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EIGHT-STAGE STEAM TURBINE ROTOR DYNAMICS ANALYSIS

Prepared for

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Prepared Under

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Task 12-6

MECHANICAL TECHNOLOGY INCORPORATED
968 Albany-Shaker Rd.
Latham, New York 12110

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TECHNICAL REPORT

EIGHT-STAGE STEAM TURBINE ROTOR DYNAMICS ANALYSIS

George Siegrist   A.E. Richey

Author (s) George Siegrist , A.E. Richey

Paul Lewis

Approved P. Lewis

Approved

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968 ALBANY - SHAKER ROAD — LATHAM, NEW YORK — PHONE 785-0922

Reference Report:

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Contract E(04-3)-1096

Eight-Stage Turbine Development

13 December 1976

Prepared for: Energy Research and Development Administration

By: Aerojet Liquid Rocket Company

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I. INTRODUCTION

The subject eight-stage steam turbine was built and partially tested by the Aerojet Company under U.S. ERDA Contract E(04-3)-1096. Repeated failures were experienced during the development program which have precluded operation of the turbine over its design speed range and prevented documentation of performance characteristics. The turbine design speed is 60,000 rpm; however, testing to date has been limited to a maximum speed of 54,000 rpm transiently, with an off-design steady state test point obtained at 48,000 rpm. Analysis conducted by the Aerojet Company has indicated that the rotor first critical speed occurs in the 20,000 - 28,000 rpm range, and that operation in this speed range should be minimized.

Under Task 12 of U.S. ERDA Contract EY-76-C-02-2835, MTI conducted a design review and dynamics analysis of the rotor system. The results of this review and analysis are presented in this report.

II. SUMMARY OF RESULTS

A. Analysis of the rotor system indicates the potential of a rotor dynamics problem in the first critical speed range. Good balance and an effective turbine end bearing