the reference sensitivity level and in accordance with the requirements of the Reference 6.6.

4.5.4.3 Non-geometric indications showing a signal amplitude response equal to or greater than 50% of the reference sensitivity level shall be recorded on the data sheet.

4.5.4.4 Each recorded indication shall be identified on the data sheet as to depth, length, signal amplitude and location.

4.5.4.5 In order to determine depth and length of a flaw, flaw sizing techniques, as delineated in Reference 6.7, may be required.

4.5.4.6 Calibration and examination results shall be documented on the applicable data sheets Exhibits 1 and 2.

4.6 Reporting

4.6.1 The distribution of NDE/ISI data shall be performed in accordance with Reference 6.5.

4.7 QA Records

4.7.1 All calibration and examination results shall be recorded on Exhibits 1 and 2, as applicable, and are considered permanent QA Records.

4.7.2 All forms must be totally filled out as applicable, then signed and dated for the day the examination was performed. There shall be no blank spaces on any form after completion. If there is no information available for a particular space, the space shall be filled in with "N/A".

4.7.3 Errors on data forms shall not be covered or eradicated with white-out (liquid paper). Any error which may occur shall be crossed out with a line, initialed and dated by the person making the change. All forms shall be filled out with black ink.

4.7.4 Record retention and transmittal shall be in accordance with Reference 6.5.

## 5.0 RESPONSIBILITIES

5.1 Responsibilities are as defined earlier in this procedure.

## 6.0 REFERENCES

6.1 ASME Boiler and Pressure Vessel Code, Section V, Non-destructive Examination, Article 5, 1986 Edition, No addenda

6.2 TMI-1 Technical Specifications Section 4.2.4

6.3 GPUN Procedure 5361-ADM-7230.01, Qualification and Certification of NDE Examination Personnel

6.4 GPUN Procedure 5361-NDE-7209.17, Ultrasonic Instrument Linearity

6.5 GPUN Procedure 5361-ADM-3272.03, Control and Processing of NDE Data

6.6 GPUN Procedure 5361-SPC-7230.26, Evaluation of Recordable Indications

6.7 GPUN Procedure 5361-NDE-7209.10, Ultrasonic Sizing of Planar Flaws

6.8 TMI Administrative Procedure 1104-28Q, Mixed Low Level Radioactive Waste Control Program

6.9 GPUN Procedure 5361-NDE-7209.18, Calibration and Maintenance of Nondestructive Examination Equipment

6.10 TMI Administrative Procedure 1068 - Controlled Consumable Materials

## 7.0 EXHIBITS

7.1 Exhibit 1 - UT Calibration Data Sheet (Typical).

7.2 Exhibit 2 - UT Examination Data Sheet (Typical).

7.3 Exhibit 3 - Configuration of Flywheel #1.

7.4 Exhibit 4 - Configuration of Flywheel #4.

7.5 Exhibit 5 - Scanning Requirements for flywheel #1 and 4 inside bore region and keyway

7.6 Exhibit 6 - Scanning Requirements for flywheel #1 bolt hole region

7.7 Exhibit 7 - Straight beam scan requirements for laminar reflectors

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|---|---|---|
| Title: Ultrasonic Examination of Reactor Coolant Pump Flywheels | | Revision No. 0 |

# EXHIBIT 1

## UT CALIBRATION DATA SHEET
## -TYPICAL-

**GPU Nuclear** **Calibration Sheet** Cal Sheet# ______

Components Examined: ______ Procedure: ______ Rev ______

Examiner Signature: ______ Print: ______ Initial: ______ SSN: ______ Level ______

Examiner Signature ______ Print: ______ Initial: ______ SSN: ______ Level ______

Instrument Make ______ Model ______

Instrument ID Number ______

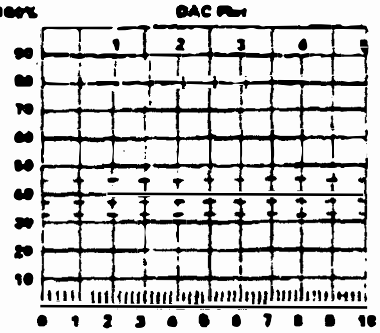
**Pulser**
Pulse Duration ______
Damping ☐ Off ☐ On ______
☐ Pulse Echo ☐ Dual
Repetition Rate ______
Voltage ______

**Gain**
Coarse ______
Fine ______
Uncal ______ %

**Receiver**
Frequency ______
Reject ☐ Off ☐ On ______ %
Display
☐ Fullwave ☐ RF
☐ Half (+) ☐ Half (-)
☐ Filter 1 2 3 4 5
☐ Other ______

**Sweep Circuit**
Coarse ______
Range ______
Delay ______
Velocity ______
Screen Depth ______ in.

**DAC Plot**




| Date | Hours | Screen Reading in Inches |
|---|---|---|
| Reflector | Amplitude % of FSH | |
| | | |
| | | |
| | | |

**Search Unit Cable**
Type ______ Length ______
No. of Inter. Connectors ______
Couplant
Make ______ Batch # ______
Thermometer
S/N: ______ Cal Due ______

**Cal Standard**
ID# ______
Size ______ Sch. ______
Thickness ______
S/S CS ______
Temp ______ °F

**Cal Direction**
☐ Axial ☐ Both
☐ Circ. ☐ Normal

**System Check**
☐ Exit Point
☐ Angle +/- 2

**Search Unit**
I.D. # ______
Type ______ Size ______
Freq ______ MHZ
Angle ______ Mode ______

**Other Instrument Settings**

| Setting | Value |
|---|---|
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |

| Date / Hours | / | | / | | / | |
|---|---|---|---|---|---|---|
| Reflector | % FSH | Inches | % FSH | Inches | % FSH | Inches |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| Initials | | | | | | |

ANII Review

Remarks:

**Technical Review**
Reviewed By ______
Level ______ Date ______

NO827 (09-93)

## EXHIBIT 2

## UT EXAMINATION DATA SHEET
## -TYPICAL-

| GPU Nuclear | Ultrasonic Examination Data Sheet | | Page ___ of ___ |
|---|---|---|---|
| Location: ☐OC ☐TMI-1 ☐TMI-2 | NDE Request | | Data Sheet No. |
| Class: | Item | | |
| Task Description: | Task No.: | | Date: |
| Comp. Desc.: | System: | | Code/Spec.: |
| Procedure/Rev.: | Drawing No./Rev.: | | |
| Test Surface: | Thickness: | | Material: |
| Examiner | Signature: | Print: ID | Level: |
| Examiner | Signature: | Print: ID | Level: |
| Scanning Direction: ☐Circumferential ☐Axial | Limited Scan: ☐Yes ☐No | Cal Sheet: | Cal Sheet: / Cal Sheet: |

| Weld Joint | Weld Profile | Cal Sheet: | Cal Sheet: | Cal Sheet: |
|---|---|---|---|---|
| Surface 1: ______ | Weld Height: ______ Weld Width: ______ | Angle: | Angle: | Angle: |
| Surface 2: ______ | ← Flow | Time Start: Hrs. | Time Start: Hrs. | Time Start: Hrs. |
| LD: ______ | Surface One / Surface Two | Time Stop: Hrs. | Time Stop: Hrs. | Time Stop: Hrs. |
| WO: ______ | BM / Haz. / Weld CL / Haz. / BM | Temp.: F | Temp.: F | Temp.: F |
| | | Date: | Date: | Date: |

| S/N ID | Ind No | Angle | Test | Surf | Beam | Dir | Max Amp | % Dac | W Max | | L Max | | Forwarded Two | | Backward Two | | End L Point 1 | | | End L Point 2 | | | Remain | Back | Reflec | Finger | Dampens |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | W | Depth | CCW | CW | W | Depth | W | Depth | W | CCW | CW | W | CCW | CW | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | |
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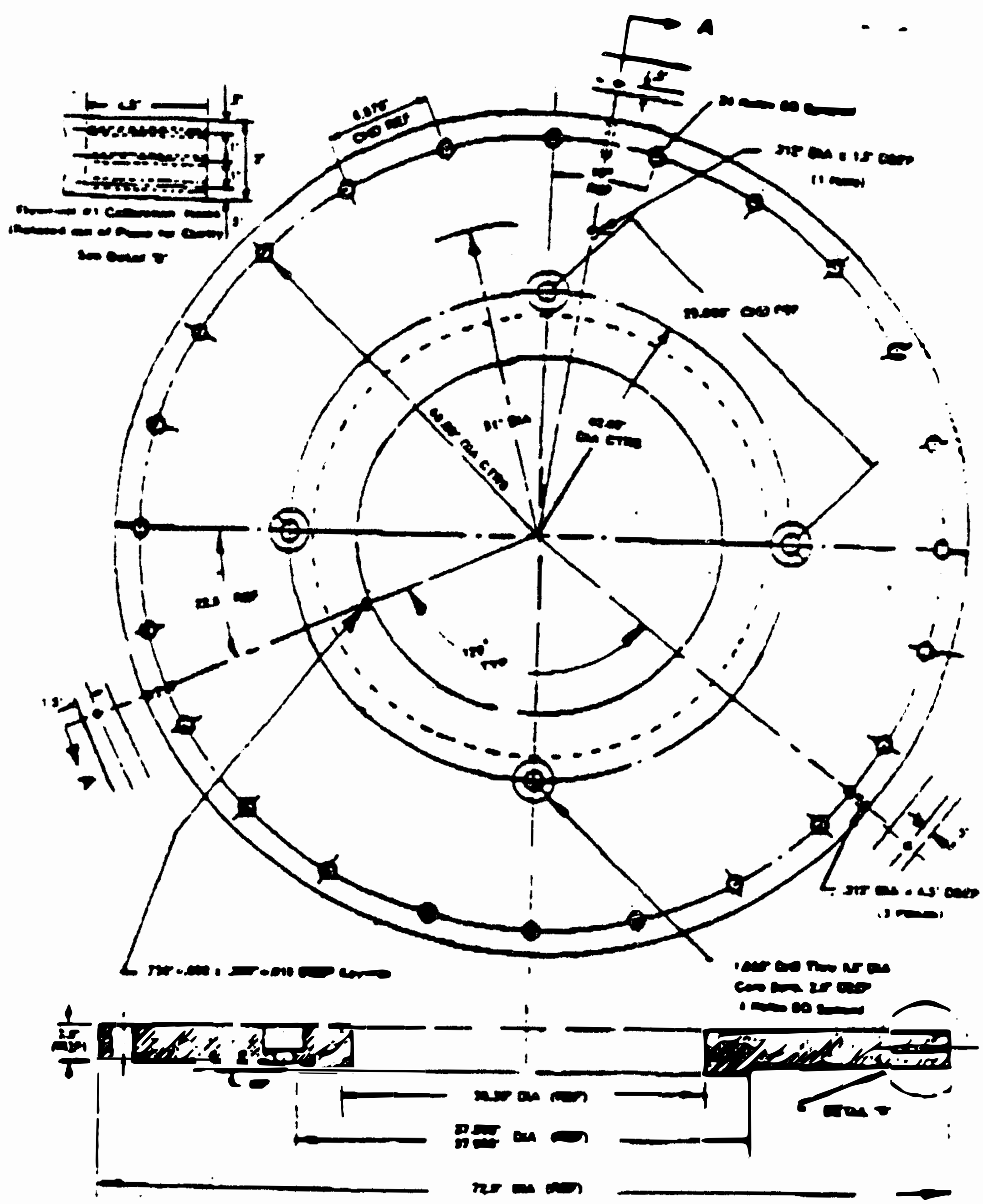
| Technical Review | Disposition | ANI Review | | |
|---|---|---|---|---|
| By: ______ | ☐ISI ☐Recordable | | | |
| Level: ______ | ☐PSI ☐No Recordable | | ER Number: | NDE Request #: |
| Date: ______ | ☐Nonrelevant | | | |

N 1008 (12-89)

# EXHIBIT 3

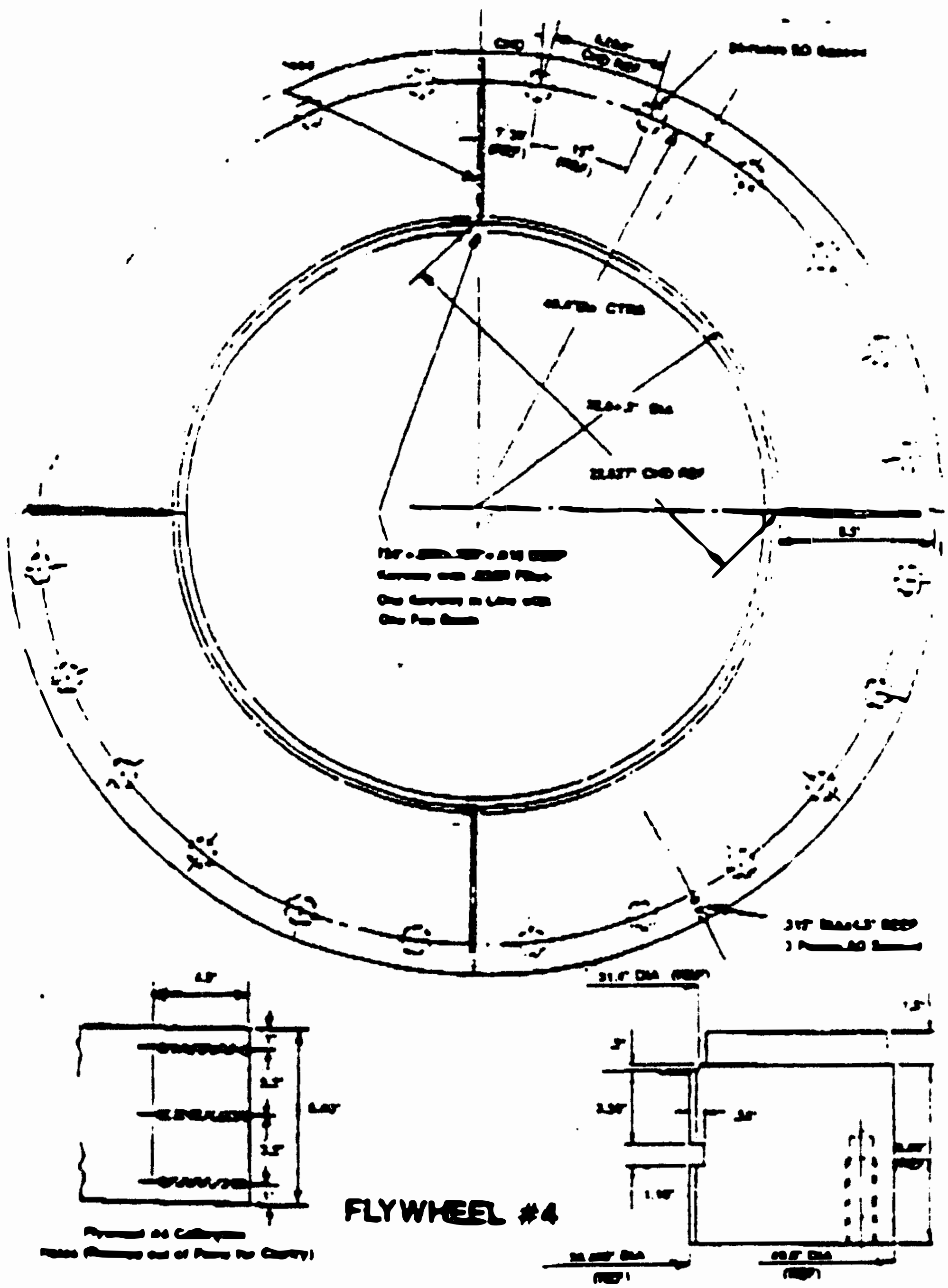
## CONFIGURATION OF FLYWHEEL #1




FLYWHEEL #1

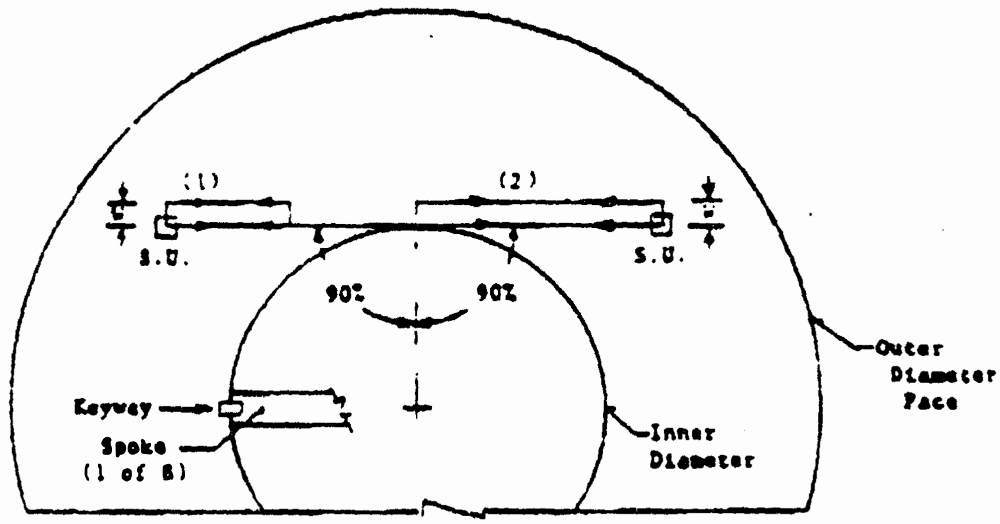
## EXHIBIT 4

## CONFIGURATION OF FLYWHEEL #4



## EXHIBIT 5

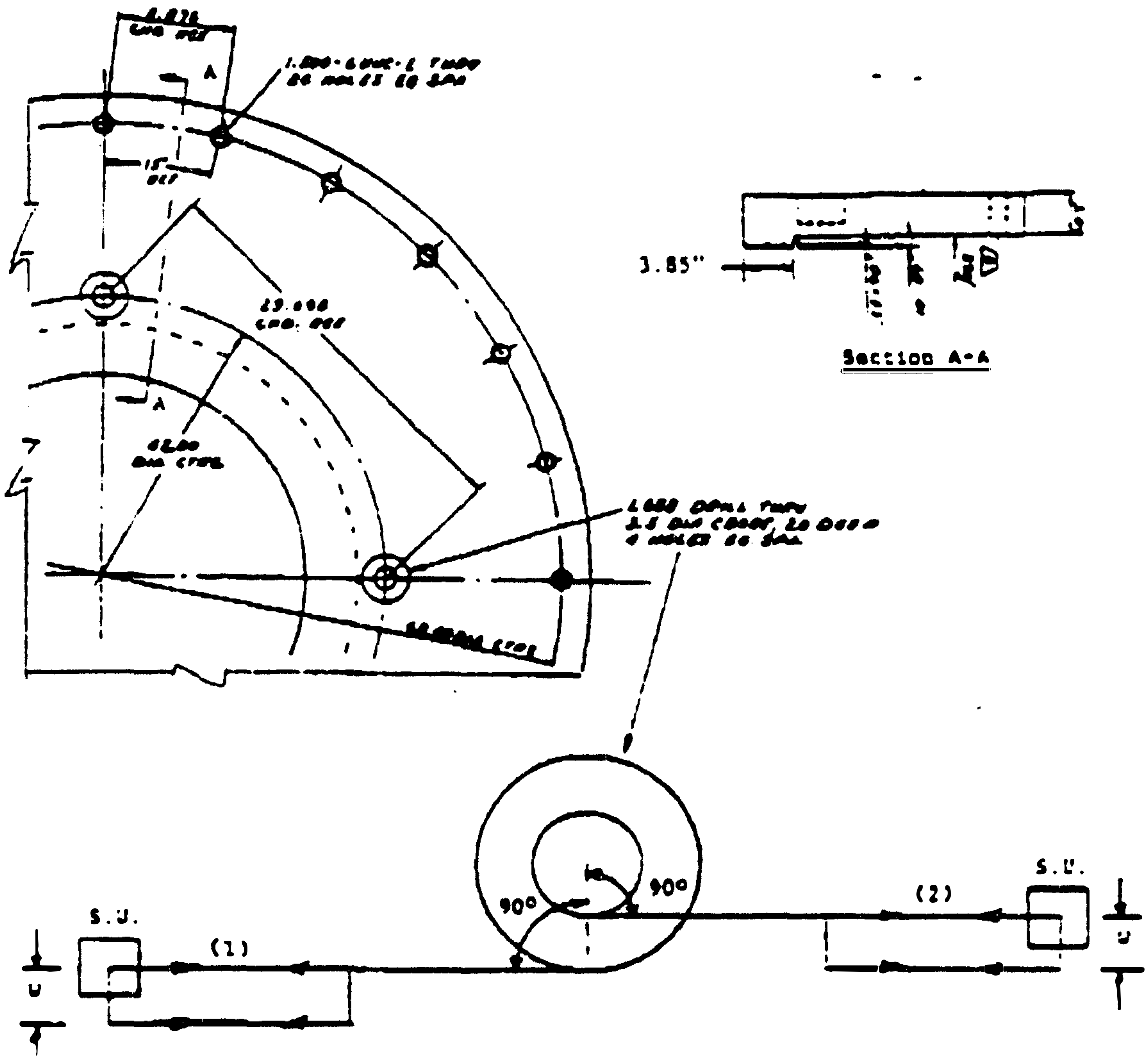
### SCANNING REQUIREMENTS FOR FLYWHEEL #1 AND #4 INSIDE BORE REGION AND KEYWAY




| | Inner bore and Keyway | Foreward/Backward Scan Distance | Scan Width(W) | Scan Direction |
|---|---|---|---|---|
| (1) | Flywheel #1 | 3.5"(1/2V) to 7"(full 'V') | 1" | 360° CW & CCW |
| (2) | Flywheel #4 | 0" (Surface) to 8.4"(1/2V) | 1" | 360° CW & CCW |

## EXHIBIT 6

## SCANNING REQUIREMENTS FOR FLYWHEEL #1 BOLT HOLE REGION




| | Bolt Hole | Foreward/Backward Scan Distance | Scan Width(W) | Scan Direction |
|---|---|---|---|---|
| (1) | 3.5" dia. | 3.5"(1/2V) to 7"(Full 'V') | 1" | 360° CW & CCW |
| (2) | 1.68" dia. | 3.5"(1/2V) to 7"(Full 'V') | 0.9 | 360° CW & CCW |

NOTE:

Scans 1 & 2 may be performed simultaneously in both CW & CCW directions.

## EXHIBIT 7

## STRAIGHT BEAM SCAN REQUIREMENTS FOR LAMINAR REFLECTORS

Straight Beam for Laminar Reflectors (all procedure requirements apply except when superseded by this exhibit).

1.0 CALIBRATION

1.1 Calibrate the screen range on the calibration standard or other similar metal standard.

1.2 Select a direct read screen range which will produce a back reflection of greater than 40% but less than 100% full screen sweep from the maximum anticipated examination thickness.

1.3 Couple the search unit to the calibration standard and calibrate the screen range by use of the sweep and delay controls.

1.4 Couple the search unit to the part being examined and adjust the initial back reflection to 80% FSH Adjustment of the gain control is permitted during examination in order to maintain the back reflection response.

2.0 RECORDING

2.1 Record all areas giving indications equal to or greater than the remaining back reflection.

2.2 Recording of straight beam laminar type reflectors requires recording the locations of all four sides of a rectangle which would contain the indication extremities at the required recording level.

2.3 Record all laminar indications which produce a response equal to or greater than the remaining back reflection. These dimensions and locations will be used to determine areas of interference with the angle beam examination.

2.4 Record all laminar indications where a continuous loss of back reflection exists along with a continuous indication in the same plane. These dimensions and locations will be used to determine acceptability of the component for continued service.

3.0 SCAN SENSITIVITY

3.1 Adjustment to the scan sensitivity may be necessary and shall be considered when recordable laminar reflectors are noted in order to maintain an acceptable back reflection.

# APPENDIX D

## SAMPLE FLYWHEEL MATERIAL TEST CERTIFICATES

U336

NON-DESTRUCTIVE TEST REPORT
QUALITY CONTROL
WESTINGHOUSE FORM 38336

FILE: SHOP ORDER 81 P352 #2

TEST: ULTRASONIC ZYGLO DYE PENETRANT MAGNAFLUX HARDNESS

C.C.: Miss Jackson SNS C.C.: M.E. 2 insp.

C.C.: Mr. Carlson

| PURCHASE ORDER NO. | SUPPLIER | SECTION | DRAWING NO. | HEAT NO. | FORGING NO. |
|---|---|---|---|---|---|
| 10 FV 06 409<br>10 PV 47470 | LUKENS | ME 2 | 6250D85 | C9474<br>C9446 | 3<br>21 |

MATERIAL

FLYWHEEL ASSY.

P.D.S.

RESULTS of dye check of 9.438 dia bore & 18" dia face shows no indications E.G. Patrick 2-23-72

9.375 bore & 18 dia face shows no indications EGP 2-28-72

DA NO.

REPORTED BY E.G. Patrick

DATE 2-28-72

LUKENS STEEL COMPANY

# INSPECTION DEPARTMENT

## NON-DESTRUCTIVE TESTING REPORT

MILL ORDER NO.: 8587-1-57107-1

TYPE TEST: [illegible]

DATE: 1/6/72

QUALITY: ASTM A-533-69A Gr. B CL 1

SPECIFICATION: CODE CASE 1338-4 ALT. 1 NO. PROC. 8-9

CUSTOMER NO: [illegible]

EQUIPMENT USED: [illegible] UM 715 # 31

SEARCH UNIT: 1-1/8 DIA. 2.25 Mhz

SPACING: 1 x 1 2.25 Mhz [illegible]

AMPERAGE:

COUPLANT: SOAP & WATER

METHOD: CONTACT

TRANSDUCER:

GRID REF:

TYPE OF SURFACE: GROUND

TYPE OF PROBES: SPERRY

100 % Sb

200 % As

INSPECTORS NAME & QUALIFICATIONS:

SIZE: 2 RINGS OD 25-1/2 x ID 8-1/4 x 6

WITNESSED BY:

MELT & SLAB: C9446-2A

MARK: Ir. 1

I HEREBY CERTIFY THAT THE ABOVE IS CORRECT TO THE BEST OF MY KNOWLEDGE AND BELIEF

U.T. OK per. SPEC.

U336

PURCHASER:
Westinghouse Elec. Corp.
3 LRA Purch. Dept.
Mr. G. E. Stepp
E.Pittsburgh, Pa. 15112

# LUKENS STEEL COMPANY

COATESVILLE PA 19320

## TEST CERTIFICATE

| MILL ORDER NO. | CUSTOMER P O | |
|---|---|---|
| 57808-1 | 10-PV-66404 | DP 122371 DD |

DATE 12-31-71 FILE NO 8587-07-14

CONSIGNEE

S.O. U336 TVA

Motor No. 81P353-2

SPECIFICATIONS:
A-533-67 Gr. B Class 1 Mod. by Sales Order

BEND TEST O.K. HOMOGENEITY TEST

CHEMICAL ANALYSIS

| MELT NO. | C | Mn | P | S | Cu | Si | Ni | Cr | Mo | V | Ti | Al | Basic Process |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C9479 | 20 | 1.32 | 010 | 020 | | 24 | 47 | | 51 | | | | Elec. E.G.P. V.I.P. Steel |

RELEASED BY Q.C.
TO FED. 71E-2
INSP. 1-17-72

PHYSICAL PROPERTIES

| MELT NO. | SLAB NO | YIELD PSI X100 | TENSILE PSI X100 | % ELONG IN 2 | % R A | BHN | IMPACTS V-Notch +10°F. | | | | DESCRIPTION |
|---|---|---|---|---|---|---|---|---|---|---|---|
| C9479 | 3 | TX 638 | 865 | 28 | | 174 | T 67 | 71 | 77 | | 1-5" x 8-1/4 ID x 65-1/2 OD |
| | | BX 673 | 880 | 27 | | 179 | | | | | |
| | | TL 646 | 873 | 29 | | 174 | | | | | |
| | | BL 667 | 881 | 28 | | 179 | L 81 | 74 | 79 | | |

74P527

Ring and tests heated to 1650°F./1700°F., held 1 hr. per inch min. and water quenched to 500°F., then tempered 1280°F., held 1 hr. per inch min. and air cooled.

Ring and tests stress relieved by heating to 1150°F., held 1 hr. per inch min. and furnace cooled to 600°F.

D

11-1-72

U336

We hereby certify the above figures are correct as contained in the records of the company.

L. G. Kline

FORM [illegible]

LUKENS STEEL COMPANY

# INSPECTION DEPARTMENT

## NON-DESTRUCTIVE TESTING REPORT

| | | | |
|---|---|---|---|
| CUSTOMER | MILL ORDER NO. 9537-14-57838-1 | TYPE TEST REFLECTOSCOPE | DATE 12/16/71 |
| | QUALITY ASTM A-533-69A GR. B CL. 1 MOD. | SPECIFICATION CODE CASE 1338-4 ALT. 1 MOD. PROC. S-9 | |
| | CUSTOMER NO. P.O.#10-IV-66401 | EQUIPMENT USED SPERRY UM 715 # 31 | |
| CONSIGNED TO | SEARCH UNIT 1-1/8 DIA. 2.25 MHz<br>SPACING 1 X 1 2.25 MHz AB | AMPLITUDE<br>AMPERAGE | COUPLANT SOAP & WATER<br>METHOD CONTACT |
| | TRANSDUCER SPERRY<br>TYPE OF PRODS | GRID REF. 100% SB<br>20% AB | TYPE OF SURFACE<br>BLASTED |
| | INSPECTORS NAME & QUALIFICATIONS [signature] | SIZE 1 RING 65-1/2 OD X 8-1/4 ID X 5 | |
| | WITNESSED BY | MELT & SLAB C9479-3 | MARK Tc. 1 |

16

U336

I HEREBY CERTIFY THAT THE ABOVE IS CORRECT TO THE BEST OF MY KNOWLEDGE AND BELIEF. [illegible]

**NON-DESTRUCTIVE TEST REPORT**
QUALITY CONTROL
WESTINGHOUSE FORM 36386

FILE: SHOP ORDER 81P352

TEST: ULTRASONIC ZYGLO DYE PENETRANT MAGNAFLUX HARDNESS

C.C.: Miss Jackson C.C.: ME-2 Insp.

C.C.: Mr. Carlson C.C.:

| PURCHASE ORDER NO. | SUPPLIER | SECTION | DRAWING NO. | HEAT NO. | FORGING NO. |
|---|---|---|---|---|---|
| 10PV47470<br>10PV47471 | Lukens | ME-2 | 6550D85 | C9446<br>C9362 | 2B<br>1A |

MATERIAL: Flywheel Assy.

P.O.S.:

RESULTS: of dye check of 9.4375 dia bore and 18" dia face shows no indications or details
and 9.375 dia bore & 18" dia face show no indications.

DA NO.

REPORTED BY: E. A. Patrick

DATE: 6-5-72

U336

**LUKENS STEEL COMPANY**
COATESVILLE, PA. 19320
**TEST CERTIFICATE**

PURCHASER:
Westinghouse Elec. Corp.
3 Mr. G. E. Stepp

| MILL ORDER NO. | CUSTOMER P.O. | |
|---|---|---|
| 57106-1 | 10-PV-47471 | DP 122371 DD |

DATE: 12-31-71 FILE NO. 8587-07-14
CONSIGNEE: S.O. U336 PYA
Motor No. 81P352

SPECIFICATIONS: A-533-69A Gr. B Class 1 Mod. by Sales Order 81P352

BEND TEST O.K. HOMOGENEITY TEST

**CHEMICAL ANALYSIS**

| MELT NO. | C | Mn | P | S | Cu | Si | Ni | Cr | Mo | V | Ti | Al | Basic Process |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C9362 | 21 | 1.30 | 010 | 020 | | 27 | 59 | | 54 | | | | Elec. F.G.P. V.I.P. Steel |

**PHYSICAL PROPERTIES**

| MELT NO | SLAB NO. | YIELD PSI x100 | TENSILE PSI x100 | % ELONG. in 2" | % R.A. | BHN | IMPACTS V-Notch +10°F. | | | DESCRIPTION |
|---|---|---|---|---|---|---|---|---|---|---|
| C9362 | 1A | TX 644 | 801 | 25 | | 182 | T 44 | 45 | 35 | 4-5" x 8-1/4 ID x 65-1/2 OD |
| | | BX 651 | 891 | 25 | | 182 | | | | |
| | | TL 617 | 870 | 27 | | 183 | | | | |
| | | BL 638 | 831 | 28 | | 187 | L 30 | 34 | 45 | |

Rings and tests heated to 1650°F./1700°F., held 1 hr. per inch min. and water quenched to 500°F., then tempered 1280°F., held 1 hr. per inch min. and air cooled.

Rings and tests stress relieved by heating to 1150°F., held 1 hr. per inch min. and furnace cooled to 600°F.

U336

LUKENS STEEL COMPANY

# INSPECTION DEPARTMENT

## NON-DESTRUCTIVE TESTING REPORT

CUSTOMER

MILL ORDER NO. A587-1A 57106-1

TYPE TEST REFLECTOSCOPE

DATE

QUALITY ASTM A-533-69A GR. B CL. 1

SPECIFICATION CODE CASE 1339-4 U.T. 1 ADD. PROC. S-9

CUSTOMER NO. P.O. 10-PV-47471

EQUIPMENT USED SPERRY UM 725 # 31

CONSIGNED TO

SEARCH UNIT 1-1/8 DIA. 2.25 MHz

SPACING

AMPLITUDE

AMPERAGE

COUPLANT

METHOD SOAP & WATER

TRANSDUCER SPERRY

TYPE OF PRODS

GRID REF. 100% SR

TYPE OF SURFACE

INSPECTORS NAME & QUALIFICATIONS

SIZE 4 RINGS 65-1/2 OD X 4-1/4 TD X 5

WITNESSED BY

MELT & SLAB C9962-1A

MARK It. 1

I HEREBY CERTIFY THAT THE ABOVE IS CORRECT TO THE BEST OF MY KNOWLEDGE AND BELIEF. U.T. OK per. SPEC.

U336

3 Westinghouse Elec. Corp.
LRA Pur. Dept.
Mr. G. E. Stepp
E. Pittsburgh, Pa. 15112

# LUKENS STEEL COMPANY

COATESVILLE, PA 19320

## TEST CERTIFICATE

| MILL ORDER NO. | CUSTOMERS P.O. | |
|---|---|---|
| 57107-1 | 10-PV-47470 | RP 1572 DR |

CORRECTED COPY: [illegible]

DATE 1-11-72 FILE NO. 3537-07-14

CONSIGNEE

S.O. U-336 TVA

Motor No. 81P393 #3

SPECIFICATIONS

A-533-69A Gr. B CL 1 Mod. by Sales Order

M JAN

BEND TEST O.K. HOMOGENEITY TEST

### CHEMICAL ANALYSIS

| MELT NO. | C | Mn | P | S | Cu | Si | Ni | Cr | Mo | V | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C9446 | 22 | 1.30 | 007 | 015 | | 22 | 57 | | 53 | | V.I.P. Steel | P.O.P. Electric |

### PHYSICAL PROPERTIES

| MELT NO. | SLAB NO. | YIELD PT. | TENSILE PT. | ELONG. % 2" | BHN | DIR. | V-Notch +10°F. | | | DESCRIPTION |
|---|---|---|---|---|---|---|---|---|---|---|
| C9446 | 2A | TX 686 | 917 | 24 | 187 | T | 52 | 54 | 48 | 2-8" x 8-1/4 ID x 75-1/2 OD |
| | | TL 660 | 921 | 28 | 187 | | | | | |
| | | BX 694 | 926 | 23 | 192 | | | | | |
| | | BL 705 | 926 | 25 | 192 | L | 106 | 70 | 70 | |
| " | 2B | TX 665 | 886 | 23 | 187 | T | 38 | 48 | 45 | 2- " |
| | | TL 693 | 905 | 26 | 183 | | | | | |
| | | BX 734 | 950 | 24 | 187 | | | | | |
| | | BL 715 | 925 | 24 | 192 | L | 92 | 89 | 102 | |

Rings and tests heated 1650-1700 F., held 1 hr. per inch min. and water quenched to 500°F., then tempered ~~1150~~ 1260 °F., held 1 hr. per inch min. and air cooled.

Rings and tests stress relieved by heating to 1100°F., held 1 hr. per inch min. and furnace cooled to 600°F.

FEB 1972
RECEIVED
L.R.A. 4
PURCHASING

We hereby certify the above figures are correct as contained in the records of the company.

SIGNATURE [signature] Kline

# LUKENS STEEL COMPANY
## INSPECTION DEPARTMENT

**NON-DESTRUCTIVE TESTING REPORT**

| Field | Entry |
|---|---|
| CUSTOMER | |
| CONSIGNED TO | |
| MILL ORDER NO. | 8307-34-57107-1 |
| QUALITY | ASTM A-533-'?A GR.B CL.1 |
| CUSTOMER NO. | P.O.# 10-FY-47470 |
| SEARCH UNIT | 1-1/8 DIA. 2.25 MHz |
| SPACING | 1 X 1 2.25 MHz AB |
| TRANSDUCER | SPERRY |
| TYPE OF PRODS | |
| INSPECTORS NAME & QUALIFICATIONS | [illegible signature] |
| WITNESSED BY | |
| TYPE TEST | [illegible] |
| DATE | 1/4/72 |
| SPECIFICATION | CODE CASE 1334-[illegible] [illegible] PROC. [illegible] |
| EQUIPMENT USED | SPERRY UM 715 # 31 |
| AMPLITUDE | |
| AMPERAGE | |
| GRID REF. | 100 % BB / 200 % AB |
| COUPLANT | SOAP & WATER |
| METHOD | CONTACT |
| TYPE OF SURFACE | GROUND |
| SIZE | 2 RINGS 75-1/2 OD X 6-1/4 ID X 6 |
| MELT & SLAB | 09446-2B |
| MARK | It. 1 |

I HEREBY CERTIFY THAT THE ABOVE IS CORRECT TO THE BEST OF MY KNOWLEDGE AND BELIEF.

U. S. [illegible] [illegible]

A. Rauck

**NON-DESTRUCTIVE TEST REPORT**

QUALITY CONTROL

WESTINGHOUSE FORM 26380

FILE: SHOP ORDER 81P352 #4

TEST: ULTRASONIC ZYGLO DYE PENETRANT MAGNAFLUX HARDNESS

C.C.: Miss Jackson C.C.: ME-2 insp.

C.C.: Mr. Carlson C.C.:

| PURCHASE ORDER NO. | SUPPLIER | SECTION | DRAWING NO. | HEAT NO. | FORGING NO. |
|---|---|---|---|---|---|
| 10PV47471<br>10PV47470 | LUKENS | ME-2 | 6550D85 | C9362<br>C9446 | 1A<br>1A |

| MATERIAL | P.C.S. |
|---|---|
| FLYWHEEL ASSY. | |

RESULTS of dye check of 9.437 dia bore & 18" dia face shows no indications E.R.P. 6-8-72

Dye Check of 9.375 Bore + 18" Dia face OK

Roberts 6/12/72

REPORTED BY Roberts DATE 6/12/72

DA NO.

U336

CORRECTED COPY: 1-20-7[illegible]

PURCHASER:

3 Westinghouse Elec. Corp.
LRA Pur. Dept.
Mr. G. E. Stepp
E. Pittsburgh, Pa. 15112

LUKENS STEEL COMPANY
COATESVILLE, PA. 19320
TEST CERTIFICATE

| MILL ORDER NO. | CUSTOMER P.O. | |
|---|---|---|
| 57107-1 | 10-PV-47470 | NP .1572 DR |

DATE 1-11-72 FILE NO 8587-0

CONSIGNEE
SO. U336, TVA
MOTOR # 81P852 #4

SPECIFICATIONS:
A-533-69A Gr. B CL 1 Mod. by Sales Order

BEND TEST O.K. HOMOGENEITY TEST

M JAN 1

## CHEMICAL ANALYSIS

| MELT NO. | C | Mn | P | S | Cu | Si | Ni | Cr | Mo | V | XXXX | XXX | XXXX | XXXX | BASIC PROC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C9446 | 22 | 1.30 | 007 | 015 | | 22 | 57 | | 53 | | V.I.P. Steel | | | | P.G.P. Electric |

## PHYSICAL PROPERTIES

| MELT NO. | SLAB NO. | YIELD POINT PSI | TENSILE PSI | % ELONG. 2" | BHN | TEST LOC. | IMPACTS V-Notch +10°F. | | | DESCRIPTION |
|---|---|---|---|---|---|---|---|---|---|---|
| C9446 | 2A | TX 659 | 917 | 24 | 187 | T | 52 | 54 | 48 | 2-8" x 8-1/4 ID x 75-1/2 |
| | | TL 660 | 901 | 28 | 187 | | | | | |
| | | BX 694 | 926 | 23 | 192 | | | | | |
| | | BL 726 | 926 | 25 | 192 | L | 106 | 79 | 79 | |
| " | 2B | TX 665 | 886 | 23 | 187 | T | 38 | 43 | 45 | 2- " |
| | | TL 693 | 905 | 25 | 183 | | | | | |
| | | BX 734 | 950 | 24 | 187 | | | | | |
| | | BL 715 | 925 | 24 | 192 | L | 92 | 89 | 102 | |

Rings and tests heated 1650-1750 F., held 1 hr. per inch min. and water quenched to 500°F., then tempered 1100°F., held 1 hr. perinch min. and air cooled.
1260

33

Rings and tests stress relieved by heating to 1100°F., held 1 hr. per inch min. and furnace cooled to 600°F.

FEB 1972
RECEIVED
L.R.A. 4
PURCHASING

**LUKENS STEEL COMPANY**
**INSPECTION DEPARTMENT**

**NON-DESTRUCTIVE TESTING REP**

| | | | |
|---|---|---|---|
| CUSTOMER | MILL ORDER NO. 8587-14-57106-1 | TYPE TEST REFLECTOSCOPE | DATE [illegible] |
| | QUALITY ASTM A-533-69A GR. B CL.1 | SPECIFICATION CODE CASE 1338-4 ALT.1 MOD. PROC.S-9 | |
| | CUSTOMER NO. P.O. 10-IY-47471 | EQUIPMENT USED SPERRY UM 715 # 31 | |
| CONSIGNED TO | SEARCH UNIT 1-1/8 DIA.2.25 MHz | AMPLITUDE | COUPLANT |
| | SPACING ~~1 X 1 2.25 MHz AB~~ | AMPERAGE | METHOD SOAP & WATER |
| | TRANSDUCER SPERRY | GRID REF. 100% SB 200% AB | TYPE OF SURFACE |
| | TYPE OF PRODS | | BLASTED |
| | INSPECTORS NAME & QUALIFICATIONS [signature] | SIZE 6 RINGS 65-1/2 OD X 8-14 ID X 5 | |
| | WITNESSED BY | MELT & SLAB C9362-1A | MARK Tc. 1 |

I HEREBY CERTIFY THAT THE ABOVE IS CORRECT TO THE BEST OF MY KNOWLEDGE AND BELIEF. U.T. OK per. SPEC.

[signature]
INSPECTION SUPERVISOR

(33)

Motor S/N

NON-DESTRUCTIVE TEST REPORT
QUALITY CONTROL
WESTINGHOUSE FORM 56336

FILE: SHOP ORDER 81P352 #1

TEST: ULTRASONIC ZYGLO DYE PENETRANT MAGNAFLUX HARDNESS

C.C.: Miss Jackson C.C.: ME-2 Insp

C.C.: Mr Carlson C.C.:

| PURCHASE ORDER NO. | SUPPLIER | SECTION | DRAWING NO. | HEAT NO. | FORGING NO. |
|---|---|---|---|---|---|
| 10PV47471<br>10PV47470 | Lukens | ME-2 | 655D855 | C9362<br>C9446 | 1A<br>2B |

MATERIAL

Flywheel Assem.

P.O.S.

RESULTS Dye check of 9.438 bore +18 face OK Baugher 2-25-72

DYE CHECK OF 9.3255 BORE +18 DIA FACE OK
Conduity 2-28-72

DA NO.

REPORTED BY

DATE

U336

**NON-DESTRUCTIVE TEST REPORT**
QUALITY CONTROL
[illegible] 26336

FILE: SHOP ORDER 81 P352 #2

TEST: ULTRASONIC ZYGLO DYE PENETRANT MAGNAFLUX HARDNESS

c.c.: Miss Jackson [illegible] c.c.: ME 2 Insp.
c.c.: Mr. Carlson [illegible] c.c.:

| PURCHASE ORDER NO. | SUPPLIER | SECTION | DRAWING NO. | HEAT NO. | FORGING NO. |
|---|---|---|---|---|---|
| 10 FV 66 469<br>10 PV 47470 | Lukens | ME 2 | [illegible] | C9474<br>C9446 | 3<br>2A |

MATERIAL: FLYWHEEL ASSY. P.D.S.

RESULTS: of dye check of 9.438 dia bore & 18" dia face shows no indications E.G. Patrick 2-23-72
9.375 bore & 18 dia face shows no indications E.G.P. 2-28-72

REPORTED BY: E.G. Patrick DATE: 2-28-72

DA NO.

U336

**NON-DESTRUCTIVE TEST REPORT**
QUALITY CONTROL
WESTINGHOUSE FORM 383[illegible]

FILE: SHOP ORDER 81P352 #3

TEST: ULTRASONIC ZYGLO DYE PENETRANT MAGNAFLUX HARDNESS

c.c.: Miss Jackson c.c.: ME-2 Insp.

c.c.: Mr. Carlson c.c.:

| PURCHASE ORDER NO. | SUPPLIER | SECTION | DRAWING NO. | HEAT NO. | FORGING NO. |
|---|---|---|---|---|---|
| 10PV47470<br>10PV47471 | LUKENS | ME-2 | 6550D85 | C9446<br>C9362 | 2B<br>1A |

| MATERIAL | P.D.S. |
|---|---|
| Flywheel Assy. | |

RESULTS of dye check of 9.4375 dia bore and 18" dia face shows no indications. E.G. Patrick 6-2-72
and 9.375 dia bore & 18" dia face show no indications.

DA NO.

REPORTED BY E. G. Patrick

DATE 6-5-72

**NON-DESTRUCTIVE TEST REPORT**
QUALITY CONTROL
[illegible] FORM 36358

FILE: SHOP ORDER 81P352 #4

TEST: ULTRASONIC ZYGLO DYE PENETRANT MAGNAFLUX HARDNESS

C.C.: Miss Jackson C.C.: ME-2 INSP.

C.C.: Mr. Carlson C.C.:

| PURCHASE ORDER NO. | SUPPLIER | SECTION | DRAWING NO. | HEAT NO. | FORGING NO. |
|---|---|---|---|---|---|
| 10PN47471<br>10PN47470 | LUKENS | ME-2 | 6550D85 | C9362<br>C9446 | 1A<br>2A |

MATERIAL: FLYWHEEL ASSY. P.D.S.:

RESULTS: al dye check of 9.437 dia bore & 18" dia face shows no indications E.a.P. 6-8-72
Dye Check of 9.375 Bore + 18" Dia face OK
Roberts 6/12/72

DA NO. REPORTED BY Roberts DATE 6/12/72

U336

NDE FOR FLYWHEELS

Shop Order 88P976

PT per 84350UD of plate prior to assembly.

P.O. P092-237 Ht. No. D5301-4 Insp.&Date J. Candrasky 5-2-78

PT per 84350UD of plate prior to assembly.

P.O. P092-238 Ht.No. B1717-4 Insp.&Date J. Candrasky 4-19-78

PT per 84350UD after first machining.

Insp. &Date J. Candrasky 5-15-78 and 6-2-78

PT per 84350UD after keyway.

Insp. & Date G. Klalko 10-18-78

UT per 84351WL of finished flywheel.

Insp. & Date J. Reno & J.C. Rice 12-6-78

C. L. Carlson

Original documents are on file at W LRAD East Pittsburgh, Penna. 15112

PURCHASER:
3. WESTINGHOUSE ELEC. CORP.
QUAL. ASSURANCE DEPT.-26A
EAST PITTSBURGH, PA. 15112

# LUKENS STEEL COMPANY

COATESVILLE, PA. 19320

## TEST CERTIFICATE

DATE: 4-11-78  FILE NO 8587-07-9

CONSIGNEE:

| MILL ORDER NO. | CUSTOMER P.O. | |
|---|---|---|
| 54173-1 | P092-238 | MP 4778 DD 2/10 |

THE MATERIAL HAS BEEN MANUFACTURED AND TESTED IN ACCORDANCE WITH PURCHASE ORDER REQUIREMENTS AND SPECIFICATION(S)

WEST PDS-10310CR REV. N 77 A-533 GR. B CL. 1

BEND TEST HOMOGENEITY TEST

1pc-55 P976

### CHEMICAL ANALYSIS

| MELT NO. | C | MN | P | S | CU | SI | NI | CR | MO | V | TI | AL | XXXX | | BASIC PROCESS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B1717 | .20 | 1.33 | .011 | .002 | | .25 | .68 | | .59 | | | | VIP STEEL | | ELEC |

### PHYSICAL PROPERTIES

| MELT NO | SLAB NO | Y.P. PSI x100 | TENSILE PSI x100 | % ELONG IN 2" | % R.A. | XXXX XXXX LOC. | IMPACTS V-NOTCH +70°F. | | | FRACTURE APPEARANCE % SHEAR | DESCRIPTION |
|---|---|---|---|---|---|---|---|---|---|---|---|
| B1717 | 4 | 701 | 925 | 23 | | T | 156 | 160 | 166 | 99-99-99 | 2- 5" -1/2 ID X 66 OD |
| | | 719 | 964 | 26 | | | | | | | |
| | | | | | LATERAL EXPANSION IN INCHES | | .096 | .098 | .098 | | |
| | | | | | | L | 172 | 166 | 180 | 99-99-99 | |
| | | | | | LATERAL EXPANSION IN INCHES | | .096 | .099 | .098 | | |

TRANS. DROP WEIGHT TESTS PER E208 (SIZE P3) @ +20°F., EXHIBIT NO BREAK
NDT IS +10°F. OR BELOW

RINGS AND TESTS HEATED 1625-1675°F., HELD 1/2 HR. PER INCH MIN. AND WATER QUENCHED, THEN TEMPERED 1260°F., HELD 1/2 HR. PER INCH MIN. AND WATER QUENCHED.

RINGS AND TESTS STRESS RELIEVED BY HEATING TO 1100-1150°F., HELD 1 HR. PER INCH MIN. AND FURNACE COOLED TO 600°F.

RELEASED BY Q.C.
TO SEC. 200K
INSP. N. MATEJEVICH DATE 4/21/78

We hereby certify the above information is correct.

E.C. R. C. Klene

FORM ...

LUKENS STEEL COMPANY
INSPECTION DEPARTMENT

NON-DESTRUCTIVE TESTING RE[PORT]

| | | |
|---|---|---|
| CUSTOMER [illegible] Purchasing Dept. ... - 3N53 East Pittsburgh, Pa. 15112 | MILL ORDER NO 5557-99-54173-1 | TYPE TEST Sonic | DATE 2/23/ |
| | QUALITY [illegible] A533 Gr B Cl. 1 | SPECIFICATION A-578 & A-577 Mod. |
| | CUSTOMER NO [illegible] 92-238 | EQUIPMENT USED [illegible] #50 4/13/78 |
| CONSIGNED TO Gate 11, 200K Stores. 700 Braddock Ave. East Pittsburgh, Pa. 15112 | SPACING [illegible] | AMPLITUDE | COUPLANT [illegible] |
| | | AMPERAGE | METHOD Contact |
| | TRANSDUCER [illegible] 2.25 MHz | GRID REF [illegible] | TYPE OF SURFACE [illegible] |
| | TYPE OF PRODS | | |
| | INSPECTORS NAME LEVEL (SNT-TC-1A) [illegible] | GAUGE 5 | WIDTH 6 1/2 I.D. | LENGTH 66 O.D. |
| | WITNESSED BY | MELT & SLAB 2 pcs. B1717-4 | MARK NO | ITEM NO 1 |

I HEREBY CERTIFY THAT THE ABOVE IS CORRECT TO THE BEST OF MY KNOWLEDGE AND BELIEF. [illegible]

[illegible]

PURCHASER:
3. WESTINGHOUSE ELEC. CORP.
QUAL. ASSURANCE DEPT.-2GA
EAST PITTSBURGH, PENNA.
15112

**LUKENS STEEL COMPANY**
COATESVILLE, PA. 19320
**TEST CERTIFICATE**

DATE: 2-24-78 FILE NO. 8587-07-99
CONSIGNEE:

88P476
(41)
92-237

| MILL ORDER NO. | CUSTOMER P.O. | |
|---|---|---|
| 52345-1 | PO92-237 | MP 22378 WM 2/24 |

THIS MATERIAL HAS BEEN MANUFACTURED AND TESTED IN ACCORDANCE WITH PURCHASE ORDER REQUIREMENTS AND SPECIFICATION(S)

WEST PDS-10310CR REV. N 77 A-533 GR. B CL. 1

BEND TEST HOMOGENEITY TEST

## CHEMICAL ANALYSIS

| MELT NO. | C | MN | P | S | CU | SI | NI | CR | MO | V | TI | AL | XXB | | BASIC PROCESS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| D5301 | .18 | 1.30 | .013 | .005 | | .22 | .65 | | .55 | | | | VIP STEEL | | ELEC. |

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## PHYSICAL PROPERTIES

| MELT NO. | SLAB NO. | YIELD PSI X100 | TENSILE PSI X100 | % ELONG IN 2" | % R.A. | BHN | IMPACTS V+70°F. | | | FRACTURE APPEARANCE % SHEAR | DESCRIPTION |
|---|---|---|---|---|---|---|---|---|---|---|---|
| D5301 | 4 | 729 | 950 | 24 | | | T 142 | 143 | 147 | 99-99-99 | 1- 7.5" X 6.5 ID X 73 OD |
| | | 707 | 925 | 25 | | | L 147 | 150 | 148 | 99-99-99 | |

LATERAL EXPANSION IN INCHES
T.090 .088 .089
L.090 .093 .091

TRANS DROP WEIGHT TESTS PER E208(SIZE P-3) @ +20°F., EXHIBIT NO BREAK.
N.D.T. IS +10°F. OR BELOW.

RINGS AND TESTS HEATED 1625-1675°F., HELD 1/2 HR. PER INCH MIN. AND WATER QUENCHED, THEN TEMPERED 1240°F., HELD 1/2 HR. PER INCH MIN. AND WATER QUENCHED.

RINGS AND TESTS STRESS RELIEVED BY HEATING TO 1100-1150°F., HELD 1 HR. PER INCH MIN. AND FURNACE COOLED TO 600°F.

RELEASED BY Q.C.
TO SEC. 20CK
INSP. N. MATEJEVICH DATE [illegible]

We hereby certify the above information is correct.

[illegible]

LUKENS STEEL COMPANY
# INSPECTION DEPARTMENT
## NON-DESTRUCTIVE TESTING REPO

| | | | |
|---|---|---|---|
| CUSTOMER [illegible] Purchasing Dept. [illegible] - 2N53 [illegible] Pittsburgh, Pa 15112 | MILL ORDER NO. [illegible]-99-[illegible]-1 | TYPE TEST [illegible] | DATE [illegible] |
| | QUALITY [illegible] | SPECIFICATION A[illegible] & A577 | |
| | CUSTOMER NO. [illegible] 92-237 | EQUIPMENT USED Mark I [illegible] | |
| CONSIGNED TO [illegible] 11, [illegible] K [illegible] [illegible] Ave [illegible] Pittsburgh, Pa 15112 | SPACING | AMPLITUDE | COUPLANT [illegible] |
| | TRANSDUCER [illegible] 2.25 MHz | AMPERAGE | METHOD [illegible] |
| | TYPE OF PROBES [illegible] 2.25 MHz | GRID REF [illegible] | TYPE OF SURFACE [illegible] |
| | INSPECTORS NAME (LEVEL I-SNT-TC-1A) [illegible] | GAUGE $7\frac{1}{2}$ / WIDTH 6.5 I.D. | LENGTH 73 O.D. |
| | WITNESSED BY | MELT & SLAB D5301-4 | MARK NO. / ITEM NO. 1 |

I HEREBY CERTIFY THAT THE ABOVE IS CORRECT TO THE BEST OF MY KNOWLEDGE AND BELIEF. [illegible signature]

[illegible signature]

INSPECTION SUPERVISOR LEVEL II-SNT-TC-1A

4473

## NDE FOR FLYWHEELS

Shop Order 89P969

PT per 84350UD of plate prior to assembly.

P.O. 179-979 Ht. No. A7503-1 Insp.&Date J. Candursky 11-21-80

PT per 84350UD of plate prior to assembly.

P.O. 179-980 Ht.No. A7503-1 Insp.&Date J. Candursky 11-17-80

PT per 84350UD after first machining.

Insp. &Date J. Candursky & H. O'Grady 1-26-81

PT per 84350UD after keyway.

Insp. & Date L. Veychek 3-25-81

UT per 84351WL of finished flywheel.

Insp. & Date J. Connelly & J. Clancy 3-25-81

C. R. Carlson

Original documents are on file at W LRAD East Pittsburgh, Penna. 15112

PURCHASER
WEST. ELEC. CORP.
QUAL. ASSURANCE DEPT.

# LUKENS STEEL COMPANY
COATESVILLE, PA. 19320
## TEST CERTIFICATE

DATE 9-10-80 FILE NO 8587-07
CONSIGNEE

| MILL ORDER NO. | CUSTOMER P.O. | |
|---|---|---|
| 39437-1 | P179-980 | MP 9480 VS L9880 3/6 |

THIS MATERIAL HAS BEEN MANUFACTURED AND TESTED IN ACCORDANCE WITH PURCHASE ORDER REQUIREMENTS AND SPECIFICATIONS

WEST PDS-10310CR REV. P 78 A-533 GR. B CL. 1 ASME CODE SECT. III SUB NCA N-1160 8/4/81

BEND TEST HOMOGENEITY TEST 89P969

CHEMICAL ANALYSIS

| MELT NO. | C | Mn | P | S | Cu | Si | Ni | Cr | Mo | V | Ti | Al | XX | | BASIC PROCESS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A7503 | .19 | 1.31 | .014 | .008 | | .27 | .67 | | .57 | | | | VIP STEEL | | ELEC. |

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PHYSICAL PROPERTIES

| MELT NO. | SLAB NO. | YIELD PSI 1000 | TENSILE PSI 1000 | % ELONG. IN 2" | % R.A. | XXX XXXX LOC | IMPACTS V +70°F. | | | FRACTURE APPEARANCE % SHEAR | DESCRIPTION |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A7503 | 1 | 757<br>724 | 950<br>924 | 24<br>24 | | T<br>L | 86<br>130 | 86<br>115 | 70<br>117 | 70-70-70<br>80-80-80 | 1- 8" X 7 ID X 66.75 OD |

LATERAL EXPANSION IN INCHES
T .056 .061 .062
L .084 .089 .090

TRANS. DROP WEIGHT TESTS PER E208 (SIZE P-3) FROM TOP & BOTTOM OF RING @ +20°F. EXHIBIT NO BREAK.

MATERIAL TRACEABILITY ...

RINGS AND TESTS HEATED 1625-1675°F., HELD 1/2 HR. PER INCH MIN. AND WATER QUENCHED, THEN TEMPERED 1220°F., HELD 1/2 HR PER INCH MIN. AND WATER QUENCHED.

RINGS AND TESTS STRESS RELIEVED BY HEATING TO 1100-1150°F., HELD 1 HR. PER INCH MIN. AND FURNACE COOLED TO 800°F.

RELEASED BY Q.C.
TO SEC. ME
INSP. N. MATEJEVICH DATE 9/17/80

## LUKENS STEEL COMPANY
## INSPECTION DEPARTMENT

**NON-DESTRUCTIVE TESTING REPORT**

| | | | |
|---|---|---|---|
| CUSTOMER: Westinghouse Elec. Corp. Purchasing Dept LWR Division - 3N53 East Pittsburgh, Pa. 15112 | MILL ORDER NO. 8587-11-39437-1 | TYPE TEST | DATE 9/2/80 |
| | QUALITY PDS-10310GR-F ASTM A533 GrB Cl.1 | SPECIFICATION 75 ASTM-L1-51 & ASTM-A8255 | |
| | CUSTOMER NO. 1R179-980 | EQUIPMENT USED Mark 1 | |
| CONSIGNED TO | SPACING | AMPLITUDE | COUPLANT |
| | | AMPERAGE | METHOD |
| | TRANSDUCER 1x1 2.25 MHz | GRID REF. | TYPE OF SURFACE |
| | TYPE OF PROBE | | |
| | INSPECTORS NAME LEVEL I-SNT-TC-1A) | GAUGE 8 | WIDTH |
| | | | LENGTH |
| | WITNESSED BY | MELT & SLAB A7503-1 | MARK NO |
| | | | ITEM NO 1 |

I HEREBY CERTIFY THAT THE ABOVE IS CORRECT TO THE BEST OF MY KNOWLEDGE AND BELIEF.

PURCHASER: WEST. ELEC. CORP.
QUAL. ASSURANCE DEPT.

# LUKENS STEEL COMPANY

COATESVILLE, PA. 19320

## TEST CERTIFICATE

DATE 9-10-80 FILE NO. 8587-07-11

CONSIGNEE

| MILL ORDER NO. | CUSTOMER P.O. | |
|---|---|---|
| 39438-1 | P179-979 | MP 9480 VS<br>L9880 3/7 |

THE MATERIAL HAS BEEN MANUFACTURED AND TESTED IN ACCORDANCE WITH PURCHASE ORDER REQUIREMENTS AND SPECIFICATIONS

WEST PDS-10310CR REV. P 78 A-533 GR. B CL. 1 ASME CODE SECT. III SUB NCA N-1160 8/4/81

89P969

BEND TEST HOMOGENEITY TEST

### CHEMICAL ANALYSIS

| MELT NO. | C | MN | P | S | CU | SI | NI | CR | MO | V | TI | AL | XX | | BASIC PROCESS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A7503 | .19 | 1.31 | .014 | .008 | | .27 | .67 | | .57 | | | | VIP STEEL | | ELEC. |

### PHYSICAL PROPERTIES

| MELT NO. | SLAB NO. | YIELD PSI X100 | TENSILE PSI X100 | % ELONG. IN 2. | % R.A. | XXX XXX LOC | IMPACTS V +70°F. | | | FRACTURE APPEARANCE % SHEAR | DESCRIPTION |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A7503 | 1 | 757 | 950 | 24 | | T | 86 | 86 | 70 | 70-70-70 | 1- 8" X 7 ID X 76.5 OD |
| | | 724 | 924 | 24 | | L | 130 | 115 | 117 | 80-80-80 | |
| | | | | | | LATERAL EXPANSION IN INCHES | | | | | |
| | | | | | | T | .056 | .061 | .062 | | |
| | | | | | | L | .084 | .089 | .090 | | |

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TRANS. DROP WEIGHT TESTS PER E208 (SIZE P-3) FROM TOP & BOTTOM OF RING @ +20°F. EXHIBIT NO BREAK.

RINGS AND TESTS HEATED 1625-1675°F., HELD 1/2 HR. PER INCH MIN. AND WATER QUENCHED, THEN TEMPERED 1220°F., HELD 1/2 HR. PER INCH MIN. AND WATER QUENCHED.

RING AND TESTS STRESS RELIEVED BY HEATING TO 1100-1150°F., HELD 1 HR. PER INCH MIN. AND FURNACE COOLED TO 800°F.

MATERIAL TRACEABILITY RE[illegible]

RELEASED BY Q.C.
TO SEC. ME 2
INSP. N. MATIJEVICH DATE 9-12-

We hereby certify the above information is correct.

SUPERVISOR TESTING

LUKENS STEEL COMPANY

# INSPECTION DEPARTMENT

NON-DESTRUCTIVE TESTING REPORT

| | | | |
|---|---|---|---|
| CUSTOMER Westinghouse Elec. Corp. Purchasing Dept. ... East Pittsburgh, Pa. 15112 | MILL ORDER NO. 077-11-39438-1 | TYPE TEST Sonic | DATE 9/2/81 |
| | QUALITY PDS-10310 ... ASTM A533 ... | SPECIFICATION ... | |
| | CUSTOMER NO. ... 8179-979 | EQUIPMENT USED ... | |
| CONSIGNED TO | SPACING | AMPLITUDE | COUPLANT |
| | | AMPERAGE | METHOD |
| | TRANSDUCER ... | GRID REF. ... | TYPE OF SURFACE |
| | TYPE OF PRODS | | |
| | INSPECTORS NAME LEVEL (ASNT-TC-1A) ... | GAUGE 8 ... | WIDTH ... LENGTH ... |
| | WITNESSED BY | MELT & SLAB ...3-1 | MARK NO |
| | | | ITEM NO 1 |

37

I HEREBY CERTIFY THAT THE ABOVE IS CORRECT TO THE BEST OF MY KNOWLEDGE AND BELIEF.

# APPENDIX E

## RESPONSE TO FIRST NRC REQUEST FOR ADDITIONAL INFORMATION

**Duquesne Light Company** Beaver Valley Power Station
PO Box 4
Shippingport, PA 15077-0004

SUSHIL C JAIN
Division Vice President
Nuclear Services
Nuclear Power Division

(412) 393-5512
Fax (412) 643-8069

June 14, 1996

U. S. Nuclear Regulatory Commission
Attention: Document Control Desk
Washington, DC 20555-0001

**Subject: Beaver Valley Power Station, Unit No. 1 and No. 2**
**BV-1 Docket No. 50-334, License No. DPR-66**
**BV-2 Docket No. 50-412, License No. NPF-73**
**Response to Request for Additional Information Concerning WCAP-14535**

Attached is the response to an NRC staff request for additional information provided by letter dated May 1, 1996, concerning WCAP-14535, "Topical Report on Reactor Coolant Pump Flywheel Inspection Elimination." Beaver Valley submitted the subject report by letter dated January 24, 1996, as the industry's lead plant on this issue.

Please direct questions regarding this submittal to Mr. Roy K. Brosi at (412) 393-5210.

Sincerely,

Sushil C. Jain

c: w/enclosure:
- Mr. L. W. Rossbach, Sr. Resident Inspector
- Mr. T. T. Martin, NRC Region I Administrator
- Mr. D. S. Brinkman, Sr. Project Manager - (3 copies)
- Ms. Diane Jackson, Westinghouse Electric Corporation

w/o enclosure:
- Mr. David Haile, South Carolina Electric and Gas Co.
- Mr. Pat Naughton, Virginia Power
- Mr. Don Gulling, Florida Power Corporation
- Mr. Ben Mays, TU Electric Co.
- Mr. Jim Edwards, Georgia Power Co.
- Mr. K. J. Voytell, Westinghouse Electric Corporation
- Mr. S. A. Binger, Jr., Westinghouse Electric Corporation

**Westinghouse Electric Corporation** **Energy Systems**

Box 355
Pittsburgh Pennsylvania 15230 0355

ESBU/WOG-96-212

June 17, 1996

To: Dennis Weakland, Duquesne Light Company
David Haile, South Carolina Electric & Gas
Pat Naughton, Virginia Power
Lorretta Cecilia, Florida Power Corporation
Ben Mays, TU Electric Company
Jim Edwards, Southern Nuclear Operating Company

Subject: Westinghouse Owners Group
<u>Response to NRC Request for Additional Information on WCAP-14535 "Topical Report on Reactor Coolant Pump Flywheel Inspection Elimination" (MUHP-5042)</u>

Reference: WOG Letter ESBU/WOG-96-173 dated 5/17/96 Subject: NRC Request for Additional Information on WCAP-14535 "Topical Report on Reactor Coolant Pump Flywheel Inspection Elimination" (MUHP-5042)

The original submittal on this subject was made on behalf of the WOG by Duquesne Light Company for Beaver Valley Station on January 24, 1996. A similar submittal was made by Entergy for Arkansas Nuclear One on behalf of the Combustion Engineering Owners Group. The NRC has performed a preliminary review of the Beaver Valley submittal, and has determined that additional information is required to complete the review. A letter dated May 1, 1996 requesting additional information (RAI) was transmitted to Mr. J. E. Cross of Duquesne Light Company from Mr. Donald S. Brinkman of the NRC. The NRC has requested that Duquesne Light Company provide a response to the RAI within 45 days of receipt of the letter.

The purpose of this letter is to provide input to Duquesne Light Company for input to their NRC letter responding to the RAI.

The NRC plans to resolve this issue by the end of this summer. We will keep you informed of any new developments on this subject.

Please contact Warren Bamford at (412) 374-6515 with additional questions or comments.

Regards,

Sumner Binger

S.A. Binger, Jr
Project Engineer
Westinghouse Owners Group

SAB/ygs

# Response to NRC Request for Additional Information on WCAP-14535

**Item 1:**

*Section 1.1 Previous Flywheel Integrity Evaluations, Page 1-3 - It was stated, "Since shrink fit forces would retard the growth of radial cracks in the keyway area, they were omitted from the analysis of the keyway crack." Physically, the shrink fit forces can be considered as internal pressure acting on the inner bore of the reactor coolant pump (RCP) flywheel. Thus, it would accelerate, not retard, the growth of radial cracks in the keyway area. Provide sufficient finite element modelling details and results to validate your claim or revise your results by taking into account the effect due to shrink fit forces, which was shown by the Combustion Engineering Owners Group in report SIA-94-080, "Relaxation of Reactor Coolant Pump Flywheel Inspection Requirements," which was submitted to the NRC on April 4, 1995, on dockets 50-313 and 50-368. These shrink fit forces were shown in that report to be capable of producing stresses of comparable magnitude to those produced by the centrifugal force when the flywheel was running at the normal operating speed.*

**Response to Item 1:**

The shrink fit forces do add to the stresses at the flywheel bore, but fatigue crack growth is approximately proportional to the cube of the stress range applied during a given cycle. For the flywheel, the stress range is from the rest condition (zero rpm) to normal operating speed. Therefore, if the shrink fit stresses had been used, the stress range would be smaller because the shrink fit stresses are significantly lower at normal operating speed than at the rest condition. Our calculations used a zero stress state at rest, which maximized the crack growth predictions. The amount of conservatism induced by this assumption is discussed below.

Westinghouse has evaluated the effect of shrink fit forces on crack growth. Due to the large number of flywheels in service, actual shrink fit values were not obtained for each pump, but typical shrink fit values for flywheels which are attached directly to the RCP motor shaft are 0.5 to 1.0 mil on the flywheel bore, or 0.00025 inch to 0.0005 inch on the bore radius. For conservatism, and to be consistent with Combustion Engineering Owners Group report SIA-94-080, "Relaxation of Reactor Coolant Pump Flywheel Inspection Requirements," a shrink fit of 0.0052 inch on the bore radius was imposed for evaluation purposes. This is approximately one order of magnitude higher than the typical shrink fit for flywheels which are attached directly to the RCP motor shaft. A shrink fit of 0.0125 inch was used for the spoked flywheel, as was used in the Combustion Engineering Owners Group report.

Hoop stresses control the growth of radially oriented cracks in the flywheel. Shrink fit hoop stresses for the flywheels at rest are on the order of one to three times the hoop stresses produced by centrifugal forces alone, when the flywheels are running at the normal operating speed. However, as the flywheel rotational speed increases, the shrink fit hoop stresses decrease, due to the radial growth of the flywheel bore radius. This growth may be determined by the following equation:

$$\Delta a = \frac{1}{4} \frac{\rho \omega^2}{386.4} \frac{a}{E} [(3 + \nu) b^2 + (1 - \nu) a^2]$$

| | | | |
|---|---|---|---|
| where: | a | = | bore radius (inches) |
| | b | = | outer radius (inches) |
| | $\rho$ | = | flywheel material density (0.283 $lb_m$/cubic inch) |
| | $\omega$ | = | flywheel angular velocity (radians per second) |
| | E | = | Young's modulus ($30 \times 10^6$ psi) |
| | $\nu$ | = | Poisson's ratio (0.3) |

The total hoop stress may be determined by adding the shrink fit and centrifugal force components. The stresses at the flywheel keyway location are shown in Figure 1 for Flywheel Group 1, which is representative of the Beaver Valley Units 1 and 2 flywheels. Stress plots for the other flywheel groups are similar to Figure 1.

Fatigue crack growth rate may be characterized in terms of the range of applied stress intensity factor ($\Delta K_I$), and is generally of the form:

$$\frac{da}{dN} = C_0 (\Delta K_I)^n$$

where

| | | |
|---|---|---|
| da/dN | = | crack growth rate (inches/cycle) |
| n | = | slope of the log (da/dN) versus log ($\Delta K_I$) |
| $C_0$ | = | scaling constant |

The fatigue crack growth behavior is affected by the R ratio ($K_{min}/K_{max}$) and the environment. Reference fatigue crack growth behavior of carbon and low alloy ferritic steels exposed to an air environment is provided by the above equation with $n = 3.07$ and $C_0 = 1.99 \times 10^{-10}$ S. S is a scaling parameter to account for the R ratio and is given by $S = 25.72 (2.88 - R)^{-3.07}$ where $0 \leq R < 1.0$.

In the WCAP-14535 evaluation, the maximum stress intensity factor range occurred between RCP shutdown (zero rpm) and the normal operating speed. Shrink fit was excluded, therefore the R ratio was zero, S was 1, and $C_0$ was $1.99 \times 10^{-10}$.

Including shrink fit results in an R ratio of approximately 0.9, an S of approximately 3.2, and a $C_0$ of approximately $6.4 \times 10^{-10}$. Therefore, the scaling constant ($C_0$) is approximately 3.2 times higher than not including shrink fit.

The range of applied hoop stress for excluding shrink fit was at least twice that for including shrink fit for all flywheel groups. Therefore, the relative fatigue crack growth rate for including shrink fit may be estimated by the following equation:

$$\frac{\text{Rate with Shrink Fit}}{\text{Rate without Shrink Fit}} = (3.2)(0.5)^{3.07}$$

The fatigue crack growth rate for including shrink fit is at most 40% of the rate for not including shrink fit, for the assumed shrink fit values discussed above. Therefore, shrink fit retards the growth of radial cracks in the keyway area, and excluding shrink fit yields conservative fatigue crack growth results, as reported in WCAP-14535.

**Item 2:**

*Section 1.1 Previous Flywheel Integrity Evaluations, Page 1-3 - The fatigue analysis is dependant on the premise that UT equipment used for examinations of RCP flywheels at these facilities is capable of accurately detecting and sizing 0.24 inch long near surface flaw. Provide your basis supporting the probability of detection (POD) for the examinations performed. Provide details on how the POD values were determined, qualified, and used in concluding the assumed size of the initial flaw.*

**Response to Item 2:**

The initial crack length of 0.24 inch was used in a previous evaluation of RCP flywheel integrity by Babcock and Wilcox (Report BAW-10040, December 1973, "Reactor Coolant Pump Assembly Overspeed Analysis"). This length was assumed to be the largest crack that could be missed in nondestructive testing.

As seen in Table 4-4 of WCAP-14535, crack growth assuming extremely large initial flaw lengths (from 2.04 to 3.28 inches) was found to be insignificantly small over a 60 year extended plant life. In the crack growth evaluation, 6000 RCP start/stop cycles were assumed, which is conservative with respect to actual operation. This evaluation suggests that very large initial flaws can be tolerated. Such flaws are of a size which are expected to be detectable with the examination procedure of Attachment A.

An alternative method of evaluating this issue is to define an "allowable" flaw size based on the application of a margin to the calculated critical flaw size. The approach used here is to apply the margins of ASME Section XI. The results of this approach are provided in Table 1 below. In this table, crack length is measured radially from the keyway, and percentage through the flywheel is the crack length divided by the radial length from the keyway to the flywheel outer radius.

The inspection methods used for flywheels are capable of finding flaws much smaller than the smallest allowable flaw in Table 1.

**Table 1: Allowable Crack Lengths for Flywheel Normal Speed and Overspeed**

| Flywheel Group | Allowable Crack Lengths in Inches and % through Flywheel | | | | | |
|---|---|---|---|---|---|---|
| | 1200 rpm | | | 1500 rpm | | |
| | $RT_{NDT}$ = 0°F | $RT_{NDT}$ = 30°F | $RT_{NDT}$ = 60°F | $RT_{NDT}$ = 0°F | $RT_{NDT}$ = 30°F | $RT_{NDT}$ = 60°F |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1 | 3.0" (9%) | 1.8" (5%) | 1.0" (3%) | 8.5" (26%) | 3.8" (12%) | 1.5" (4%) |
| 2 | 3.4" (10%) | 1.9" (6%) | 1.1" (3%) | 9.4" (29%) | 4.2" (13%) | 1.8" (5%) |
| 10 | 3.2" (12%) | 1.6" (6%) | 1.0" (4%) | 8.3" (31%) | 3.7" (14%) | 1.6" (6%) |
| 14 | 8.1" (29%) | 2.8" (10%) | 1.7" (6%) | 15.2" (55%) | 7.5" (27%) | 4.1" (15%) |
| 15 | 2.6" (13%) | 1.1" (5%) | 0.7" (3%) | 5.7" (28%) | 2.6" (13%) | 1.3" (6%) |
| 16 | 5.8" (24%) | 1.8" (7%) | 1.4" (6%) | 12.2" (50%) | 5.7" (23%) | 3.0" (12%) |

Over the past ten years, the examination techniques employed have improved, particularly with the use of the defocused gage hole probe. The detectability of the gage holes at various metal paths displayed in Attachment B indicate that the inspection methods used for flywheels are capable of finding flaws much smaller than those identified in Table 1.

In Attachment B, the 1.25 inch diameter gage holes (effectively side drilled holes) were clearly identified at a metal path which is nearly twice the metal path distance involved in the inspection of the keyway area. It should be noted that it is conservatively estimated that the effective reflective surface of a side drilled hole is a 30° arc. The reflective surface from a 1.25 inch gage hole would therefore be 0.33 inch. This is clearly smaller than the smallest allowable flaw in Table 1.

**Item 3:**

*Inspection, Page 3-1 to 3-6 - Provide additional information regarding whether the UT examinations at Beaver Valley Power Station, Units Nos. 1 and 2 were qualified relative to inspection of RCP flywheels. Regardless of whether a formal qualification was performed, please include in your response the following:*

*a. Any information supporting qualification of the examinations of RCP flywheels.*

*b. Any information supporting qualification of the personnel performing the examinations of RCP flywheels.*

*c. Any information regarding the degree of uncertainty in UT measurements based on the procedures and personnel qualification basis.*

**Response to Item 3:**

All of the plants covered by WCAP-14535, except one, have flywheels which are made of A533 Grade B Class 1 or A516 Grade 70 steel, which is reactor vessel quality steel. (The exception is Haddam Neck, which has flywheels made of boiler plate steel. A discussion on this plant is provided in WCAP-14535, Appendix B. Haddam Neck has conducted a separate demonstration of their inspection capability, as documented in Docket No. 50-213 B15230, dated 08/10/95).

The ultrasonic examination procedure used at Beaver Valley is included as Attachment A. This procedure includes qualification requirements of the personnel and equipment for the RCP flywheels. Additional information supporting requalification of the personnel performing the examinations of RCP flywheels is provided in Attachment B. Attachment B also includes enhancements made to the probe design to improve examination capabilities, and an evaluation of those enhancements.

Examination personnel are qualified to SN-TC1A a are trained in the use of the UT procedure (Attachment A). Duquesne Light Company NDE Level III personnel perform the examinations.

**Item 4:**

*Section 4.3 Nonductile Failure Analysis - It was stated, "It was shown that cracks emanating from the center of the keyway yielded higher stress intensity factors than cracks emanating from the keyway corner, and ...." Provide the detailed stress plot around the keyway area from your finite element method analysis and provide an estimation of the stress intensity factors for the case when the perturbed stress distribution due to the keyway is used instead of the closed form solution used in this report.*

**Response to Item 4:**

Finite element analyses were completed for cracks emanating from the center of the keyway and from the corner of the keyway. The results clearly show that a crack at the center of the keyway is more severe. This work was documented in an earlier submittal to the NRC in 1974-1975, and in the attached ASME technical paper (Attachment C) entitled "Reactor Coolant Pump Flywheel Overspeed Evaluation," by P. C. Riccardella and W. H. Bamford. The comparison of interest is shown in Figure 4 of the technical paper.

Note that the difference in stress intensity factor occurs only for short crack lengths, and the effect of the keyway on the stress intensity factor is only seen for cracks shorter than one inch. Results of the overall fracture evaluation show that flywheel limiting speed for small crack lengths is governed by ductile failure limits, as shown in Figure 10 of Attachment C. Therefore, this item is not relevant to the flywheel integrity.

**Item 5:**

*Section 4.4 Excessive Deformation Analysis - Table 4-5 listed the change in bore radius at the speed of 1500 rpm for flywheels in various flywheel groups. Provide the amount of original shrink-fit and the percentage of shrink-fit lost at 1500 rpm for the typical flywheel in each flywheel group of the table.*

**Response to Item 5:**

The percentage of shrink fit lost at 1500 rpm is shown in Table 2 below for the assumed worst case shrink fit values discussed in item 1 above. (For the typical shrink fits of 0.00025 to 0.0005 inch for flywheels which are attached directly to the RCP motor shaft, discussed in item 1 above, 100% of the shrink fit would be lost at 1500 rpm for all flywheel groups). Figure 2 provides flywheel bore expansion and corresponding shrink fit for speeds of zero to 1500 rpm, for Flywheel Group 1, which is representative of the Beaver Valley Units 1 and 2 flywheels. Displacement plots for the other flywheel groups are similar to Figure 2.

**Table 2: Shrink Fit Lost at 1500 rpm**

| Flywheel Group | Flywheel Outer Radius (inches) | Flywheel Bore Radius (inches) | Assumed Shrink Fit (inches) | Shaft Radial Expansion (inches) | Flywheel Bore Radial Expansion (inches) | Shrink Fit at 1500 rpm (inches) | Shrink Fit Lost at 1500 rpm (%) |
|---|---|---|---|---|---|---|---|
| 1 | 38.250 | 4.6875 | 0.0052 | 0.0000 | 0.0034 | 0.0018 | 65 |
| 2 | 37.875 | 4.1875 | 0.0052 | 0.0000 | 0.0030 | 0.0022 | 58 |
| 10 | 36.000 | 8.0625 | 0.0052 | 0.0000 | 0.0052 | 0.0000 | 100 |
| 14 | 32.500 | 4.1875 | 0.0052 | 0.0000 | 0.0022 | 0.0030 | 42 |
| 15 | 36.000 | 15.2500 | 0.0125 | 0.0004 | 0.0102 | 0.0027 | 78 |
| 16 | 32.500 | 6.900 | 0.0052 | 0.0000 | 0.0037 | 0.0015 | 71 |

Notes for Table 2:

1) Shrink Fit at 1500 rpm = Assumed Shrink Fit + Shaft Radial Expansion - Flywheel Bore Radial Expansion.
2) Shrink Fit Lost at 1500 rpm = (Assumed Shrink Fit - Shrink Fit at 1500 rpm)/Assumed Shrink Fit.

Based on the worst case assumed shrink fits shown in Table 2, shrink fit will exist at 1500 rpm for all flywheel groups except Flywheel Group 10. The shrink fit stresses at 1500 rpm will reduce the critical crack lengths reported in WCAP-14535, Table 4-3. Critical crack lengths including shrink fit stresses at 1500 rpm are provided in Table 3 below. As shown, these lengths are significantly larger than the lengths which are expected to be detectable with the examination procedure of Attachment A. Stress intensity factor as a function of critical crack length is shown in Figure 3, for Flywheel Group 1, which is representative of the Beaver Valley Units 1 and 2 flywheels. Stress intensity factor plots for the other flywheel groups are similar to Figure 3.

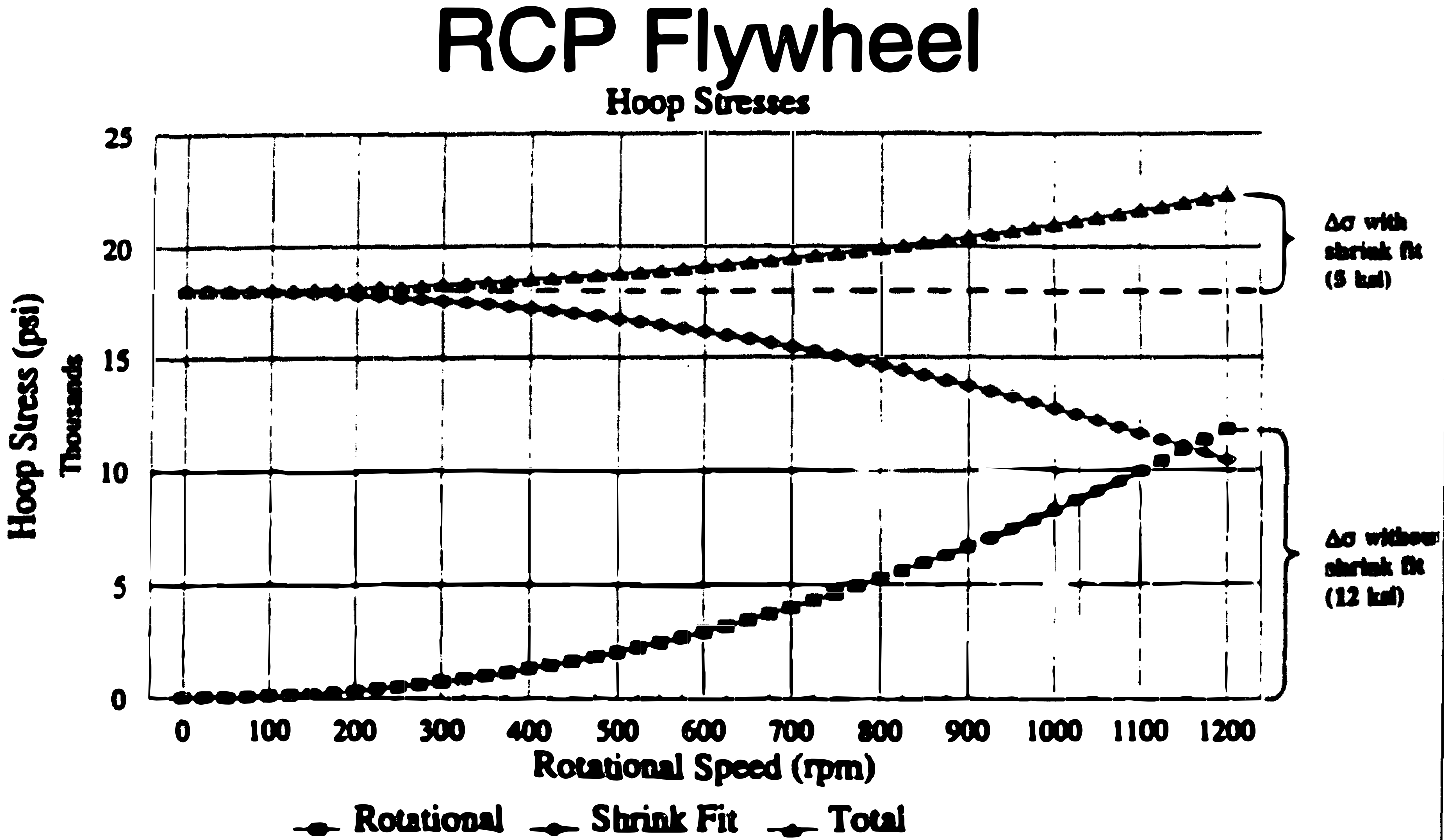
**Table 3: Critical Crack Lengths Including Shrink Fit for Flywheel Overspeed of 1500 rpm**

| Flywheel Group | Critical Crack Length in Inches and % through Flywheel | | |
|---|---|---|---|
| | $RT_{NDT}$ = 0°F | $RT_{NDT}$ = 30°F | $RT_{NDT}$ = 60°F |
| 1 | 15.2" (46%) | 5.4" (16%) | 1.3" (4%) |
| 2 | 16.0" (49%) | 5.6" (17%) | 1.1" (3%) |
| 10 | 15.1" (56%) | 7.5" (27%) | 3.3" (12%) |
| 14 | 18.7" (67%) | 10.9" (39%) | 2.5" (9%) |
| 15 | 8.2" (40%) | 3.6" (18%) | 1.6" (8%) |
| 16 | 16.1" (66%) | 9.3" (38%) | 3.7" (15%) |

It is important to point out that most flywheels are designed to lose their shrink fit at operating speed. The three keyways maintain the centering of the flywheels, which assures that balance is maintained. The imposition of a very large shrink fit would be detrimental to flywheel reliability, because of the difficulty in installation and removal of the flywheel. This would in tern detract from the consistency of assembly.

A concern was raised about excessive deformation in the Regulatory Guide. Excessive deformation was defined as "any deformation such as an enlargement of the bore that could cause separation directly or could cause an unbalance of the flywheel leading to structural failure or separation of the flywheel from the shaft." Therefore, the concern about excessive deformation is not related to the loss of shrink fit, but instead relates to the amount of deformation which could cause unbalance or failure.

Our extensive calculations have shown that the speed at which excessive deformations could occur is greater than or equal to the limiting flywheel speed for ductile failure. The flywheel would fail due to plastic instability at speeds of 3155 to 4032 rpm, as shown in Table 4-2, page 4-5 of WCAP-14535. Even with large flaws, the failure speed exceeds 3000 rpm, which is twice the maximum overspeed of 1500 rpm. Therefore, there is no concern with excessive deformation.




| | | |
|---|---|---|
| Flywheel Group 1 | | |
| Radial Location for Plot = | 5.6245 | inch |
| Assumed Shrink Fit (Delta a) = | 0.0052 | inch |
| Flywheel Outer Radius (b) = | 38.25 | inch |
| Flywheel Bore Radius (a) = | 4.6875 | inch |
| Keyway Radial Length = | 0.937 | inch |

**Figure 1: Flywheel Group 1 Rotational and Shrink Fit Stresses**

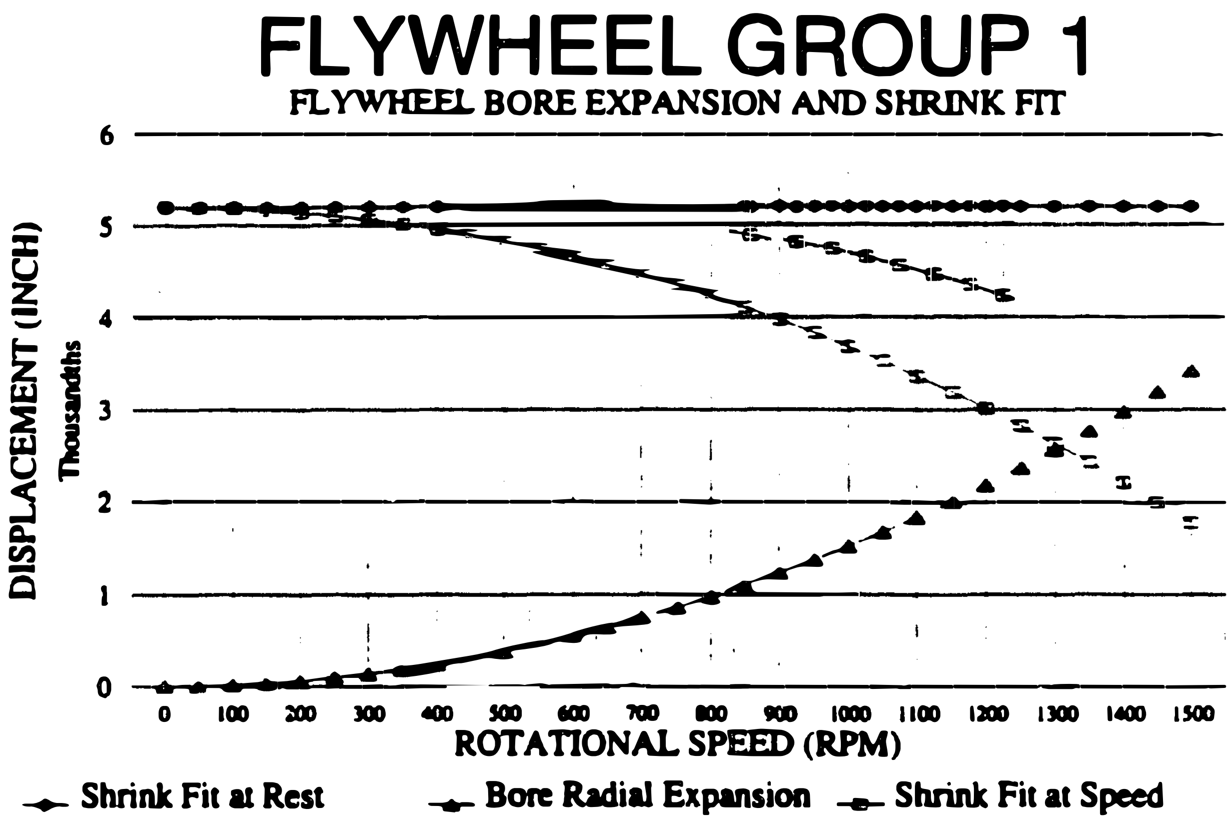
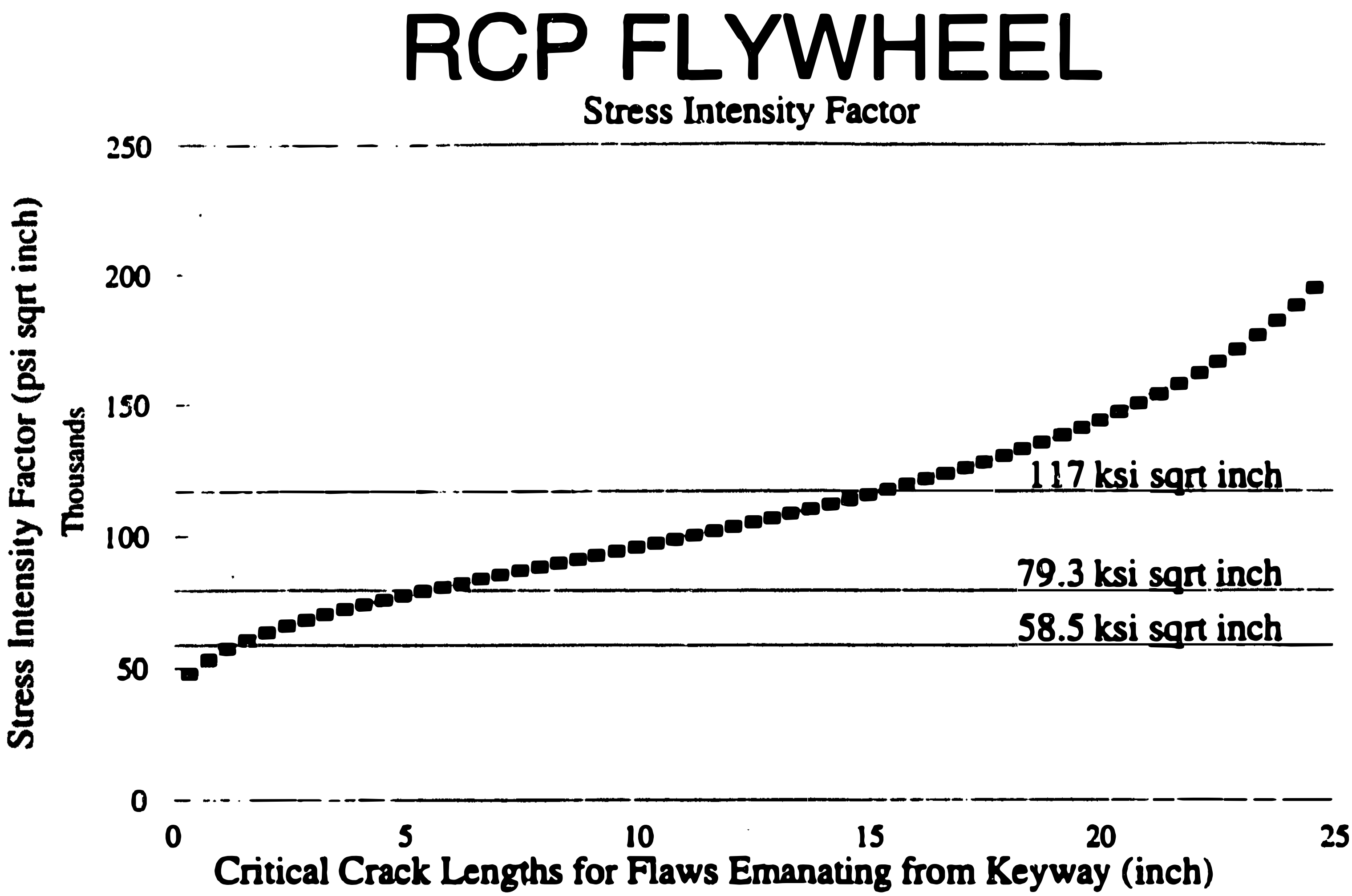



**Figure 2: Flywheel Group 1 Bore Expansion and Corresponding Shrink Fit**




| | |
|---|---|
| **Flywheel Group 1** | |
| **Outer Radius (b) =** | **38.25 inches** |
| **Flywheel Bore (a) =** | **4.6875 inches** |
| **Keyway Length (d1) =** | **0.937 inches** |
| **Shrink Fit (Delta a) =** | **0.0018 inch @ 1500 rpm** |

**Figure 3: Flywheel Group 1 Stress Intensity Factor Including Shrink Fit**

**ATTACHMENT A**

**INFORMATION ON QUALIFICATION OF RCP FLYWHEEL EXAMINATIONS AT BEAVER VALLEY**

DUQUESNE LIGHT COMPANY
Nuclear Power Division
Quality Services Unit
Quality Services Inspection & Examination Department

| TITLE: Manual Ultrasonic Examination of Reactor Coolant Pump (RCP) Flywheel | NDE PROCEDURE NUMBER UT-304 | |
|---|---|---|
| | REVISION 7 | PAGE 1 OF 11 |

| | | | |
|---|---|---|---|
| Ronald A. Pey | 11/9/94 | Timothy E. Hemmick L.III | 11-14-94 |
| PREPARED BY | DATE | LEVEL III APPROVAL | DATE |
| M. A. Reyan | 11-17-94 | Robert Dunn | 11/18/94 |
| QSIE DIRECTOR | DATE | ANII REVIEW | DATE |
| N/A Non-Intent | | K. Wham | 11/22/94 |
| OSC REVIEW | DATE | QS MANAGER APPROVAL | DATE |
| K. Wham for LRF | 11/22/94 | | |
| GENERAL MANAGER NUCLEAR OPS. | DATE | | |

## INDEX

| PAGE | REVISION | EFFECTIVE DATE |
|---|---|---|
| Entire Procedure | 4 | January 3, 1991 |
| Entire Procedure | 5 | November 27, 1992 |
| Entire Procedure | 6 | April 6, 1993 |
| Entire Procedure | 7 | December 9, 1994 |

## 1.0 PURPOSE AND SCOPE

1.1 To provide minimum requirements for the manual ultrasonic straight beam examination of RCP flywheels.

1.2 This procedure is intended to meet the ultrasonic requirements of NRC Regulatory Guide 1.14 Revision 1 (Reference 6.1).

1.3 This procedure is applicable to BVPS Units 1 and 2.

## 2.0 EXAMINATION REQUIREMENTS

NOTE: When using Ultragel II couplant, safety glasses or goggles are required. Individuals that are sensitive to detergents should wear gloves.

2.1 Ensure contact surfaces are clean and free from all foreign matter, pits, nicks, or dents, etc., that would adversely affect or limit the examination. If such conditions are noted, correct them prior to conducting the examination.

2.2 Examine the entire volume of the RCP flywheel to the maximum extent possible. Attach a drawing of any limitations encountered to the Flywheel UT Examination Report (Attachment 7.1).

2.3 Prior to beginning examinations, calibrate the ultrasonic instrument sweep to represent a linear 40 inch longitudinal wave sound path. This may be accomplished using a carbon steel IIW block and the straight beam search unit specified in Para. 5.2.2.

2.4 Keyway Corner Examination.

2.4.1 Calibration

A. Apply couplant to one of the 1 inch diameter gage holes (A, B, C or D for Unit 1; A, B, C, D, E, or F for Unit 2).

B. Insert the gage hole probe into the hole and direct the beam toward the flywheel center bore hole.

C. Measure the distance from the gage hole to the center bore hole. Adjust the delay control only to position the response at the proper sweep position corresponding to the physical measurement.

D. Obtain the maximum response from the center bore hole and adjust the gain to bring the response to 80% (±5%) FSH.

E. Record the instrument gain setting and reflector sweep position on the Flywheel UT Examination Report.

2.4.2 Examination

A. Increase the instrument gain a minimum of 6 dB.

B. Starting at the top of the gage hole, rotate the probe from the maximum bore signal area to obtain the maximum response from the keyway corner, then back to the bore response. Continue to examine the full length of the keyway by inserting the probe in 1/2" increments.

C. Examine the keyway corners for indications propagating from the keyway at approximately 90 degrees to the sound path.

D. Repeat the entire calibration and examination cycle from each of the remaining gage holes, confirming calibration after each examination.

2.4.3 Recording

A. Record all indications that exhibit a deviation from the normal keyway geometry response observed from each gage hole examination.

2.5 Radial Gage Hole Examination.

2.5.1 Calibration (Unit 1 Attachment 7.2)

A. Apply couplant to gage hole D.

B. Insert the gage hole probe into gage hole D and obtain the maximum response from ream bolt hole 5.

C. Adjust the instrument gain to bring the response to 80% (±5%) FSH.

D. Rotate the probe to obtain the maximum response from ream bolt hole 2.

E. Construct a distance-amplitude correction (DAC) curve by connecting the maximum response points with a line.

F. Record the instrument gain setting, sweep positions and amplitudes on the Flywheel UT Examination Report.

2.5.2 Calibration (Unit 2 Attachment 7.3)

A. Apply couplant to gage hole F.

B. Insert the gage hole probe into gage hole F and obtain the maximum response from ream bolt hole 4.

C. Adjust the instrument gain to bring the response to 80% (±5%) FSH.

D. Rotate the probe to obtain the maximum response from ream bolt hole 1.

E. Construct a distance-amplitude correction (DAC) curve by connecting the maximum response points with a line.

F. Record the instrument gain setting, sweep positions, and amplitudes on the Flywheel UT Examination Report.

2.5.3 Examination

A. Increase the instrument gain a minimum of 6 dB.

B. Starting at the top of the gage hole, slowly rotate the probe 360 degrees to examine the volume of the flywheel. Observe reflectors from flywheel geometric features as the probe is rotated, identifying each reflector source as it appears. Continue to examine the volume by inserting the probe in 1/2" increments.

C. Repeat the examination from the remaining gage holes using the initial calibration settings.

D. Confirm instrument calibration when radial gage hole examinations are completed using the steps outlined in para. 2.5.1 or 2.5.2.

2.5.4 Recording

A. Record all <u>unidentified</u> reflectors equal to or greater than 50% DAC.

2.6 Periphery Examination (Attachment 7.2 and 7.3)

2.6.1 Calibration

A. Couple the straight beam search unit to the outside edge of the <u>lower</u> flywheel plate and obtain the maximum response from ream bolt hole 5.

B. Adjust the gain to bring the response to 80% (±5%) FSH and mark the point on the screen.

C. Couple the straight beam search unit to the outside edge of the upper flywheel plate and obtain the maximum response from ream bolt hole 5. Mark this point on the screen.

D. Construct a DAC curve by connecting the response points with a line.

E. Record the instrument gain setting, sweep positions and amplitudes on the Flywheel UT Examination Report.

2.6.2 Examination

A. Increase the instrument gain a minimum of 6 dB.

B. Scan the flywheel periphery face to include the area from the edge up to and including the ream bolt holes. Conduct this exam on both the upper and lower plates, 360 degrees, around the periphery.

C. Where possible, progressively move the probe across and along the flywheel edge so as to scan the entire edge overlapping each previous scan by at least 25% of the transducer diameter.

2.6.3 Recording

A. Record all unidentified reflectors equal to or greater than 50% DAC.

2.7 Calibration Confirmation

2.7.1 Confirm calibration at the intervals specified within each examination category.

2.7.2 Evaluate calibration confirmation in accordance with the following criteria:

A. A DECREASE in sensitivity of more than 2dB requires recalibration and reexamination of all items examined since the previous acceptable calibration or calibration confirmation.

B. An INCREASE in sensitivity of more than 2dB requires recalibration and reinvestigation of all indications recorded since the previous acceptable calibration or calibration confirmation.

C. If any point on the DAC curve has moved more than 10% of the sweep division reading, correct the sweep range calibration and note the correction on the flywheel examination report. If reflectors were recorded, recalibrate and reexamine all items examined since the previous acceptable calibration or calibration confirmation.

2.8 Post-Examination Cleaning

2.8.1 Dry-wipe the area to remove any temporary markings and couplant.

## 3.0 RECORDING REQUIREMENTS

3.1 Record data specified within each examination category on the Reactor Coolant Pump Flywheel Ultrasonic Examination Report.

3.2 Reports are to be numbered in accordance with QSP 9.4.

3.3 Documentation is considered as lifetime and treated as such in accordance with QSP 17.1.

## 4.0 ACCEPTANCE STANDARDS

4.1 Due to the technique employed and the unique nature of this examination, all recorded reflectors will be evaluated by a UT Level III to determine their origin, size, location and orientation. This evaluation process will be performed and documented in accordance with GP-105.

## 5.0 PERSONNEL AND EQUIPMENT QUALIFICATIONS

5.1 Personnel Qualifications

5.1.1 Personnel performing examinations shall only perform tasks commensurate with their experience and level of certification.

A. Duquesne Light personnel are certified in accordance with QSP 2.3.

B. All individuals performing examinations to DLC UT procedure(s) shall receive sufficient training and orientation to ensure understanding of procedural requirements.

C. Ultrasonic examination personnel who determine which indications ~~are to be recorded~~ shall have successfully completed a qualification program administered by the Quality Services Inspection & Examination Department which demonstrates proficiency in discriminating between ~~flaw~~ indications and indications of geometric or metallurgical origin.

5.2 Equipment Qualifications

5.2.1 UT Instrument - Use a pulse-echo instrument capable of establishing a minimum 40 inch metal path in the flywheel material. Additionally the instrument must meet the linearity requirements of UT-301.

5.2.2 Search Unit(s) - Use a 1.0 inch diameter, 2.25 MHz straight beam search unit for initial metal path calibration and for the periphery scans. For the gage hole examinations, use a .5" x .1", 2.25 MHz gage hole inspection wand. (Megasonics C1281 1" bore probe).

5.2.3 Couplant - Use Ultragel II, Sonotrace 40 or equivalent as permitted by the Pre-Engineered Material List.

## 6.0 REFERENCES

6.1 USNRC Regulatory Guide 1.14, Revision 1, dated August 1975

6.2 Duquesne Light Company Quality Services Inspection Examination NDE Procedures

6.3 ASME Boiler and Pressure Vessel Code, Section V, 1983 Edition, Summer 1983 Addenda

6.4 DLCo. Nuclear Engineering Memorandum 90104, dated 4-19-85

6.5 ISI Letter ND3ISI:0106, dated 11-8-85

6.6 Westinghouse response #DLW-86-512, dated 2-19-86

6.7 NPDAP 9.6 Expendable Products Control

6.8 Duquesne Light Company Quality Services Procedures 9.4, "Nondestructive Examinations"; 17.1 "Control of the Quality Services Unit QA Records"; 2.3 "Written Practice For Qualification and Certification of Nondestructive Examination and Testing Personnel"

6.9 DLCo Quality Control Report #638, dated 3-9-93.

7.0 ATTACHMENTS

7.1 RCP Flywheel UT Examination Report

7.2 Unit 1 Flywheel Hole Identification Drawing

7.3 Unit 2 Flywheel Hole Id fication Drawing

8.0 CHRONOLOGY OF CHANGES

8.1 Revision 7 - Incorporate safety requirements with the use of Ultragel II couplant, add Chronology of Changes Section, made administrative changes, and perform two year review.

## RCP Flywheel UT Examination Report

Duquesne Light

FTI 0
AD 72ID

### REACTOR COOLANT PUMP FLYWHEEL ULTRASONIC EXAMINATION REPORT

ULTRASONIC EXAM REPORT NO
PROCEDURE NO ______
REVISION NO.
PAGE ____ OF ____

| PLANT: | LOOP/PUMP ID | ISO/DWG | APPLICABLE EM, GIR, etc |
|---|---|---|---|

| UT INSTRUMENT | | TRANSDUCERS | |
|---|---|---|---|
| | | PERIPHERY EXAM | GAGE HOLE PROBE |
| MFG. | MODEL NO | SIZE | SIZE |
| SERIAL NO / DATABASE NO.: | CAL DUE DATE | FREQ | FREQ |
| SWEEP DELAY | SWEEP LENGTH | SERIAL NO: | SERIAL NO |
| TEMPERATURE OBS / CAL DUE | CAL BLOCK FLYWHEEL | | |

### CALIBRATION(S)

**#1) KEYWAY CORNER**

HOLE A
CAL TIME ______
AMPLITUDE ______ %FSH
dB ______ SWEEP ______
CAL CONF ______

HOLE B
CAL TIME ______
AMPLITUDE ______ %FSH
dB ______ SWEEP ______
CAL CONF ______

HOLE C
CAL TIME ______
AMPLITUDE ______ %FSH
dB ______ SWEEP ______
CAL CONF ______

HOLE D
CAL TIME ______
AMPLITUDE ______ %FSH
dB ______ SWEEP ______
CAL CONF ______

**#2) RADIAL GAGE HOLE**

CAL TIME ______
BOLT HOLE 5 RESPONSE ______ %FSH
dB ______ SWEEP ______
BOLT HOLE 2 RESPONSE ______ %FSH
SWEEP ______
CAL CONF ______

**#3) PERIPHERY**

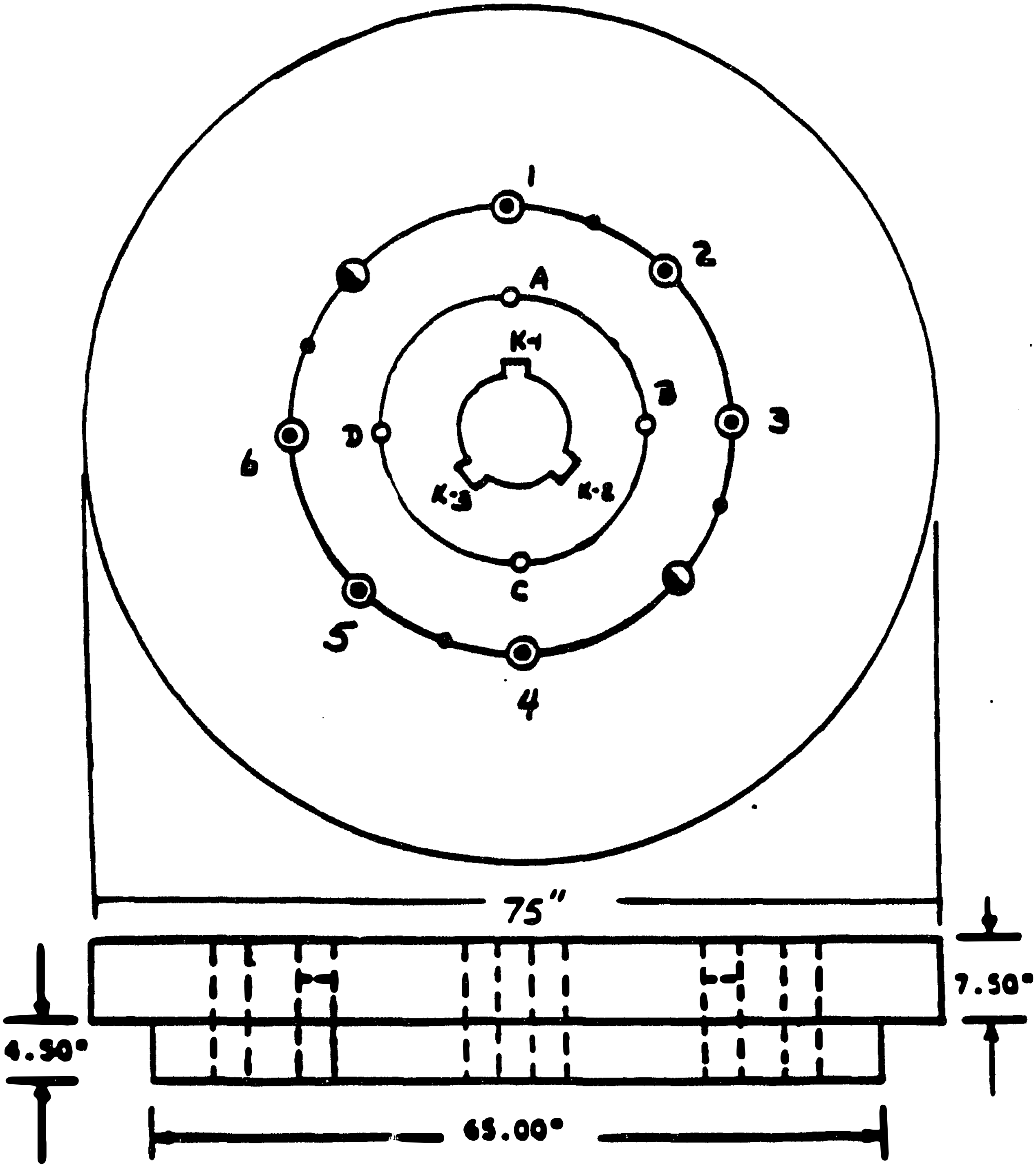
CAL TIME ______
BOLT HOLE 5 RESPONSE ______ %FSH (FROM LOWER PLATE)
dB ______ SWEEP ______
BOLT HOLE 5 RESPONSE ______ %FSH (FROM UPPER PLATE)
SWEEP ______
CAL CONF ______

### EXAMINATION RESULTS

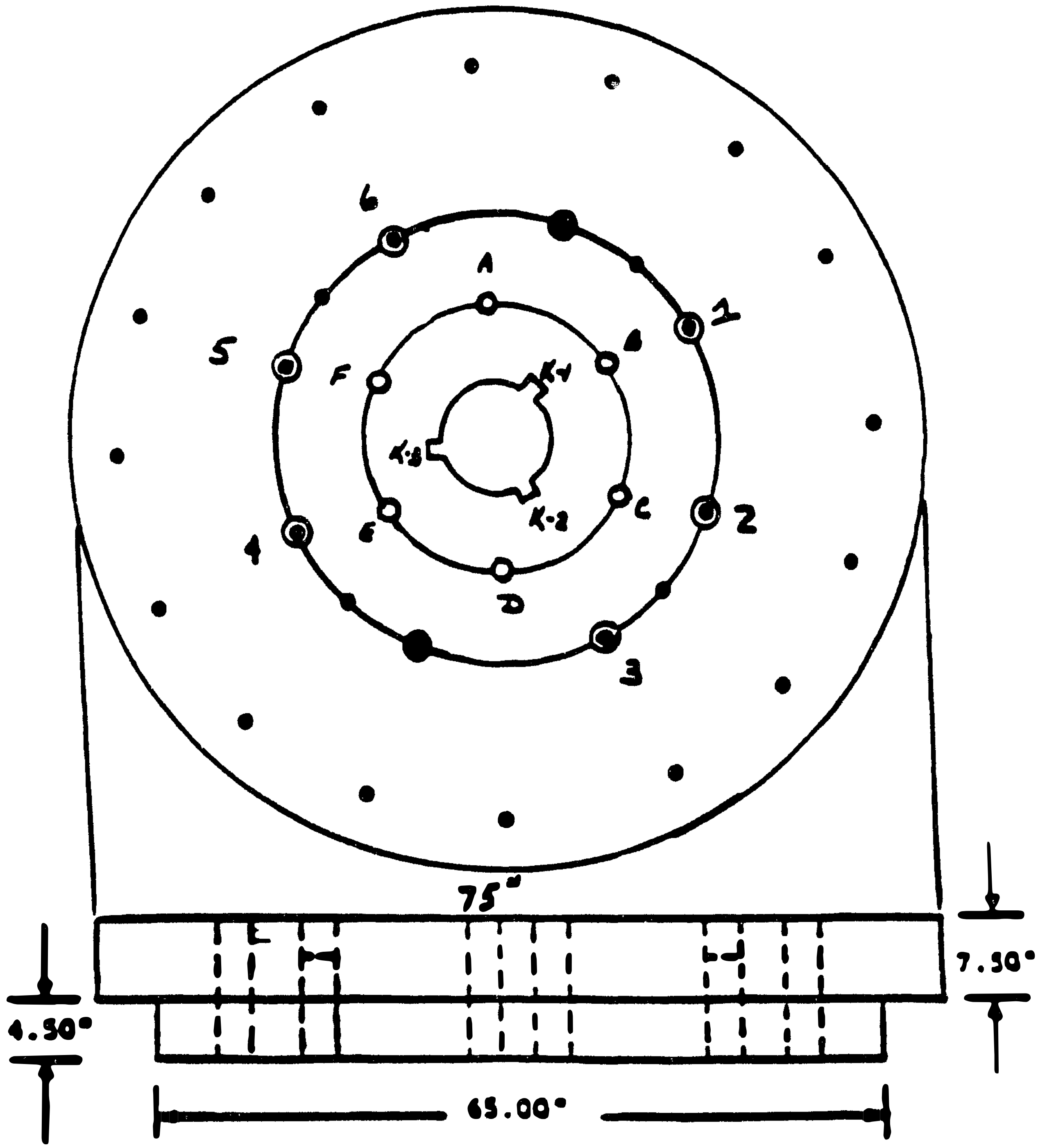
| #1) KEYWAY CORNER ☐ NI ☐ NRI ☐ RI | | #2) RADIAL GAGE HOLE ☐ NI ☐ NRI ☐ RI | | #3) PERIPHERY ☐ NI [ ] NRI [ ] RI | |
|---|---|---|---|---|---|
| SCAN 1 2 3 A B C D | IND LENGTH: | IND DEPTH | SCAN 1 2 3 A B C D | IND LENGTH | IND DEPTH |
| IND LOCATION | IND MAX AMPLITUDE | IND LOCATION | IND MAX AMPLITUDE | | |

| EXAMINER | LEVEL | DATE | DLCo LEVEL III | DATE |
|---|---|---|---|---|
| EXAMINER | LEVEL | DATE | REVIEWER (TITLE) | DATE |

Flywheel Hole Identification Drawing (Unit 1)



Flywheel Hole Identification Drawing (Unit 2)



## ATTACHMENT B

## INFORMATION ON REQUALIFICATION OF PERSONNEL AND EVALUATION OF MEGASONICS PROBE FOR RCP FLYWHEEL EXAMINATIONS AT BEAVER VALLEY

FORM D37-122153

| QCR NUMBER |
| --- |
| 638 |

DUQUESNE LIGHT COMPANY
Quality Services Unit
QUALITY CONTROL REPORT

STATION BVPS Units 1 & 2

EQUIPMENT/SYSTEM Reactor Coolant Pump Flywheel UT Exams

REPORT TITLE Trip Report-Westinghouse Electro-Mechanical Division, Cheswick, PA

Evaluation of Megasonics RCP Flywheel UT Examination Probe

On March 8, 1993, the author and George Ruck, Senior NDE Examiner traveled to the Westinghouse Electro-Mechanical Division in Cheswick, PA. The purpose of the trip was to perform an evaluation of the recently purchased reactor coolant pump flywheel UT examination probe.

The trip was arranged as a mutually beneficial evaluation of the Megasonics RCP flywheel probe on an actual RCP flywheel. Mr. Douglas Iseman, Westinghouse NDE Level III, assisted in setting up a time when the Cheswick Plant would have a 75" diameter RCP flywheel available. The flywheel being manufactured had 6 gage holes in a circle 29" from the flywheel centerline. This design is similar to the RCP flywheels at BVPS Unit 2. (The Unit 1 flywheel has only 4 gage holes.)

The Megasonics flywheel probe differs in design from previously used probes in that the search unit element is curved to compensate for the convex entry surface required to make contact in the 1" diameter gage holes. The demonstrated net effect of this curvature is that the ultrasonic beam spread is greatly reduced due to the acoustic focusing effect. This focused beam allows easier identification of reflectors encountered as well as reduced signal to noise ratio from material characteristics.

The bore probe is used to perform two separate types of UT examinations on a RCP flywheel. The first type is the examination of the area surrounding the center bore hole and keyway corners from the gage holes. The Megasonics bore probe performed this task readily, exhibiting far less beam spread than the previously used probe, which was used for comparison.

The second type of examination is a 360° scan of the flywheel volume from each of the gage holes. In this examination, the Megasonics bore probe performed exceptionally well, providing excellent resolution of closely spaced holes at significant metal paths. The attached pages show specific calibration scenarios representative of UT-304 procedural requirements. As a result of observations made, several procedure revisions have been requested to fully take advantage of the probe capabilities.

Procedure UT-304 Revision 6 Date 3-16-93

[ ] initial qualification [✓] requalification* [ ] requalification not required*

TEST OBJECT DESCRIPTION: UNIT 1 REACTOR COOLANT PUMP FLYWHEEL*

QUALIFICATION LIMITATIONS/COMMENTS: *"PRELIMINARY" QUALIFICATION documented ON ATTACHED QCR #638. ACTUAL QUALIFICATION TO BE CONDUCTED IN CONJUNCTION WITH EXAMINATION.

ATTACHMENTS:

[ ] calibration record

[ ] test object drawing

[ ] examination record

[✓] other QCR #638

| | | | | | |
|---|---|---|---|---|---|
| [signature] | II | 3-16-93 | [signature] | III | 3-16-93 |
| Performed By | Level | Date | Performed By | Level | Date |
| N/A | N/A | N/A | N/A | N/A | N/A |
| Witness | Level | Date | Witness | Level | Date |

Procedure qualification results are acceptable and procedure is qualified within the procedure scope and subject to the limitations noted above.

| | | | |
|---|---|---|---|
| [signature] | 3-16-93 | [signature] | 3-19-93 |
| DLCo Level III | Date | ANII | Date |

* If requalification is not required, the DLCo. Level III should write a brief explanation in the comments section.

While the configuration of the flywheel examined is similar to the BVPS Unit 2 flywheel design, differences in actual flywheel configuration will necessitate procedure qualification on the actual flywheel(s). This qualification of the revised UT-304 will take place on the BVPS Unit 1 flywheel at Cheswick during April, 1993 in conjunction with the UT examinations. Unit 2 flywheel configuration will also be qualified in conjunction with UT examinations. This report will serve as a preliminary procedure qualification to validate the technique and to document the improved examination capabilities of the Megasonics focused bore probe.

TCH/lmd

cc: M. A. Pergar
J. J. Giocondi
G. L. Buck
Factory Mutual ANII
QSIE File

REPORTED BY: ~~[signature]~~ UT-LIII DATE: 3-11-93

REVIEWED BY: J J Giocondi 3/11/93

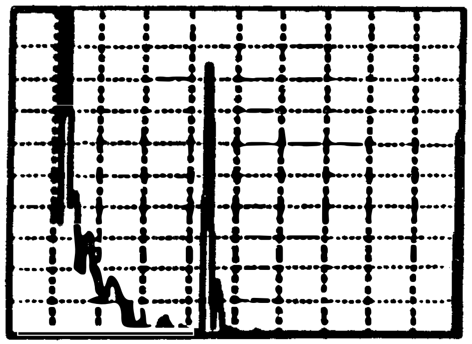
| | | |
|---|---|---|
| Duquesne Light<br>FILE #<br>AB 730K | NDE SUPPLEMENTARY REPORT | REPORT NO. QCR 638 | PAGE OF |

Megasonics Flywheel Probe

Preliminary Procedure Qualification (Westinghouse Cheswick 3/8/93)

Westinghouse 6 Bolt 75" diameter Flywheel (Similar to BVPS unit 2)

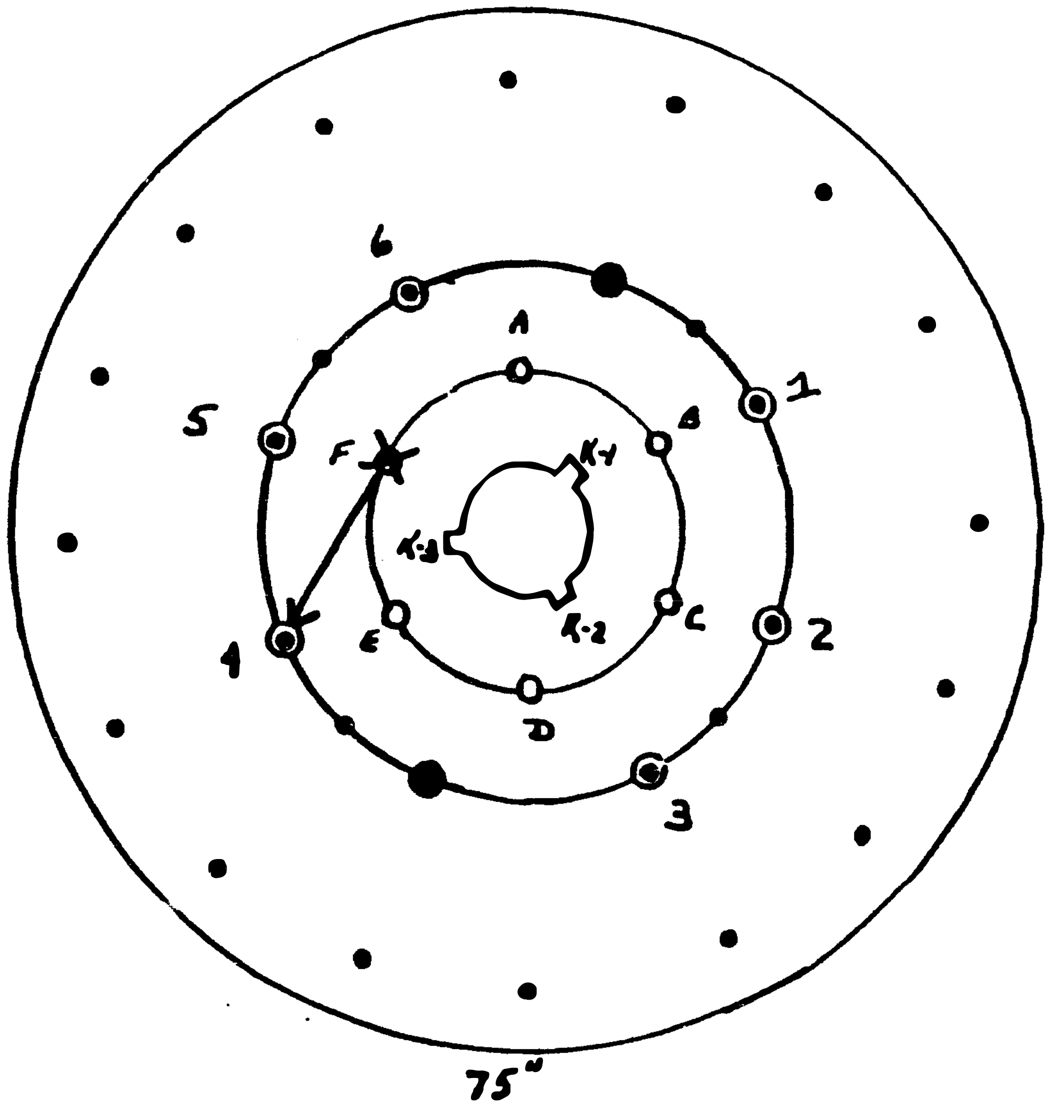
REMARKS/SKETCH/DETAILS



↑

17.6" metal path

| | |
|---|---|
| RANGE | 40.0 in |
| DELAY | 0.023 in |
| VEL | 0.237 in/us |
| UNITS | in |
| LEVEL | OFF |
| POSN | 29.0 in |
| WIDTH | 3.00 in |
| POLARITY | + |
| GAIN | 66.0 dB |
| DISPLAY | FILT1 |
| FREQ | 2.25 MHz |
| REJECT | OFF |
| PULSE | [illegible] |
| DAMPING | [illegible] |
| PULSE ECHO | |
| REP RATE | 1 kHz |
| GAIN | 66.0 dB |
| REF LVL | 40.0 dB |
| X CHANGE | [illegible] |
| dB CHANGE | 26.0 |




Radial gage hole examination

Probe in gage hole "F"

Reflection from Ream Bolt hole "4"

Duquesne Light

FILE NO. [illegible]

# NDE SUPPLEMENTARY REPORT

REPORT NO. QCR 638

PAGE OF

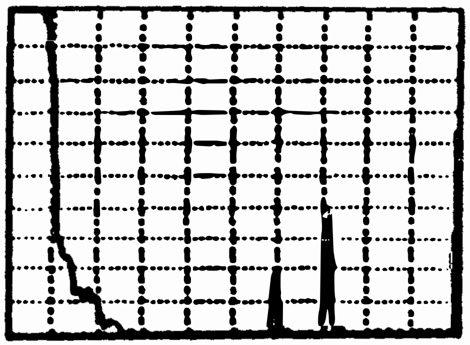
Megasonics Flywheel Probe

Preliminary Procedure Qualification (Westinghouse Cheswick 3/8/93)

Westinghouse 6 Bolt 75" diameter Flywheel (Similar to BV's Unit 2)

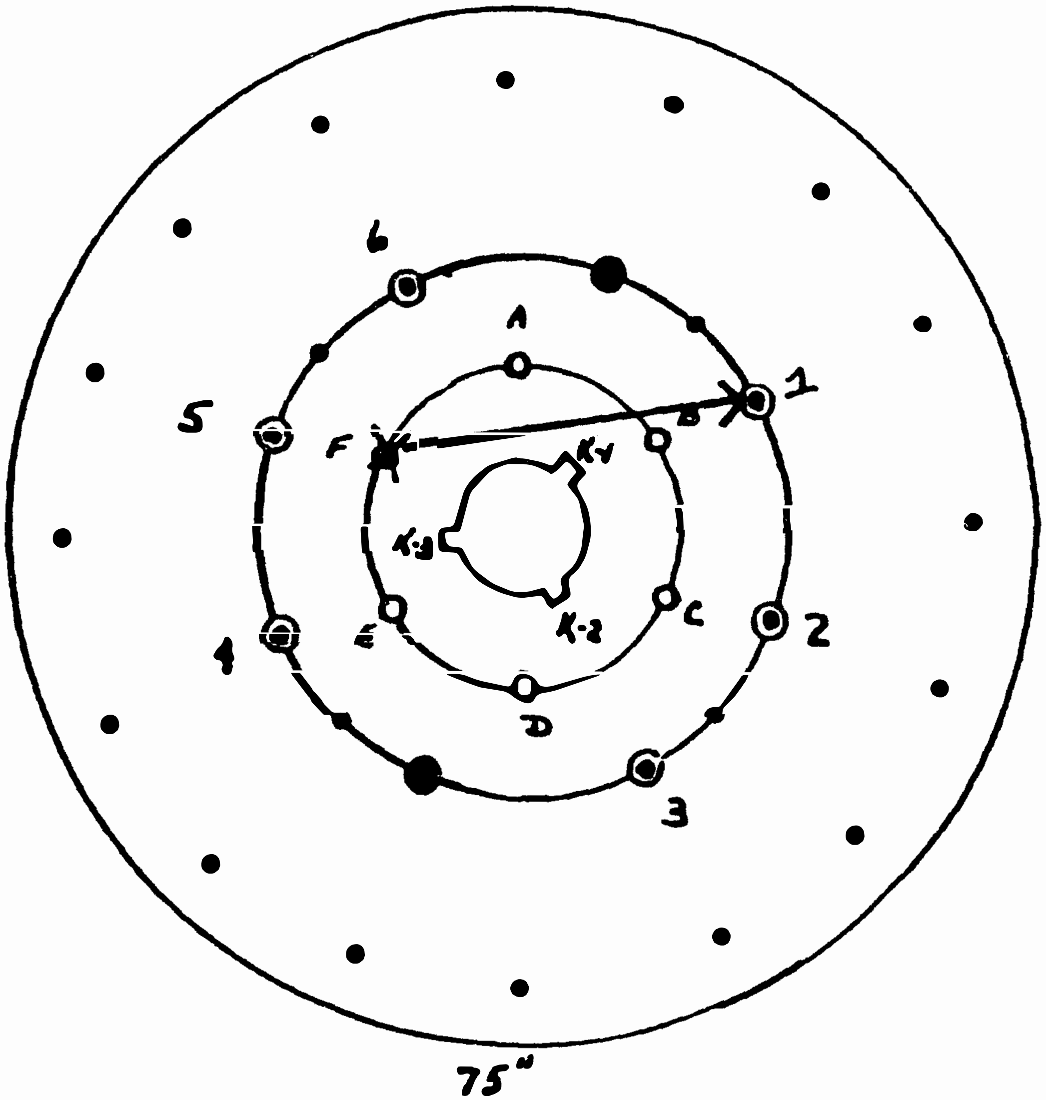
REMARKS/SKETCH/DETAILS

| | |
|---|---|
| RANGE | [illegible].0in |
| DELAY | 1.23in |
| VEL 0.237 | in/us |
| UNITS | in |
| LEVEL | OFF |
| POSN | 31.0in |
| WIDTH | 3.00in |
| POLARITY | + |
| GAIN | 77.0dB |
| DISPLAY | FILT1 |
| FREQ | 2.25MHz |
| REJECT | OFF |
| PULSE | [illegible] |
| DAMPING | [illegible] |
| PULSE EDGE | |
| REP RATE | 1 kHz |
| GAIN | 77.0dB |
| REF LVL | [illegible].0dB |
| X CHANGE | [illegible] |
| dB CHANGE | 37.4 |



28" metal path

(23.2" metal path (gage hole B))



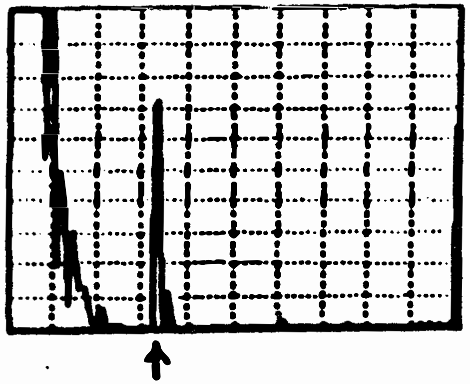

Radial Gage hole Examination

Probe in gage hole "F"

Reflection from ream bolt hole "1"

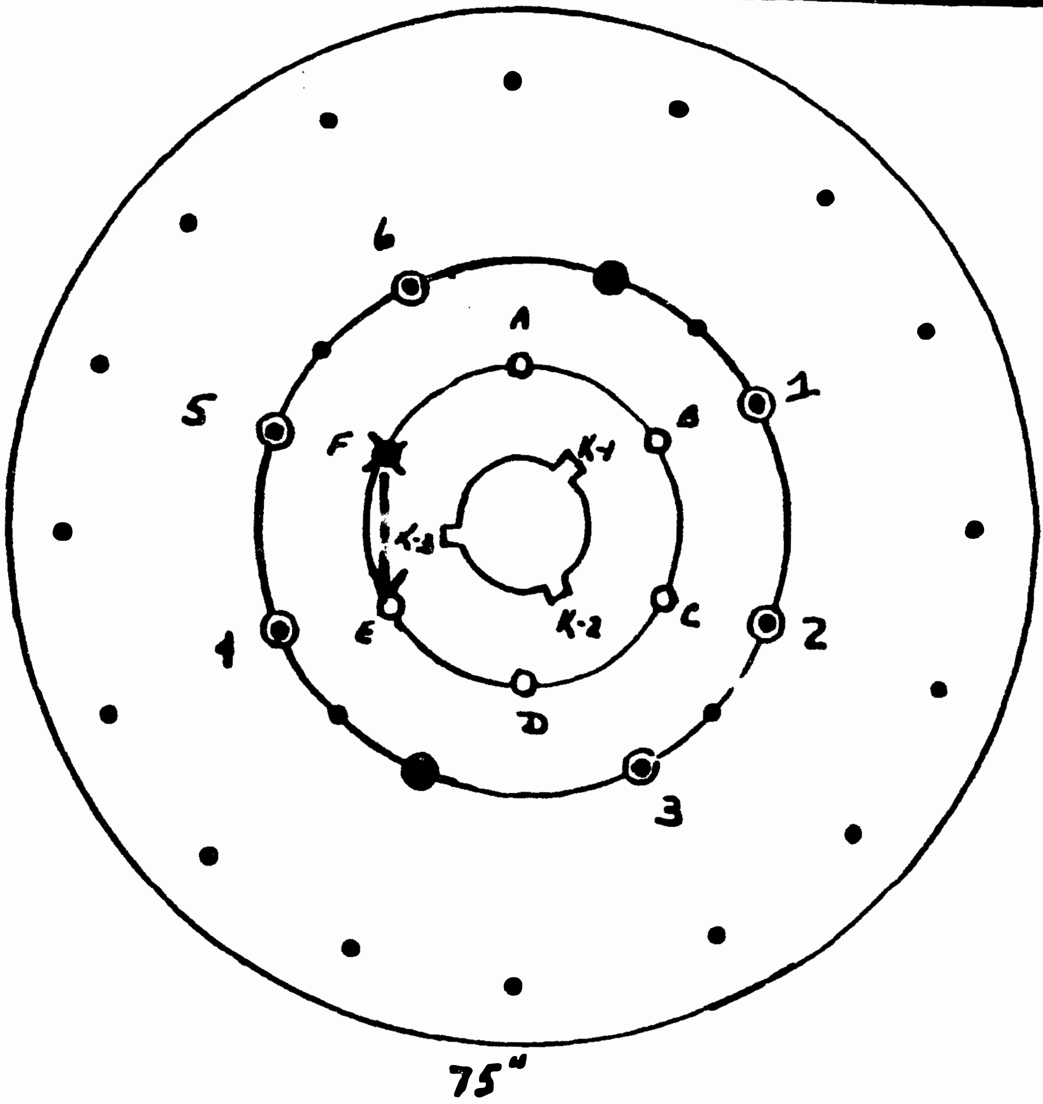
| Duquesne Light | NDE SUPPLEMENTARY REPORT | REPORT NO QCR 638 | PAGE OF |
|---|---|---|---|
| FILE NO. [illegible] | Megasonics Flywheel Probe | | |
| | Preliminary Procedure Qualification (Westinghouse Cheswick 3/8/93) | | |
| | Westinghouse 6 bolt 75" diameter flywheel (Similar to BVPS Unit 2) | | |

REMARKS/SKETCH/DETAILS



12.8" METAL PATH

| | |
|---|---|
| RANGE | 60.0in |
| DELAY | 1.23in |
| VEL 0.237 | in/us |
| UNITS | in |
| LEVEL | OFF |
| POSN | 31.0in |
| WIDTH | 3.00in |
| POLARITY | + |
| GAIN | 75.4dB |
| DISPLAY | FILT1 |
| FREQ | 2.25MHz |
| REJECT | OFF |
| PULSE | [illegible] |
| DAMPING | [illegible] |
| PULSE EDGE | |
| REP RATE | 1 kHz |
| GAIN | 75.4dB |
| REF LVL | 40.0dB |
| X CURSOR | [illegible] |
| dB CURSOR | 35.4 |




## Radial Gage hole Examination

Probe in gage hole "F"

Reflection from gage hole "E"

Duquesne Light

FILE#
AD 730K

# NDE SUPPLEMENTARY REPORT

REPORT NO. QCR 638

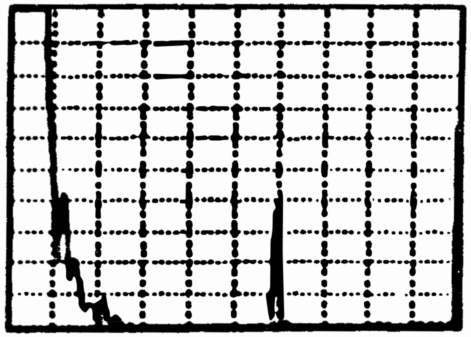
PAGE OF

MEGASONICS FLYWHEEL PROBE

PRELIMINARY PROCEDURE QUALIFICATION (WESTINGHOUSE CHESWICK 3/6/93)

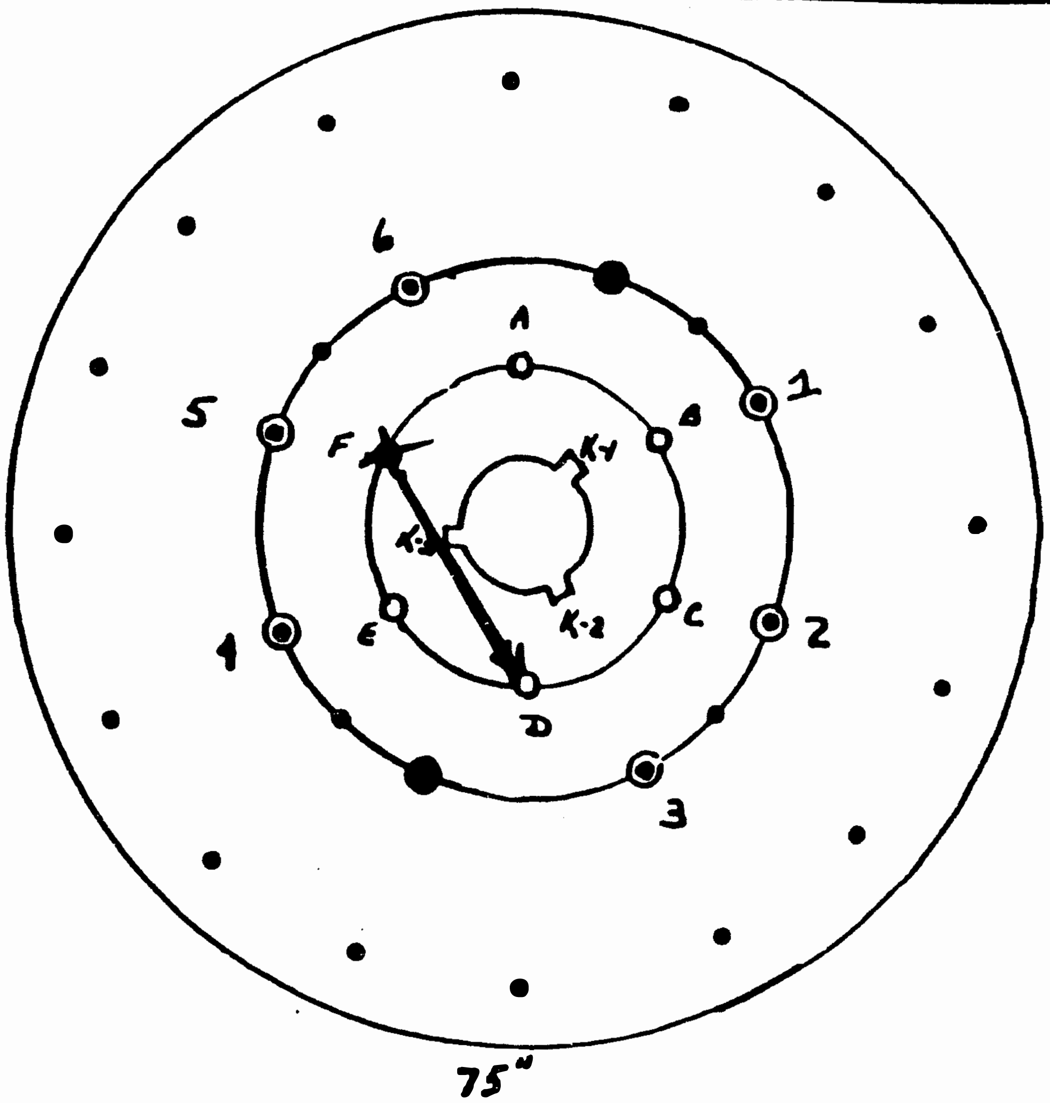
WESTINGHOUSE 6 BOLT 75" DIAMETER FLYWHEEL (SIMILAR TO BVPS UNIT 2)

REMARKS/SKETCH/DETAILS



23.2" METAL PATH

| | |
|---|---|
| RANGE | 40.0in |
| DELAY | 1.23in |
| VEL 0.237 | in/us |
| UNITS | in |
| LEVEL | OFF |
| POSN | 31.0in |
| WIDTH | 3.00in |
| POLARITY | + |
| GAIN | 75.4dB |
| DISPLAY | FILT1 |
| FREQ | 2.25MHz |
| REJECT | OFF |
| PULSE | [illegible] |
| DAMPING | [illegible] |
| PULSE ECHO | |
| REP RATE | 1 kHz |
| GAIN | 75.4dB |
| REF LVL | 40.0dB |
| X CHANGE | [illegible] |
| dB CHANGE | 35.4 |




RADIAL GAGE HOLE EXAMINATION

PROBE IN GAGE HOLE "F"
REFLECTION FROM GAGE HOLE "d"

**ATTACHMENT C**

**ASME TECHNICAL PUBLICATION**
**PAPER NO. 74-PVP-25**
**REACTOR COOLANT PUMP FLYWHEEL OVERSPEED EVALUATION**

an ASME publication

# Reactor Coolant Pump Flywheel Overspeed Evaluation

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*The overspeed capability of the large steel flywheels used on light water reactor primary coolant pumps has been evaluated through a combined analytical and experimental effort. Limiting speeds of the prototype flywheel design were calculated for the ductile failure mode using the principles of Section III of the ASME Boiler and Pressure Vessel Code, and for the brittle fracture mode using a fracture mechanics approach in which stress intensity factors were determined from finite element computer analysis. The accuracy of the analytical approach was verified by a scale model test program which demonstrates excellent agreement between experiment and analysis. The results of the evaluation are presented in this paper, and they illustrate the kinds of things which can be accomplished through application of modern fracture mechanics technology, including plasticity considerations, to the solution of hardware problems of real engineering interest.*

## Introduction

In the event of a postulated loss of coolant accident in a pressurized water reactor plant, it is possible for the reactor primary coolant pump to achieve speeds on the order of two to three times its normal design speed. At speeds of this magnitude, concern arises as to the likelihood of components of the pump-motor assembly fracturing and producing high energy missiles within the containment. Of utmost concern in this regard is the reactor coolant pump flywheel, since it possesses the most rotational inertia in the pump-motor assembly, and thus the highest amount of energy at a given speed.

The Westinghouse coolant pump flywheel design consists of two large steel disks, 75 in. and 65 in. in diameter, which are bolted together in order to provide the necessary rotational inertia to maintain flow and thus prevent core overheating in the event of loss of power to the pumps. A sketch of the flywheel assembly, showing the significant details and dimensions is given in Fig. 1. The two plates are 7.5 in. thick and 6.5 in. thick, respectively, and contain numerous holes and keyways as shown. The flywheel is fabricated from A-533, Grade B, Class 1 steel plate.

The purpose of this evaluation is to determine the speed at which this flywheel design becomes critical from the standpoint of fracture and subsequent missile production. An analytical approach is taken, utilizing the methods of Section III of the ASME Boiler and Pressure Vessel Code for ductile failure considerations, and utilizing the principles of linear elastic fracture mechanics (LEFM) for brittle fracture considerations. Due to plasticity, the LEFM approach is not strictly applicable to this

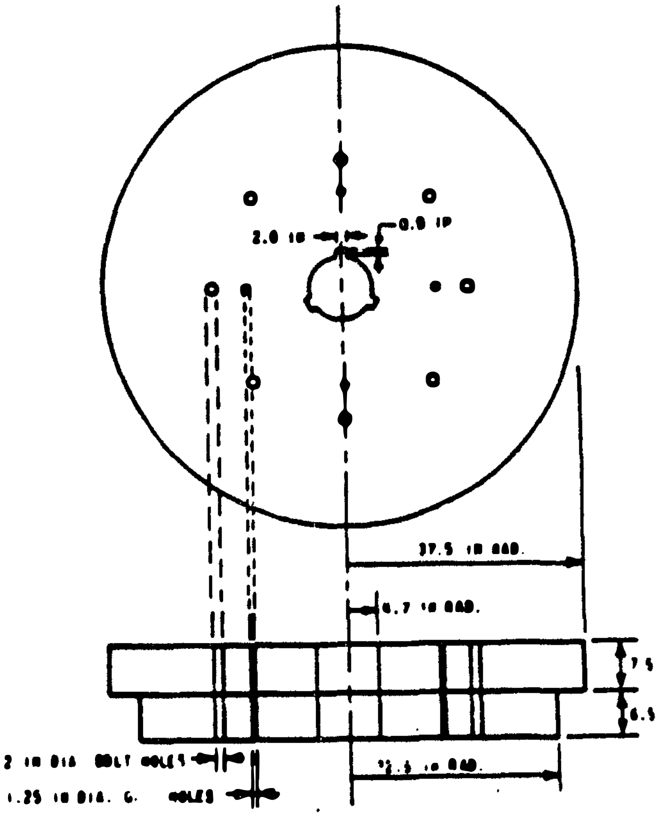


Fig. 1 Reactor coolant pump flywheel geometry

[1]Formerly, of Westinghouse Nuclear Energy Systems.

[2]Numbers in brackets designate References at end of paper.

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Copies will be available until March, 1975.



Discussion on this paper will be accepted at ASME Headquarters until ... 1974

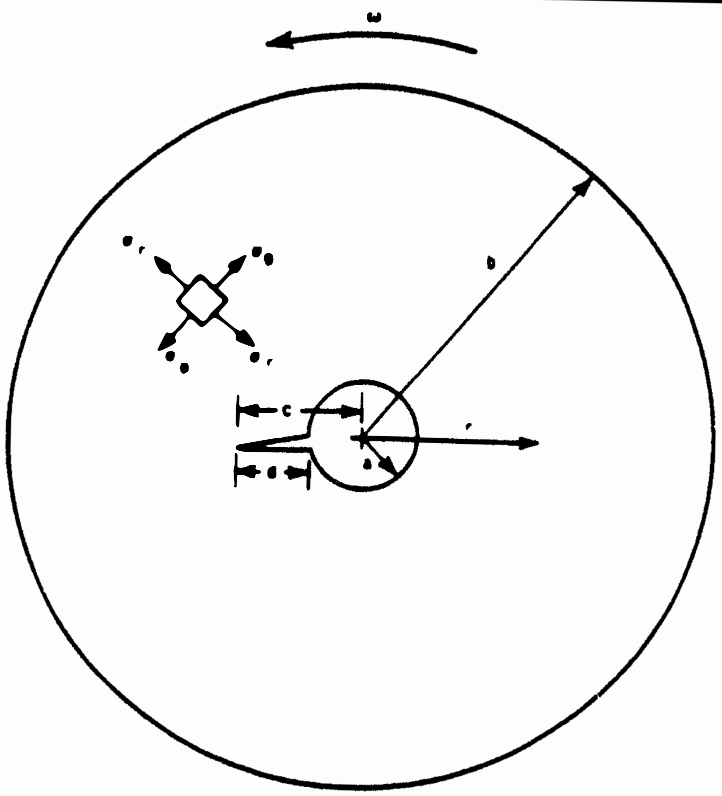


Fig. 2 Notation used in flywheel evaluation

problem, and thus a scale model test program was implemented to verify the analysis. A summary of the flywheel evaluation and the supporting test program is given in this paper. A more detailed report on this work can be found in [1].[3]

## Ductile Failure Analysis

**Flywheel Stresses.** The stresses in the reactor coolant pump flywheel, neglecting local stress concentrations such as holes and keyways, can be calculated by the following equations [2],

$$\sigma_r = \left(\frac{3+\nu}{8}\right)\rho\omega^2\left[b^2 + a^2 - \frac{a^2b^2}{r^2} - r^2\right]$$

$$\sigma_\theta = \left(\frac{3+\nu}{8}\right)\rho\omega^2\left[b^2 + a^2 + \frac{a^2b^2}{r^2} - \left(\frac{1+3\nu}{3+\nu}\right)r^2\right] \quad (1)$$

where the notation is defined in Fig. 2. Substituting the appropriate geometric data for the reactor coolant pump flywheel (Fig. 1) into equation (1), and noting that the material density ($\rho$) is given by 0.238 lbm/in³, the stresses at various radial depths can be described as a function of angular velocity $\omega$ (rad/sec)

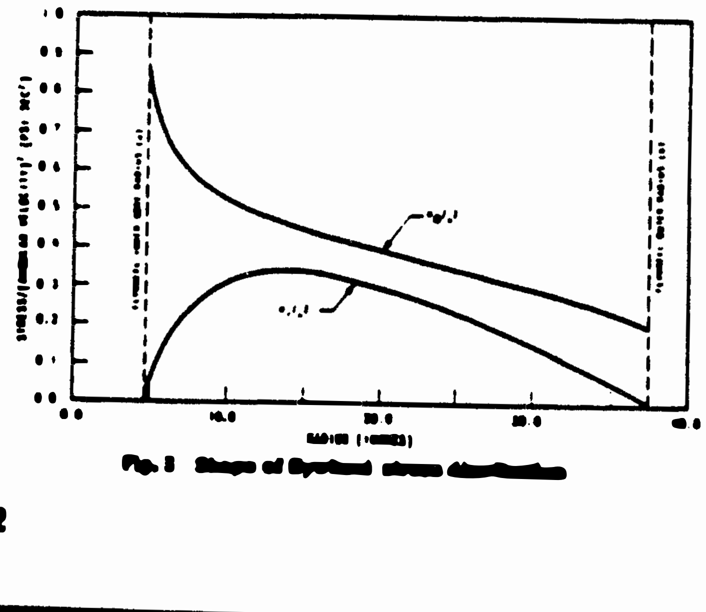


Fig. 3 Shape of flywheel stress distribution

as shown in Fig. 3. Note that the circumferential stress ($\sigma_\theta$) is essentially linear over about 90 percent of the flywheel radius, with a sharp peaking effect due to the stress concentration at the bore. Although the magnitude of the stresses will vary with angular velocity, the shape of the stress distribution shown in Fig. 3 will be the same at any speed. The shape of the stress distribution has an important effect upon the behavior of the flywheel and must be considered explicitly when applying stress limits to the calculated stresses.

**Faulted Condition Stress Limits.** The capacity of a structure to resist ductile failure with sufficient margin of safety during faulted conditions can be demonstrated by meeting the faulted condition criteria of Section III of the ASME Boiler and Pressure Vessel Code [3] (Appendix F). The faulted condition limits for elastic analysis are as follows

$$P_m < 0.7\, S_u$$

$$P_m + P_b < 1.05\, S_u, \quad (2)$$

where $S_u$ is the minimum specified ultimate tensile strength of the material, $P_m$ is the primary membrane stress intensity under faulted condition loading, and $P_b$ is the primary bending stress intensity. (The term stress intensity is defined here as twice the Tresca maximum shear stress in accordance with the Section III definition of the term, and should not be confused with the linear elastic fracture mechanics stress intensity factor which is used later in this paper.)

Since the thickness direction stress ($\sigma_z$) in the flywheel is assumed to be negligible, and the radial stress ($\sigma_r$) always falls between the thickness direction stress and the circumferential stress ($\sigma_\theta$), the maximum stress intensity at any point in the flywheel is equal to the circumferential stress. In order to apply the stress limits of equation (2) to a nonlinear stress distribution such as that shown for $\sigma_\theta$ in Fig. 3, the actual stress distribution must be resolved into its membrane and bending components

$$P_m = \frac{1}{(b-a)}\int_a^b \sigma_\theta dr$$

$$P_b = \frac{6}{(b-a)^2}\int_a^b \sigma_\theta (r_m - r)dr, \quad (3)$$

where $r_m$ is the flywheel mean radius defined as $(a+b)/2$. Substituting the cricumferential stress term from equation (1) and carrying out the integrals in (3) yields

$$P_m = \left(\frac{3+\nu}{8}\right)\frac{\rho\omega^2}{(b-a)}\,(b^3 - a^3)\left[1 - \frac{1}{3}\left(\frac{1+3\nu}{3+\nu}\right)\right]$$

$$P_b = \left(\frac{3+\nu}{8}\right)\frac{6\rho\omega^2}{(b-a)^2}\left\{\frac{b^4}{12}\left(\frac{1+3\nu}{3+\nu}\right)\right.$$

$$+ \frac{b^3a}{2}\left[1 - \frac{1}{3}\left(\frac{1+2\nu}{3+\nu}\right)\right] - a^2b^2\ln(b/a)$$

$$\left. - \frac{ba^3}{2}\left[1 + \frac{1}{3}\left(\frac{1+2\nu}{3+\nu}\right)\right] - \frac{a^4}{12}\left(\frac{1+3\nu}{3+\nu}\right)\right\} \quad (4)$$

Finally, substitution of the appropriate geometric data from Fig. 1 into equation (4) yields

$$P_m = 0.40\,\omega^2 \text{ (psi)}$$

$$P_b = 0.22\,\omega^2 \text{ (psi)} \quad (5)$$

Equations (2) and (5) will now be compared in order to evaluate the speed at which the flywheel stresses exceed the Section III faulted condition criteria.

**Results.** Values of $P_m$ and $(P_m + P_b)$ have been calculated from equation (5) and compared to the faulted condition stress limits of equation (2) to determine the limiting flywheel speed of 80,000 psi was used in computing the faulted condition limits which is the minimum specified value for A-533 Grade B, Class 1 steel given in [3]. The limiting speed based on the membrane + bending stress limit is 365 rad/sec or 3485 rpm, and the limiting speed based on the membrane stress limit is 372 rad/sec or 3550 rpm. Therefore, the membrane + bending limit is governing.

In summary, the results of the analysis performed in this section demonstrate that the reactor coolant pump flywheel can withstand a rotational speed of 3485 rpm, which corresponds to approximately a 290 percent overspeed condition (Fig. 10) without exceeding the faulted condition criteria (Appendix F) of Section III of the ASME Boiler and Pressure Vessel Code. Compliance with these limits assures that the flywheel can withstand this overspeed condition with sufficient margin from the standpoint of ductile failure.

## Brittle Fracture Evaluation

**Closed Form Stress Intensity Factor Solution.** An approximate solution for the stress intensity factor for a radial crack emanating from the bore of a rotating disk has been reported by Williams and Isherwood [4], and is given by the following expression

$$K_I = \rho\omega^2 b^{5/2}\Phi \left[ \frac{\pi\left(\frac{c}{b} - \frac{a}{b}\right)}{(1-\nu^2)} \right]^{1/2} \tag{6}$$

where

$$\Phi = \left(\frac{3+\nu}{32}\right)\left[3\left(1+\frac{a^2}{b^2}\right)+3\left(\frac{a}{b}\right)\left(\frac{b}{c}\right) + \left(1+\frac{a}{b}+\frac{a^2}{b^2}\right)\frac{\left(1-\frac{a}{b}\right)}{\left(1-\frac{c}{b}\right)}\right] - \left(\frac{1+3\nu}{32}\right)\left[\frac{\left(\frac{c}{b}\right)^3-\left(\frac{a}{b}\right)^3}{\left(\frac{c}{b}-\frac{a}{b}\right)} + \frac{1}{3}\,\frac{\left(1-\frac{a}{b}\right)^3}{\left(1-\frac{c}{b}\right)}\right] \tag{7}$$

and where the geometric quantities $a$, $b$, and $c$ are defined in Fig. 2. The quantities $\rho$ and $\omega$ refer to the material density and angular velocity as before. Substituting and appropriate geometric data from Fig. 1 into equations (6) and (7) leads to stress intensity factor as a function of angular velocity for various assumed cracked depths as shown by the solid curve in Fig. 4. Note that for the case of a crack emanating from a keyway, the keyway depth is included as part of the total crack depth for conservatism.

Inspection of Fig. 4 indicates that the closed form solution technique erroneously gives a nonzero value of stress intensity factor for zero crack depth. Thus it becomes obvious that the assumption of adding keyway depth ~~to crack~~ depth is overly conservative for very short crack depths. In order to eliminate this undue conservatism, and to consider the effect of the keyway more accurately, a detailed finite element model of the flywheel with a crack emanating from the keyway was set up and analyzed.

**Finite Element Analysis.** Approximately 500 constant strain triangular finite elements were used to model the reactor coolant pump flywheel for analysis using the computer program PPCNT [5]. A detailed illustration of the models used in the analyses is shown in Fig. 5. Due to symmetry, only a 60-deg segment of

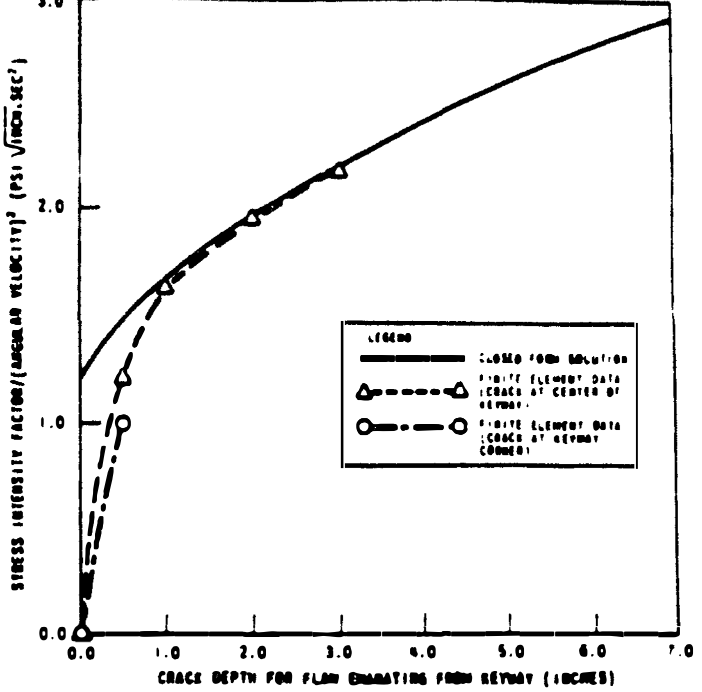


**Fig. 4 Stress intensity factor computations for reactor coolant pump flywheel**

the flywheel, including half of one keyway, is required to model the complete flywheel. A number of different crack depths and locations were studied by placing the special cracktip model at various locations within the fine grid region. Elastic solutions were obtained for all cases assuming the loading to be due only to centrifugal forces resulting from flywheel spinning. The effects of contact loading at the inner bore and keyways were assumed to be negligible, and the flywheel was assumed to be in a state of plane strain. Values of stress intensity factor were estimated from the numerical stress results in the vicinity of the cracktip by fitting the data to the first two terms of the series expansion for the crack tip stress field along the plane of the crack given by

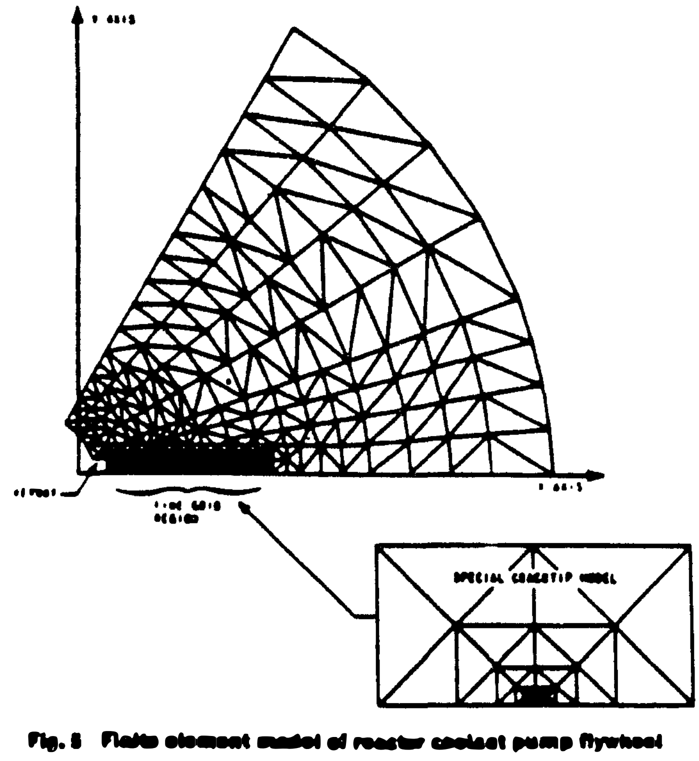


**Fig. 5 Finite element model of reactor coolant pump flywheel**

$$\sigma_y = \frac{[illegible]}{\sqrt{2\pi r}} + C, \quad (8)$$

where $r$ is the radial distance from the crack tip, $C$ is an arbitrary constant, and $K_I$ is the cracktip stress intensity factor. This procedure is described in detail elsewhere [6], and leads to the finite element stress intensity factor data shown by the dashed curves in Fig. 4.

The agreement between the closed form and numerical results in Fig. 4 is excellent for crack depths of 1.0 in. and greater, thus providing an independent check of one technique against the other for those crack depths. For crack depths less than 1.0 in., however, the closed form solution with its ultraconservative keyway assumption gives unrealistically high stress intensity predictions. It is also noteworthy that, contrary to what one would expect, the stress intensity factor for a 0.5 in. crack emanating from the keyway corner is smaller than that for the same crack emanating from the center of the keyway. This phenomenon can be explained by the fact that the stress concentrating effect of the keyway corner is extremely localized, and thus has no effect at a distance 0.5 in. from the corner. The stress intensity factor for cracks of this size is governed by the overall flywheel stress distribution rather than by local stress concentrations.

The stress intensity factor data of Fig. 4 will now be compared to the material fracture toughness to determine critical speeds for the flywheel as a function of assumed crack depth. Based on the above discussion, the most meaningful stress intensity factor data of Fig. 4 is the finite element curve for a crack emanating from the center of the keyway, and this curve will therefore be used in the remainder of the evaluation.

**Fracture Toughness.** The fracture toughness and other mechanical properties of A-533 Grade B, Class 1 steel have been studied extensively under the AEC Heavy Section Steel Technology Program [7, 8, 9, 10]. Lower bound fracture toughness versus temperature data for both the longitudinal (RW) and transverse (WR) directions were obtained in this program using the equivalent energy concept for lower bound fracture toughness testing. The data were obtained from several heats of steel, all of which had drop weight nil ductility transition temperatures in the range of 0 deg F to +10 deg F. Therefore this data should be applicable to reactor coolant pump flywheel material with the same transition temperature.

**Results.** The flywheel operation temperature is +120 deg F, and the minimum material fracture toughness at this temperature from [9] is 220,000 psi$\sqrt{\text{in}}$. This value is for the weak or transverse direction, the longitudinal direction toughness being much higher. Thus, the analysis assumes the worst possible location and orientation of any flaws which may exist. Using this toughness value, and the finite element data for a center keyway crack (Fig. 4), critical flywheel speeds have been determined as a function of crack depth, and are shown along with the ductile failure limit in Fig. 10.

**Plasticity Considerations.** Strict applicability of linear elastic fracture mechanics is limited to situations in which the extent of plastic flow in the vicinity of the cracktip is small in comparison to the crack depth and other pertinent geometric quantities of the problem. Irwin [11] has suggested the following approximation for plastic zone size in a plane strain crack problem

$$r_y = \frac{1}{6\pi}\left(\frac{K_I}{\sigma_{ys}}\right)^2, \quad (9)$$

where $K_I$ is the applied stress intensity factor and $\sigma_{ys}$ is the material yield strength. Values of plastic zone size have been calculated according to this expression for the reactor coolant pump flywheel at incipient fracture ($K_I = K_{IC}$), and the results are summarized in Table 1.

| Flaw size ($d$) | Plastic zone size ($r_y$) | Ratio ($r_y/d$) |
|---|---|---|
| 0.5 in | 0.52 in | 1.04 |
| 1.0 in | 0.52 in | 0.52 |
| 2.0 in | 0.52 in | 0.26 |

The plastic zone sizes listed in Table 1 are far too large to satisfy the plasticity limitations of linear elastic fracture mechanics. Nonetheless, the critical speed calculations of the previous section are expected to be accurate.

In the pump flywheel problem, the plasticity is completely contained. That is, due to the large stress gradients (Fig. 3), the outer periphery of the flywheel remains elastic even at the calculated critical speed levels. Contained plasticity such as this creates, in effect, a strain controlled loading situation for which experience has shown [12, 13] that elastically calculated strain distributions are accurate well beyond the limits of strict applicability of the theory of elasticity. This concept of "strain equivalence" is well accepted in low cycle fatigue applications, and its extension to fracture problems is straightforward.

Accepting this strain equivalence argument allows one to justify the use of linear elastic fracture mechanics for the flywheel evaluation using Rice's J-integral Concept [14]. It has been shown experimentally [15, 16] that the J-integral is a parameter which takes on a critical value ($J_{IC}$) at fracture over the complete range from linear elastic to fully plastic behavior. It is well established that in the elastic range the J-integral approach is identical to linear elastic fracture mechanics. However, due to the principle of strain equivalence discussed above, the identity between J and LEFM can be extended well into the elastoplastic range in strain controlled loading situations [17]. Hence, the reactor coolant pump flywheel evaluation presented herein is essentially a J-integral evaluation, and as such is valid regardless of the excessive plastic zone sizes developed.

In summary, the methods used to predict brittle fracture in the reactor coolant pump flywheel are not strictly applicable because of excessive plasticity. However, it is argued that the flywheel is a strain controlled loading situation for which the methods used correspond to an elastoplastic J-integral approach which is applicable. In order to confirm these arguments, a scale model test program was implemented and is discussed later in this paper.

## Flywheel Inspection and Quality Assurance

**Material Qualification Tests.** Westinghouse reactor coolant pump flywheels are fabricated from A-533 Grade B Class 1 steel plate which is produced by a process that minimizes flaws in the material and improves its fracture toughness properties (vacuum degassing, vacuum melting, or electroslag remelting). Supplier certification reports are available for all plates and they demonstrate the acceptability of the flywheel material on the basis of the following requirements [18]:

(a) The nil-ductility transition temperature (NDTT) is obtained by two drop weight tests which must exhibit "no-break" performance at 20 deg F in accordance with the rules of ASTM Testing Procedure E-208 [19]. These drop weight tests assure that the NDTT of the flywheel material is no higher than +10 deg F.

(b) A minimum of three Charpy V-notch impact specimens are tested at ambient (+70 deg F) temperature in accordance with ASTM specification E-23 [20]. The Charpy V-notch energy in both the parallel and normal orientation with respect to the rolling direction of the flywheel material must be at least 50 ft-lb.

Compliance with the foregoing criteria insures that all reactor coolant pump flywheel material has a low enough NDT temperature and a high enough upper shelf toughness so that the lower bound fracture toughness data of [9] are applicable.

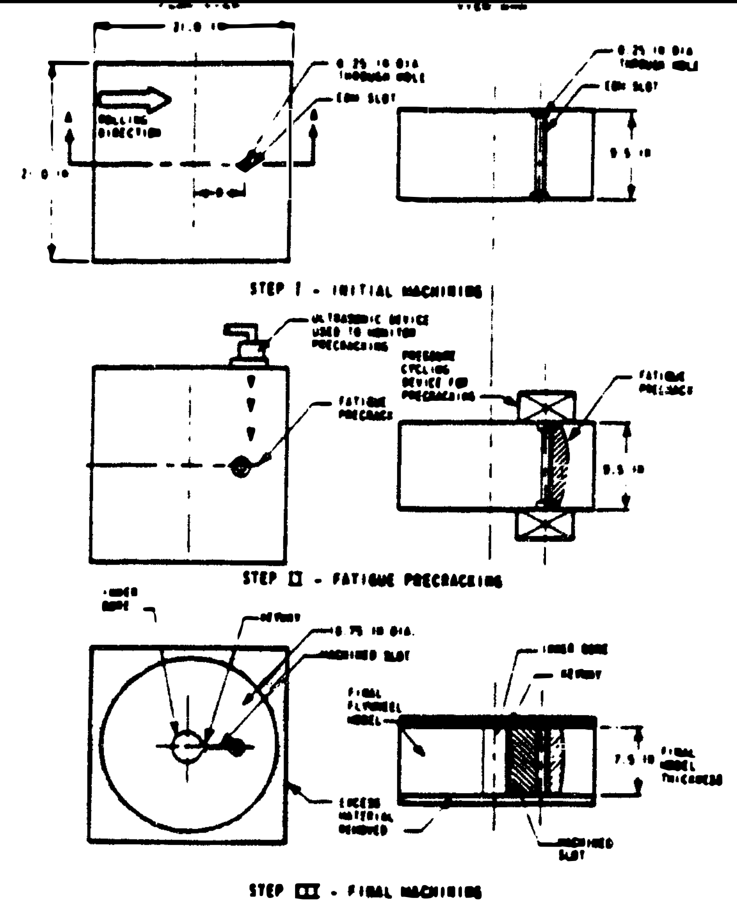


Fig. 6 Scale model flywheel fabrication procedure

**Nondestructive Examination.** Each flywheel plate is subjected to 100 percent volumetric ultrasonic examination in accordance with paragraphs NB-2532.1 and NB-2532.2 of Section III of the ASME Boiler and Pressure Vessel Code [3] for acceptance. After fabrication, the finished machined bore and keyways are subjected to magnetic particle or liquid penetrant surface examinations. The finished flywheels are also subjected to a 100 percent ultrasonic examination according to the above referenced paragraphs of [3].

In addition to the aforementioned shop inspections, the flywheels receive extensive further examination as part of the required inservice inspection program for reactor coolant pump flywheels [18]. A surface examination and full 100 percent ultrasonic examination are performed at approximate ten-year intervals. Westinghouse is also introducing a new inspection procedure [21], in which the critical regions of the flywheel (bore, keyway, and bolt hole regions) can be examined ultrasonically by passing a transducer through each of the four gage holes in the flywheel (see Fig. 1). This new procedure provides a more thorough examination of these critical regions, and can be used at more frequent intervals since it does not require removal of the flywheel.

All of the ultrasonic tests discussed in the foregoing are calibrated to provide detectability of flaws as small as 0.25 in. in radial penetration. Thus flaws on the order of 0.5 in. are a factor of two greater than the inspection capability of the techniques being used. Furthermore, inspections of the flywheel are both extensive and frequent. It can, therefore, be concluded that flaws of this size will not escape detection in flywheels and that flywheels containing such flaws will not be accepted for service.

## Scale Model Test Program

In order to verify the analytical procedures used in the present flywheel overspeed evaluation, a scale model flywheel test program was implemented. Three scale model flywheels (quarter-scale in-plane dimensions, full thickness) were fabricated with flaws present in the most critical location and orientation. Analytical failure predictions were made using the same methods as were used for the prototype flywheel evaluation. The models were then tested to failure and the actual fracture speeds compared favorably with the analytical predictions, thus lending a high degree of credibility to the pump flywheel analysis.

**Model Fabrication.** Fabrication of scale model flywheels with sharp cracks requires a relatively complex multistep procedure (see Fig. 6) which has been developed at the Westinghouse Research and Development Laboratories [22]. In the initial machining phase (Step I), three 21 in. square blanks with thicknesses of 9.5 in. were machined from a 12-in-thick plate of A533 Grade B Class 1 steel. One-quarter in. holes were then bored at prespecified distances (*D*) from the centerpoint of the blanks. The holes were also counterbored at the top and bottom surface as shown in Fig. 6 to accommodate the pressure cycling device used for precracking. Finally, an electric arc discharge machining (EDM) technique was used to produce a 1/8-in-long slot emanating from the 1/4 in. hole. Step II in the model fabrication procedure was fatigue precracking. A pressure cycling device was used to pulsate pressure in the holes at a frequency of 60 cpm, and an ultrasonic flaw detection scheme was used to continuously monitor and control crack growth during the pressure cycling operation. Maximum pressure during fatigue precracking was limited as a function of crack length in order to avoid the problems associated with excessive cracktip plasticity during precracking [22]. In the final phase of fabrication (Step III), the models were machined to their final dimensions by removing the excess peripheral and surface material as shown in Fig. 6. The inner bore, keyway and a slot from the keyway to the 1/4-in. hole were also machined in this step.

The final models thus contained composite cracks of prespecified lengths consisting of a machined slot, a 1/4-in. hole, an EDM slot, and a fatigue precrack, all emanating from the keyways in the flywheel bores. The irregularity of the crack surface does not affect the validity of the experiment since the magnitude of stress intensity factor is only affected by crack shape in the very near cracktip region. Note also that the final crack is oriented in the transverse or weak direction with respect to the rolling direction (WR). The crack size parameter *D* was chosen so as to yield nominal final crack depths of 1 in., 3 in., and 5 in. The exact value of crack depth could not be determined until after the tests, however, due to variability in the lengths of the fatigue precracks.

**Preliminary Fracture Toughness Tests.** In order to characterize the fracture toughness of the specific heat of material used to fabricate the scale model flywheels, six standard compact tension specimens [23] were fabricated from the same plate. The specimens were taken in the transverse (WR) orientation and were 2.0 in. in thickness (2TCT). Tests were performed at 0 deg F, +50 deg F and +70 deg F, and values of fracture toughness were determined from the specimen load-deflection curves using Witt's equivalent energy concept for lower bound fracture toughness testing [illegible], since the specimens were not large enough to be interpreted according to the ASTM recommended testing procedure [23]. Fig. 7 shows the fracture toughness data obtained in this manner. For comparison, the lower bound fracture toughness curve used in the flywheel analysis [9] has been indexed to the model material drop weight NDTT and is shown in this figure. Note that the experimental data are significantly higher than the lower bound curve, which is an indication of the conservatism associated with that curve for this heat of steel. The experimental data rather than the lower bound curve will be used in making the fracture predictions for the scale model flywheels in order to provide a meaningful evaluation of the accuracy of the analytical techniques used.

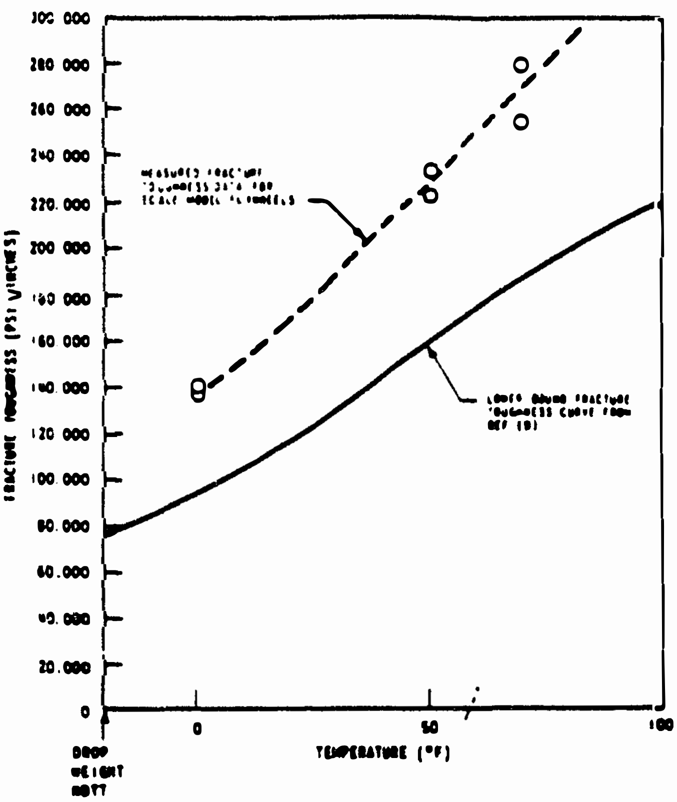


Fig. 7 Fracture toughness data for scale model flywheel materia

**Analytical Fracture Predictions.** As in the prototype flywheel overspeed evaluation, the scale model flywheels were evaluated on the basis of both ductile failure and brittle fracture considerations.

The method for ductile failure analysis follows the foregoing description for the prototype flywheel, except the ultimate tensile strength of the material ($S_u$ = 80,000) is used in place of the Section III faulted condition limit (0.7 $S_u$) since no safety margin is desired when making the failure prediction. Substituting the scale model flywheel dimensions into equations (4) yields

$$P_m = 0.025\ \omega^2\ \text{(psi)}$$

$$P_b = 0.014\ \omega^2\ \text{(psi)} \qquad (10)$$

For the scale model flywheels, the prefabricated cracks represent a significant reduction in load bearing area of the cracked plane. Referring to Fig. 2, the effect of reduced bearing area can be incorporated into equations (10) by the following approximation

$$P_m = 0.025\ \omega^2 R\ \text{(psi)}$$

$$P_b = 0.014\ \omega^2 R\ \text{(psi)} \qquad (11)$$

where

$$R = \frac{2(b-a)}{2(b-a)-d}. \qquad (12)$$

Assuming that failure occurs when $P_m$ exceeds $S_u$ or when $(P_m + P_b)$ exceeds 1.5 $S_u$ leads to the following expressions for ductile failure speed as a function of crack size

$$\omega_1 = \sqrt{\frac{S_u}{0.025\ R}}$$

$$(13)$$

$$\omega_2 = \sqrt{\frac{1.5\ S_u}{0.039\ R}},$$

where $\omega_1$ is the critical speed based on the membrane stress and

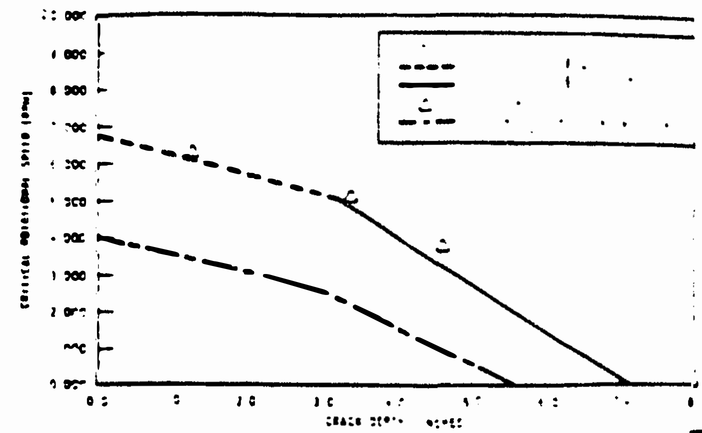

Fig. 8 Comparison of analysis and experiment for scale model flywheel tests

$\omega_2$ is the critical speed based on the membrane + bending stress. Values of $\omega_1$ and $\omega_2$ have been calculated as a function of crack depth. As in the case of the prototype flywheel, the two limiting speeds are very close; however, the membrane + bending limit ($\omega_2$) is governing. This limit is shown as a dashed line in Fig. 8.

The method for brittle fracture analysis of the scale models also follows that of the prototype evaluation, however, the experimentally measured material fracture toughness data of Fig. 7 are used in place of the lower bound fracture toughness curve. Substituting the scale model flywheel parameters into equations (6) and (7) yields model flywheel stress intensity factor data which have been compared to the average value of measured fracture toughness of the model material at the test temperature (+75 deg) to predict critical speeds for brittle fracture of the scale model flywheels. These limiting speeds are shown as the solid line in Fig. 8.

A third set of limiting speeds is shown in Fig. 8, which is representative of critical speeds as determined in the prototype flywheel evaluation. The critical speeds for the pump flywheel calculated in the sections, entitled "Ductile Failure Analysis" and "Brittle Fracture Evaluation" are not failure speeds since they are based upon 0.7 $S_u$ for ductile failure and a lower bound fracture toughness curve for brittle fracture. The safety margins associated with these methods of critical speed determination are illustrated in this figure.

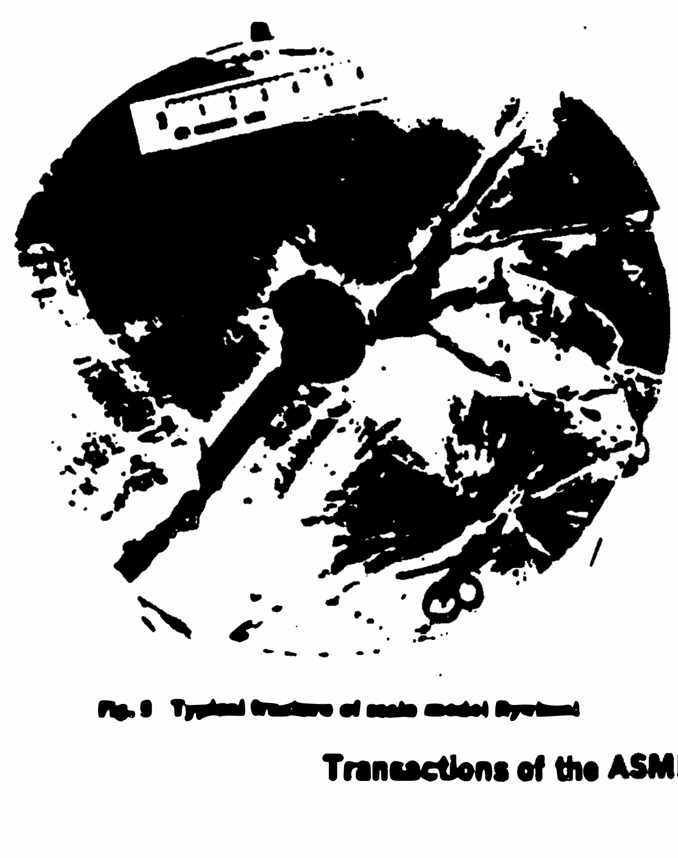

Fig. 9 Typical fracture of scale model flywheel

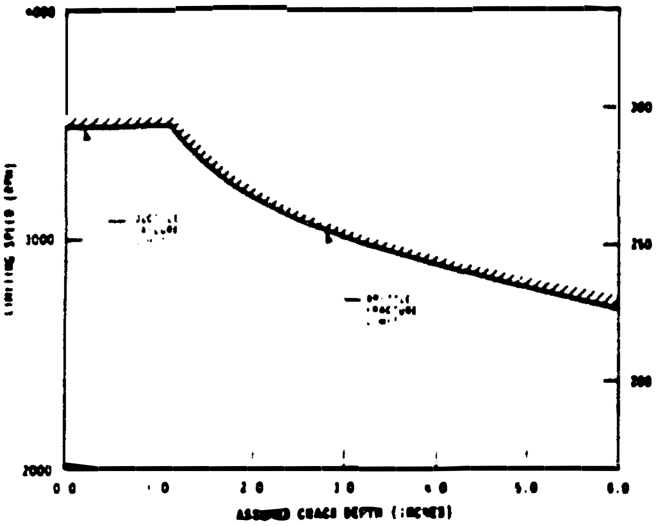


**Fig. 10 Results of reactor coolant pump flywheel overspeed evaluation**

**Test Results.** The three scale model flywheels, fabricated as described above, were tested to failure in the high speed turbine rotor testing machine at Westinghouse Research Laboratories. The tests were performed at room temperature (+75 deg) and test temperature and rotational speed were monitored continuously throughout the test.

The specimens fractured in the manner shown in Fig. 9. The fracture data from these experiments are plotted on Fig. 8, in terms of fracture speed versus actual crack depth for comparison with analysis. The agreement between the fracture predictions and the experimental data is excellent, thus lending a high degree of credibility to the analytical procedures used in the prototype flywheel evaluation, even in the presence of excessive plastic zone sizes.

## Conclusions

A detailed evaluation has been performed to determine the critical speed for the Westinghouse reactor coolant pump flywheel design from the standpoint of fracture and subsequent missile production. The results of this study are summarized in Fig. 10.

Ductile failure and brittle fracture of the flywheel were considered separately and limiting speeds were established for each. The limiting speed curve of Fig. 10 shows that the ductile failure limit of 3485 rpm (290 percent overspeed) is governing for crack sizes less than 1.15 in., and that the brittle fracture limit becomes governing for larger crack sizes. Since this crack size is very large in comparison to that which is detectable under current inspection and quality assurance procedures for the flywheel design, it can be concluded that 3485 rpm is the limiting speed for the design.

Finally, a scale model flywheel test program was carried out to verify the analytical procedures used in this evaluation. Three tests were performed, and the results of all three were highly confirmatory. On the basis of this scale model test program, it can be concluded that the methods used to predict flywheel fracture in this report are highly accurate and, in conjunction with the conservative materials property data used, should serve to preclude flywheel fracture under overspeed loading conditions providing the calculated limiting speeds are not exceeded.


## Acknowledgment

The authors gratefully acknowledge the assistance of Messrs. L. R. Singer, G. O. Sankey, and L. J. Ceschini in carrying out the experimental portion of this program.


## References


1 Riccardella, P. C., and Bamford, W. A., "Reactor Coolant Pump Overspeed Evaluation," Westinghouse Nuclear Energy Systems, WCAP-8145, Dec. 1973.

2 Timoshenko, S., and Goodier, J. N., "Theory of Elasticity," 3rd edition, McGraw-Hill, New York, 1970.

3 ASME Boiler and Pressure Vessel Code, Section III, "Rules for Construction of Nuclear Power Plant Components," American Society of Mechanical Engineers, New York, 1971 Edition & Addenda.

4 Williams, J. G., and Isherwood, D. P., "Calculation of the Strain-Energy Release Rates of Cracked Plates by an Approximate Method," *Journal of Strain Analysis*, Vol. 3, No. 1, 1968, pp. 17–22.

5 Gabrielse, S. E., "User's Manual for Westinghouse Research General Purpose Finite Element Programs," Westinghouse Research Report 70-1E7-POPSC-R1, April 23, 1970.

6 Oglesby, J. J., and Lomacky, O., "An Evaluation of Finite Element Methods for the Computation of Elastic Stress Intensity Factors," Trans. ASME, Vol. 95, Series B, 1973, pp. 177–185.

7 Mager, T. R., and Thomas, F. O., "Evaluation by Linear Elastic Fracture Mechanics of Radiation Damage to Pressure Vessel Steels," Westinghouse Nuclear Energy Systems, WCAP-7328.

8 Mager, T. R., "Fracture Toughness Characterization Study of A533, Grade B, Class 1 Steel," Westinghouse Nuclear Energy Systems, WCAP-7578, Oct. 1970.

9 Mager, T. R., and Buchalet, C., "Experimental Verification of Lower Bound $K_{Ic}$ Values Utilizing the Equivalent Energy Concept," HSST Program 6th Annual Information Meeting, Paper No. 23, Apr. 1972.

10 Witt, F. J., "A Procedure for Determining Bounding Values on Fracture Toughness $K_{Ic}$ at any Temperature," Oak Ridge National Laboratory, ORNL-TM-3894, Oct. 1972.

11 Irwin, G. R., "Fracture," *Encyclopedia of Physics*, Vol. 6, edited by S. Fluegge, Springer-Verlag, NY, 1958, pp. 551–590.

12 Manson, S. S., "Thermal Stress and Low-Cycle Fatigue," McGraw-Hill, New York, 1966.

13 Langer, B. F., "Design of Pressure Vessels for Low-Cycle Fatigue," Trans. ASME, Vol. 84, Series D, 1973, pp. 389–402.

14 Rice, J. R., "A Path Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks," Trans. ASME, Vol. 90, Series E, 1968, pp. 379–386.

15 Begley, J. A., and Landes, J. D., "The J-Integral as a Fracture Criterion," *Fracture Toughness*, ASTM-STP-514, American Society for Testing and Materials, Philadelphia, 1972, pp. 1–23.

16 Landes, J. D., and Begley, J. A., "The Effect of Specimen Geometry on $J_{Ic}$" *Fracture Toughness*, ASTM-STP-514, American Society for Testing and Materials, Philadelphia, 1972, pp. 24–39.

17 Riccardella, P. C., and Swedlow, J. L., "A Combined Analytical-Experimental Fracture Study," presented at Seventh National Symposium on Fracture Mechanics, August 27–29, 1973, University of Maryland, American Society for Testing and Materials, Philadelphia, Pa. (to be published).

18 AEC Safety Guide 14, "Reactor Coolant Pump Flywheel Integrity," USAEC, Oct. 1971.

19 ASTM Standard E-208, "Standard Method for Conducting Drop Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels," *ASTM Standards (1973), Part 31*, American Society for Testing and Materials, Philadelphia, Pa., 1973, pp. 597–616.

20 ASTM Standard E-23, "Standard Methods for Notched Bar Impact Testing of Metallic Materials," *ASTM Standards (1973), Part 31*, American Society for Testing and Materials, Philadelphia, Pa., 1973, pp. 277–298.

21 Clark, G., "Ultrasonic Procedure for the Examination of Main Coolant Pump Flywheels," Westinghouse Process Specification 94351 RU, Rev. 1, Apr. 1972.

22 Clark, W. G., and Ceschini, L. J., "Fatigue Precracking of Spin-Burst Toughness Specimens," *Experimental Mechanics*, Vol. 9, 1969, pp. 123–128.

23 ASTM Standard E-399, "Standard Method of Test for Plane-Strain Fracture Toughness of Metallic Materials," *ASTM Standards (1973) Part 31*, American Society for Testing and Materials, Philadelphia, Pa., 1973, pp. 960–979.


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SUSHIL C. JAIN
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June 21, 1996

U. S. Nuclear Regulatory Commission
Attention: Document Control Desk
Washington, DC 20555-0001

**Subject: Beaver Valley Power Station, Unit No. 1 and No. 2**
**BV-1 Docket No. 50-334, License No. DPR-66**
**BV-2 Docket No. 50-412, License No. NPF-73**
**Response to Request for Additional Information Concerning**
**WCAP-14535; Revised Item 2 Response**

Attached is a revised response to Item 2 to an NRC staff request for additional information provided by letter dated May 1, 1996, concerning WCAP-14535, "Topical Report on Reactor Coolant Pump Flywheel Inspection Elimination." Beaver Valley submitted the subject report by letter dated January 24, 1996, as the industry's lead plant on this issue, and submitted a response to the request for additional information on June 14, 1996. On June 18, 1996, a teleconference between the NRC staff reviewers, Westinghouse Electric Corporation staff, and members of the Beaver Valley staff discussed the June 14, 1996, submittal, in particular Item 2.

This revised response to Item 2 is intended to clarify the interaction and impact of adding the stresses associated with a conservative shrink fit and flaw sizing conservatism associated typically with Section XI acceptance criteria of the ASME Boiler and Pressure Vessel Code. The response to Item 2 and Table 1 has been revised to reflect additional conservatism in the allowable crack lengths for reactor coolant pump flywheels.

Please direct questions regarding this submittal to Mr. Roy K. Brosi at (412) 393-5210.

Sincerely,

Sushil C. Jain

DELIVERING QUALITY ENERGY

# Response to NRC Request for Additional Information on WCAP-14535 (Revised Response to Item 2)

**Item 2:**

*Section 1.1 Previous Flywheel Integrity Evaluations, Page 1-3 - The fatigue analysis is dependant on the premise that UT equipment used for examinations of RCP flywheels at these facilities is capable of accurately detecting and sizing 0.24 inch long near surface flaw. Provide your basis supporting the probability of detection (POD) for the examinations performed. Provide details on how the POD values were determined, qualified, and used in concluding the assumed size of the initial flaw.*

**Response to Item 2:**

The initial crack length of 0.24 inch was used in a previous evaluation of RCP flywheel integrity by Babcock and Wilcox (Report BAW-10040, December 1973, "Reactor Coolant Pump Assembly Overspeed Analysis"). This length was assumed to be the largest crack that could be missed in nondestructive testing.

As seen in Table 4-4 of WCAP-14535, crack growth assuming extremely large initial flaw lengths (from 2.04 to 3.28 inches) was found to be insignificantly small over a 60 year extended plant life. In the crack growth evaluation, 6000 RCP start/stop cycles were assumed, which is conservative with respect to actual operation. Shrink fit was not included in the WCAP-14535 evaluation. This is conservative, since shrink fit retards crack growth, as discussed in the Response to Item 1, above. This evaluation suggests that very large initial flaws can be structurally tolerated, from a crack growth perspective. As noted later in this discussion, the reflective reference area used for calibration of the inspection procedure is nearly an order of magnitude smaller than these structurally stable flaws.

An alternative method of evaluating this issue is to define an "allowable" flaw size based on the application of margins to the calculated critical flaw size and the calculated stress intensity factor. The approach used here is to apply the Code pressure boundary margins of ASME Section XI to the flywheel, which is a non-pressure boundary, non-Code component. This application is considered to be extremely conservative. The Section XI criteria are as follows:

| | | |
|---|---|---|
| Criteria based on flaw size: | $a_{allow}$ $0.1\ a_{critical}$ | (Normal, Upset and Test Conditions) |
| | $a_{allow}$ $0.5\ a_{critical}$ | (Emergency and Faulted Conditions) |
| Criteria based on stress intensity factor: | $K_I$ Toughness/ 10 | (Normal, Upset and Test Conditions) |
| | $K_I$ Toughness/ 2 | (Emergency and Faulted Conditions) |

The normal condition for the flywheel is the normal operating speed of 1200 rpm. The faulted condition for the flywheel is the overspeed of 1500 rpm.

The results of this approach are provided in Table 1 below. Shrink fit is included in these results, since shrink fit increases the magnitude of the hoop stresses (as shown in Figure 1) and consequently, the stress intensity factor. In Table 1, crack length is measured radially from the keyway, and percentage through the flywheel is the crack length divided by the radial length from the keyway to the flywheel outer radius.

**Table 1: Allowable Crack Lengths for Flywheels Including the Effect of Shrink Fit and Section XI Criteria**

| Flywheel Group | Allowable Crack Lengths in Inches and % through Flywheel | | | | | |
|---|---|---|---|---|---|---|
| | 1200 rpm (Normal Speed) | | | 1500 rpm (Overspeed) | | |
| | $RT_{NDT}$ = 0°F | $RT_{NDT}$ = 30°F | $RT_{NDT}$ = 60°F | $RT_{NDT}$ = 0°F | $RT_{NDT}$ = 30°F | $RT_{NDT}$ = 60°F |
| 1 | 2.3" (7%) | 1.4" (4%) | 0.4" (1%) | 7.6" (23%) | 2.7" (8%) | 0.6" (2%) |
| 2 | 2.3" (7%) | 1.5" (4%) | 0.4" (1%) | 8.0" (24%) | 2.8" (8%) | 0.5" (2%) |
| 10 | 1.9" (7%) | 1.3" (5%) | 0.6" (2%) | 8.3" (31%) | 3.7" (14%) | 1.6" (6%) |
| 14 | 2.2" (8%) | 1.8" (7%) | 1.1" (4%) | 12.0" (43%) | 5.4" (20%) | 1.2" (4%) |
| 15 | 1.0" (5%) | 0.5" (2%) | 0.2" (1%) | 4.3" (21%) | 1.9" (9%) | 0.9" (4%) |
| 16 | 1.9" (8%) | 1.4" (6%) | 0.7" (3%) | 10.2" (42%) | 4.6" (19%) | 1.8" (7%) |

It is important to note that several conservative assumptions were included in the determination of the allowable crack lengths provided in Table 1. These are discussed as follows:

a) The closed form solution for the stress intensity factor was used. This solution assumes that the keyway radial length is included in the crack length, which is conservative for smaller crack lengths. This conservatism is evident in Figure 3 for Flywheel Group 1, which indicates that a zero length crack has a stress intensity factor of about 42 ksi √inch, since a crack of 0.937 inches (the keyway length) is assumed. As shown in Figure 4 of the attached ASME technical paper (Attachment C), finite element analysis shows that the stress intensity factor for cracks less than about one inch long is significantly less than the closed form solution would predict. Therefore, there is significant conservatism in the smaller allowable crack lengths ( 1 inch and smaller) provided in Table 1 above.

b) A conservative shrink fit was assumed, as discussed in the Response to Item 1.

c) A lower bound fracture toughness for ferritic steels was used, as discussed in Section 4.3, page 4-7 of WCAP-14535.

d) The very conservative criteria of Section XI were used. These criteria apply margins of ten (10) to normal, upset and test conditions, and two (2) to emergency and faulted conditions. These margins account for uncertainties in flaw sizing and loading. It should be noted that the loadings associated with the flywheel (centrifugal forces and shrink fit) are well defined and were conservatively applied in this evaluation.

e) The ambient temperature used for the fracture evaluation (70°F) represents a much lower temperature than would be expected in the containment building during normal plant operating conditions (typically 100°F to 120°F).

f) The stress intensity factor is calculated using the methods of linear elastic fracture mechanics. This method assumes rapid crack extension in a linear elastic material (i.e., material properties below $RT_{NDT}$). The flywheel material would remain highly ductile since the operating temperature is well above the $RT_{NDT}$ of the material. The conservatism using this method is therefore inherent.

Over the past ten years, the examination techniques employed have improved, particularly with the use of the defocused gage hole probe. The detectability of the gage holes at various metal paths displayed in Attachment B indicate that the inspection methods used for flywheels are capable of finding flaws of the sizes identified in Table 1.

In Attachment B, the 1.25 inch diameter gage holes (effectively side drilled holes) were clearly identified at a metal path which is nearly twice the metal path distance involved in the inspection of the keyway area. It should be noted that it is conservatively estimated that the effective reflective surface of a side drilled hole is a $30^{0}$ arc. The reflective surface from a 1.25 inch gage hole would therefore be 0.33 inch. This length is smaller than all but the smallest of the allowable crack lengths in Table 1 (0.2 inch, Flywheel Group 15, $RT_{NDT}$ of $60^{0}$F, 1200 rpm). As discussed above, a significant amount of conservatism is inherent in the smaller allowable crack lengths ( 1 inch and smaller) provided in Table 1. In addition, Flywheel Group 15 includes only one plant, Three Mile Island Unit 1. Per Babcock and Wilcox Power Generation Group, Nuclear Power Generation Division Topical Report BAW-10040, December 1973, "Reactor Coolant Pump Assembly Overspeed Analysis," the $RT_{NDT}$ value of the flywheel material is estimated to be $-10^{0}$F. Therefore, a crack length of greater than one inch would be allowed, which is larger than the 0.33 inch reflective surface from a 1.25 inch gage hole discussed above.

Therefore, the inspection methods used for flywheels are capable of finding the flaw sizes shown in Table 1.

# APPENDIX F

## RESPONSE TO SECOND NRC REQUEST FOR ADDITIONAL INFORMATION

**Duquesne Light Company**
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SUSHIL C JAIN
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Nuclear Power Division

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August 2, 1996

U. S. Nuclear Regulatory Commission
Attention: Document Control Desk
Washington, DC 20555-0001

Subject: **Beaver Valley Power Station, Unit No. 1 and No. 2**
**BV-1 Docket No. 50-334, License No. DPR-66**
**BV-2 Docket No. 50-412, License No. NPF-73**
**Response to Request for Additional Information Concerning**
**WCAP-14535; RAI Dated July 24, 1996**

Attached is our response to an NRC staff request for additional information provided by letter dated July 24, 1996, following a meeting between Duquesne Light Company and NRC staff on July 17, 1996. This response concerns the maintenance history and frequency of pump motor overhauls for the types of pumps proposed to be covered by WCAP-14535, "Topical Report on Reactor Coolant Pump Flywheel Inspection Elimination."

Currently a reactor coolant pump flywheel inspection would be required during the Beaver Valley Power Station Unit No. 2 sixth refueling outage scheduled to begin on August 30, 1996. Therefore, NRC approval is requested by this date.

Please direct questions regarding this submittal to Mr. Roy K. Brosi at (412) 393-5210.

Sincerely,

Sushil C. Jain

c: w/enclosure:
Mr. L. W. Rossbach, Sr. Resident Inspector
Mr. H. J. Miller, NRC Region I Administrator
Mr. D. S. Brinkman, Sr. Project Manager (3 copies)
Ms. Diane Jackson, Westinghouse Electric Corporation

DELIVERING QUALITY ENERGY

## Response to NRC Request for Additional Information on WCAP-14535
## RAI Dated July 24, 1996

On July 17, 1996, a meeting with the NRC staff was held to provide information concerning the costs of reactor coolant pump (RCP) motor flywheel inspections, and the frequency of RCP motor disassembly for maintenance. Duquesne Light Company (DLC) personnel discussed actions performed at the Beaver Valley Power Station. The applicability of the responses to the industry as a whole could not be addressed; accordingly, a survey of the flywheel group was conducted. The results of this survey are discussed below along with an alternative flywheel inspection.

Survey responses were received for 35 of the 57 plants which are covered by WCAP-14535. The results show a wide range of responses to the question of how often RCP motors are disassembled for maintenance, but most are disassembled on an average frequency of about every 8 years. The other two questions concerned the cost and exposure involved with flywheel inspections now being done per Regulatory Guide 1.14 (dollars and man-rem). For inspections with the flywheel in place (not removed from the motor shaft), the average cost and exposure are $5,300 and 0.34 man-rem, respectively. For the flywheel removed from the motor shaft, the average cost and exposure are $28,100 and 0.88 man-rem, respectively.

WCAP-14535 presents a strong technical case for the elimination of RCP flywheel inspections. This elimination would not affect the frequency of RCP motor maintenance, but would significantly reduce the risk of RCP motor flywheel failure, since the only credible mechanism for flywheel damage is from removal, handling and reassembly, as discussed in WCAP-14535. This potential for damage during handling was also discussed at the meeting, and in response to the concerns raised by the staff concerning flywheel integrity following RCP motor maintenance, the following is proposed.

An alternative inspection patterned after Code Case N481 for RCP casings which integrates inspections into normal maintenance activities is recommended. Inspections using visual, liquid penetrant or ultrasonic techniques would be performed on the bore and keyway region whenever the flywheel is removed from the shaft for RCP maintenance. This is in concert with the conclusion of the technical assessment that only the bore and keyway regions need to be inspected, not 100% of the flywheel volume, as presently required by the regulatory guide.

Therefore, the following will be incorporated in DLC's maintenance program:

Upon disassembly (removal of the flywheel from the shaft of the RCP motor) for normal maintenance activities, the bore and keyway region of the RCP motor flywheel shall be inspected by visual, surface or ultrasonic techniques.

# APPENDIX G

## UNITED STATES NUCLEAR REGULATORY COMMISSION
## SAFETY EVALUATION REPORT

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

Nuclear Safety Dept.
SEP 24 1996

SEP 12 1996

Mr. Sushil C. Jain, Division Vice President
Nuclear Power Division
Duquesne Light Company
Beaver Valley Power Station
P.O. Box 4
Shippingport, Pennsylvania 15077-0004

SUBJECT: ACCEPTANCE FOR REFERENCING OF TOPICAL REPORT WCAP-14535, "TOPICAL REPORT ON REACTOR COOLANT PUMP FLYWHEEL INSPECTION ELIMINATION"

Dear Mr. Jain:

We have completed our review of the subject topical report submitted by Duquesne Light Company (DLC) for Beaver Valley 1 & 2 as the two leading plants by letter dated January 24, 1996. We find the report to be acceptable for referencing in license applications to the extent specified and under the limitations delineated in the report and the associated NRC safety evaluation (SE), which is enclosed. The evaluation defines the basis for acceptance of the report as limited by an inspection period acceptable to the staff.

We do not intend to repeat our review of the matters described in the report when the report appears as a reference in license applications, except to ensure that the material presented is applicable to the specific plant involved as indicated in the conclusion section of the SE. Our acceptance applies only to the matters described in the report.

In accordance with procedures established in NUREG-0390, it is requested that DLC coordinate with the Westinghouse Owners Group and publish this report within three months of receipt of this letter. The final version shall incorporate this letter, the enclosed evaluation, and DLC's responses to the NRC RAI dated June 14 (without attachments) and June 21, 1996, between the title page and the abstract. The final version shall include an -A (designating accepted) following the report identification symbol.

Licensees having Group-15 flywheels need to demonstrate that material properties of their A516 material is equivalent to SA 533 B material, and its reference temperature, $RT_{NDT}$, is less than 30°F. Licensees with Group-10 flywheels need to confirm in the near term that their flywheels have an adequate shrink fit to preclude loss of shrink fit of the flywheel at maximum overspeed or to provide an evaluation demonstrating that no detrimental effects would occur if the shrink fit was lost at maximum overspeed.

Sincerely,

Brian W. Sheron

~~Brian W. Sheron, Director~~
Division of Engineering
Office of Nuclear Reactor Regulation

Enclosure: As stated

# SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

## TOPICAL REPORT ON REACTOR COOLANT PUMP FLYWHEEL INSPECTION ELIMINATION

## BEAVER VALLEY 1 & 2

## MATERIALS AND CHEMICAL ENGINEERING BRANCH

## DIVISION OF ENGINEERING

### 1.0 INTRODUCTION

On January 24, 1996, Duquesne Light Company (DLC), the licensee for Beaver Valley 1 & 2) submitted a Westinghouse report, WCAP-14535 [1], "Topical Report on Reactor Coolant Pump Flywheel Inspection Elimination," for NRC review. This report, which provides an engineering analysis based on fracture mechanics, is intended to eliminate reactor coolant pump (RCP) flywheel inservice inspection (ISI) requirements for all operating Westinghouse plants and some Babcock and Wilcox Plants. Presently, Beaver Valley's RCP flywheel inspection is performed in accordance with its licensing commitment to Regulatory Guide (RG) 1.14 [2], which provides guidelines on conducting surface and ultrasonic volumetric examinations of RCP flywheels coinciding with each individual plant's ISI schedule as required by Section XI of the American Society of Mechanical Engineers (ASME) Code.

### 2.0 BACKGROUND

The function of the RCP in the reactor coolant system (RCS) of a pressurized water reactor plant is to maintain an adequate cooling flow rate by circulating a large volume of primary coolant water at high temperature and pressure through the RCS. A concern over overspeed of the RCP and its potential for failure led to the issuance of RG 1.14 in 1971. The regulatory position of RG 1.14 concerning ISI calls for an in-place ultrasonic volumetric examination of the areas of higher stress concentration at the bore and keyway at approximately 3-year intervals and a surface examination of all exposed surfaces and complete ultrasonic volumetric examination at approximately 10-year intervals. The flywheel inspection schedule is to coincide with the individual plant's ISI schedule as required by Section XI of the ASME Code.

Operating power plants have been inspecting their flywheels for over twenty years, and no flaws have been identified which affect flywheel integrity. This inspection record, plus the licensee's concern over inspection costs and personnel radiation exposure, prompted it to submit this topical report to demonstrate through fracture mechanics analysis that flywheel inspections can be eliminated without impairing plant safety.

### 3.0 EVALUATION AND VERIFICATION

The primary regulatory position of RG 1.14 regarding flywheel design concerns three critical speeds: (a) the critical speed for ductile fracture, (b) the critical speed for nonductile fracture, and (c) the critical speed for excessive deformation of the flywheel. This regulatory position specifies, as a design criterion, that the normal speed of the flywheel should be less than one-half of the lowest of these three critical speeds, and the LOCA overspeed should be less than the lowest of these three critical speeds.

### 3.1 MATERIAL INFORMATION

As shown in Table 2-1 of WCAP-14535, all flywheels have been classified into 16 groups according to their material and geometric information. Except for flywheels in Groups 14 to 16, all flywheels were made of reactor pressure vessel plate steel, SA 533 Grade B (SA 533 B). The analytical results presented in this report are for SA 533 B material. To cover a wide range of flywheels, the results were presented for three reference temperatures, that is, $RT_{NDT}$ = 0°F, 30°F, and 60°F. A reference temperature of 60°F is a reasonable bounding value for material SA 533 B, and has been used in the subsequent evaluation.

### 3.2 ANALYSIS FOR CRITICAL SPEED BASED ON DUCTILE FRACTURE

RG 1.14 permits the use of elastic stress analysis methods and the acceptance criteria of Section III of the ASME Code to predict the critical speed based on ductile fracture of the flywheel. The ASME Code requires that the stress limits for the general primary membrane stress intensity $P_m$ and the primary membrane plus primary bending stress intensity $P_L + P_b$ be $0.7S_u$ and $1.05S_u$ for the faulted loading combination, where $S_u$ is the minimum specified ultimate tensile stress of the material. The topical report used these limits and employed the minimum specified $S_u$ value of 80 ksi for flywheel material SA-533 B to arrive at the critical speeds for six groups of flywheels under ductile fracture conditions shown in Table 4-2. These six groups were selected from a total of 16 groups so that they cover all flywheel dimensions. Table 4-2 indicates that the lowest calculated critical speed is 2698 rpm (Group 15 flywheels), and the normal speed of 1200 rpm is clearly less than one-half of that value. The type of analyses performed above satisfies RG 1.14. However, since RG 1.14 was published in 1975, more appropriate elastic-plastic fracture mechanics (EPFM) methodology has been developed to predict ductile fracture. Performing an EPFM analysis is not necessary because the linear elastic fracture mechanics (LEFM) analysis in Section 3.3 is the appropriate analysis method for the thick section of the flywheel and temperature regime of operation.

### 3.3 ANALYSIS FOR CRITICAL SPEED BASED ON NONDUCTILE FRACTURE

The topical report provided a linear elastic fracture mechanics analysis to address the prediction of critical speed for nonductile fracture of the flywheel specified in Item 2.d of RG 1.14.

The analysis used the closed-form solution for a radial full-depth crack emanating from the bore of a rotating disk to calculate the applied stress intensity factor (applied K). The fracture resistance for the SA-533 B plate was obtained from the lower bound $K_{Ic}$ curve of Section XI of the ASME Code. Use of $K_{Ic}$ was suggested by RG 1.14. The loads used in calculating the applied K were from an overspeed of 1500 rpm. Further, three values of $RT_{NDT}$, 0°F, 30°F, and 60°F, were used in calculating the $K_{Ic}$. The resulting critical crack lengths for the six groups of flywheels were summarized in Table 4-3. It showed that the smallest critical crack length is 2.6 inches for Group-15 flywheels having an assumed $RT_{NDT}$ value of 60°F.

The flaw evaluation including fatigue analysis in the original submittal did not determine a critical speed based on an assumed initial flaw size as requested by RG 1.14, or show that the acceptance criteria of IWB-3610 of Section XI of the ASME Code were satisfied. In response to this, the licensee applied in Reference 3 the margins of IWB-3610 of Section XI of the ASME Code and expanded Table 4-3 of the topical report to include critical crack lengths at the normal speed for the six groups of flywheels. The new table was called Table 1. The staff also determined that the applied K due to shrink-fit stresses were not considered in the initial response. In the second response to the staff's RAI [4], the licensee revised Table 1 one more time to include the shrink-fit effect. This table indicates that normal/upset conditions are controlling for the flywheels. The allowable crack lengths, with IWB-3610 margins applied, are 0.2 inch for Group 15 and 0.4 inch for the remaining groups of flywheels. In Attachment B to Reference 3, the 1.25 inch diameter gage holes were identified at a metal path which is about twice the metal path distance involved in the inspection of the keyway area. The reflective surface from a 1.25 inch gage hole would therefore be 0.33 inch. Since the ASME IWB-3610 minimum allowable crack length, 0.4 inch, for all groups except for Group 15 is greater than the 0.33 inch that was demonstrated to be detected, all flywheels except those in Group 15 satisfy the nonductile fracture criterion. For licensees having Group-15 flywheels, they need to demonstrate that the reference temperature, $RT_{NDT}$, for their SA 533 B material or its equivalent is less than 30°F because Table 1 of Reference 4 indicates that the allowable crack length for this $RT_{NDT}$ value is greater than 0.4 inch. Further, it should be noted that the minimum initial crack length, considering shrink fit but not the ASME margin, is 1.0 inches at the normal speed of 1200 rpm for all groups. Based on experience with the inspection of ferritic components with short metal paths, the staff considers that it is unlikely that any defect that could challenge flywheel integrity would be missed by the inspection. In addition, the staff agrees that other conservatisms that are identified in Reference 4 were not accounted for in the analysis.

RG 1.14 requires the normal speed of the flywheel be one half the critical speed. Meeting the margins based on applied K of IWB-3610 of Section XI of the ASME Code is acceptable to the staff for satisfying this criterion. When this is translated into the concept of factor of safety on applied stress, it is equivalent to a factor of 4. Since the toughness used is $K_{Ia}$ in the ASME Code (for the limiting normal condition) and $K_{Ic}$ in RG 1.14, and $K_{Ic}$ is larger than $K_{Ia}$, the RG margin will be very close to the ASME margin of $(10)^{1/2}$ after having applied the ratio of $K_{Ia}$ to $K_{Ic}$.

Fatigue crack growth was determined from the rate formula in Appendix A of Section XI. For the flywheel in each group, an initial crack length of 10% of the distance from the keyway to the flywheel outer radius was assumed (ranging from 2.04 inches to 3.28 inches). As to the loading, 6000 cycles of RCP starts and stops were assumed for a 60-year plant life. The crack growth after 6000 cycles are tabulated in Table 4-4 of WCAP-14535 for the six groups of flywheels. The largest growth is for cracks in Groups 1 and 2 flywheels, for which a value of 0.08 inch is reported.

The fatigue crack growth calculation did not include the stresses due to shrink fit. However, in Reference 3 it was demonstrated that excluding the shrink-fit stresses is conservative in the crack growth calculation. This is because the key parameter now is $\Delta K$ instead of K. The explanation provided in Reference 3 is acceptable and the staff agrees that the crack growth calculation is conservative. The staff concludes that after 10 years the maximum fatigue growth would be expected to be about 0.013 inch. If it is assumed that a crack of 0.33 inches were missed and the maximum expected fatigue crack growth were applied, the end of cycle crack size would be 0.343 inch. Therefore, the ASME margins would be maintained during the service period and a 10-year inspection period appears reasonable.

### 3.4 COMPLIANCE WITH THE EXCESSIVE DEFORMATION FAILURE CRITERION

The analyses in the report used standard closed-form formulas for rotating disks to calculate the change of flywheel inner and outer radii at 1500 rpm. The results are tabulated in Table 4-5 for the six groups of flywheels. The largest value is 0.010 inch for the change in the inner radius. Without referring to any criterion, this report stated that these increases would not result in any adverse conditions.

The primary concern of RG 1.14 over excessive deformation is the enlargement of the bore that could cause a separation of the flywheel from the shaft or could cause an unbalance of the flywheel leading to structural failure. The staff believes that the concern here is the loss of shrink-fit at high speed. Once it happens, the keys on the flywheels may not be able to prevent the slight relative displacement between the wheel and the shaft from happening. Consequently, the balance of the flywheel might be altered. The staff concludes that most flywheels satisfy the excessive deformation failure criterion based on loss of shrink-fit. However, it appears that using the generic initial shrink-fit assumed in the topical report, the shrink fit may be lost for Group-10 flywheels at a speed of 1500 rpm. Licensees having these flywheels need to use the plant-specific shrink-fit value to check the loss of shrink-fit of the flywheel at this speed.

### 3.5 COMPLIANCE WITH THE LOCA OVERSPEED CRITERION

RG 1.14 requires that the LOCA overspeed should be less than the lowest of the three critical speeds mentioned in Section 3.0. Since the predicted LOCA overspeed reported in the submittal is in all cases less than 1500 rpm, which happens to be the lowest critical speed discussed above, the LOCA overspeed criterion is satisfied.

### 3.6 RISK ASSESSMENT

The staff relied solely on deterministic methodology to review this submittal. The risk assessment in Section 5, which used a Monte-Carlo simulation with importance sampling for assessing the effect of inspections, concluded that flywheel inspections beyond ten years of plant life have no significant benefit on reducing the risk of flywheel failure. Since the risk assessment was not reviewed, acceptance of this report shall not be interpreted as the staff accepting the probabilistic methodology in Section 5.

## 4.0 CONCLUSIONS

The Materials and Chemical Engineering Branch has completed its review of the licensee's submittals and has determined that the evaluation methodology in the reports is appropriate and the criteria are in accordance with the design criteria of Rg 1.14.

For the RG criteria on the three critical speeds, the staff concluded that (1) all flywheels satisfy the ductile fracture criterion of RG 1.14; (2) except for Group-15 flywheels, all flywheels satisfy the nonductile fracture criteria of Section XI of the ASME Code because their allowable crack length (≥ 0.4 inch) is greater than the minimum flaw size that would be found by periodic inspections used for flywheels describes in Attachment B to Reference 3; and (3) all flywheels except those in Group 10 satisfy the excessive deformation criterion of RG 1.14.

This report requests complete flywheel inspection elimination. The staff believes that even for flywheels meeting all the design criteria of RG 1.14, as modified in this SER, inspections should not be completely eliminated. Inspections are performed in part to protect against events or degradation that is not anticipated and has not been considered in the analysis. This philosophy is consistent with the requirements in the ASME Code for successive inspections for flaws evaluated to the Section XI acceptance criteria. Therefore, the staff will not accept elimination of flywheel inspection. However, conducting flywheel inspection when RCP motor maintenance is required (about every 8 years from a limited survey [5]), the staff finds the following acceptable:

(1) Licensees who plan to submit a plant-specific application of this topical report for flywheels made of SA 533 B material need to confirm that their flywheels are made of SA 533 B material. Further, licensees having Group-15 flywheels need to demonstrate that material properties of their A516 material is equivalent to SA 533 B material, and its reference temperature, $RT_{NDT}$, is less than 30°F.

(2) Licensees who plan to submit a plant-specific application of this topical report for their flywheels not made of SA 533 B or A516 material need to either demonstrate that their flywheel material properties are bounded by those of SA 533 B material, or provide the minimum specified ultimate tensile stress, $S_u$, the fracture toughness, $K_{Ic}$, and the reference temperature, $RT_{NDT}$, for that material. For the latter, the licensees should employ these material properties, and use the methodology in the topical report, as extended in the two responses to the staff's RAI, to provide an assessment to justify a change in inspection schedule for their plants.

(3) Licensees meeting either (1) or (2) above should either conduct a qualified in-place UT examination over the volume from the inner bore of the flywheel to the circle of one-half the outer radius or conduct a surface examination (MT and/or PT) of exposed surfaces defined by the volume of the disassembled flywheels once every 10 years. The staff considers this 10-year inspection requirement not burdensome when the flywheel inspection is conducted during scheduled ISI inspection or RCP motor maintenance. This

would provide an appropriate level of defence in depth.

Licensees with Gro p-10 flywheels need to confirm in the near term that their flywheels have an adequate shrink fit to preclude loss of shrink fit of the flywheel at maximum overspeed or to provide an evaluation demonstrating that no detrimental effects would occur if the shrink fit was lost at maximum overspeed.

Since this topical report and all related documents were submitted by DLC, no demonstration of plant-specific applicability is required from DLC.

## 5.0 REFERENCES

1.0 Duquesne Light Co., letter from George S. Thomas (DLC) to USNRC Document Control Desk with enclosed report, WCAP-14535, "Topical Report on Reactor Coolant Pump Flywheel Inspection Elimination," January 24, 1996.

2.0 USNRC, Regulatory Guide 1.14, "Reactor Coolant Pump Flywheel Integrity," 1971; Revision 1, August 1975.

3.0 Duquesne Light Co., letter from George Sushil C. Jain (DLC) to USNRC Document Control Desk, "Response to Request for Additional Information Concerning WCAP-14535," June 14, 1996.

4.0 Duquesne Light Co., letter from George Sushil C. Jain (DLC) to USNRC Document Control Desk, "Response to Request for Additional Information Concerning WCAP-14535; Revised Item 2 Response" June 21, 1996.

5.0 Duquesne Light Co., letter from George Sushil C. Jain (DLC) to USNRC Document Control Desk, "Response to Request for Additional Information Concerning WCAP-14535; RAI Dated July 24, 1996" August, 2, 1996.

# APPENDIX H

## KEY PROVISIONS AND FOLLOWUP CLARIFICATIONS

**Safety Evaluation Report on RC Pump Flywheel Inspection**

The NRC staff has completed their review of the topical report submitted by Duquesne Light Company on your behalf, and has issued a Safety Evaluation Report, which is attached. The report is dated September 12, 1996, but was not received by Duquesne Light until September 19. Our review of the SER has revealed several mistakes, and a number of areas where the wording is not clear. We have obtained clarifications through several phone calls with the NRC staff, and these are discussed below. First, a brief summary of the key provisions of the SER.

**Key Provisions**

1. Inspections need only be done on a ten year interval, instead of 40 months.

2. Acceptable inspection methods are either UT or surface exams (magnetic particle or liquid penetrant).

3. UT inspection coverage is required only on the inner half of the flywheel radius.

4. Surface examination coverage is the exposed surfaces of the flywheel when the pump is disassembled for maintenance.

5. All licensees can reference this SER in license applications, and detailed technical reviews of the submittals will not be required, unless new technical information is presented.

**Follow-up Clarifications**

1. The new inspections are meant to be a relief from those contained in Regulatory Guide 1.14.

2. The term "qualified" as applied to the UT has no hidden meaning. The inspections under this SER should be qualified in the same way the inspections under RG 1.14 were qualified. Specifically, the staff said that Appendix VIII of Section XI does not apply.

3. Referring to item (3) on page 5, the area to be examined by surface examination is stated as the "exposed surfaces defined by the volume of the disassembled flywheels". This was clarified to mean the "exposed surfaces of the disassembled flywheels".

4. The questions about the toughness of the Group 15 flywheels and the shrink fit for Group 10 flywheels have been answered earlier in response to the staff request for additional information, but for some reason were missed by the staff when they issued the SER. The staff suggested that this information be included in the submittals of the affected utilities, with a note mentioning the earlier submittal.

## Follow-up Actions

The original WCAP-14535 will be republished, along with the two requests for additional information and the responses, and the SER. The information needed by Group 15 and Group 10 owners will be clearly laid out. This report will be numbered WCAP-14535A.

## Conclusions

The SER provides some relief, but the extent of relief was somewhat disappointing. The NRC staff said that technically the basis for further minimizing flywheel inspections has been established, but they felt they could go no further at the present time. This leaves the door open for future actions on this subject.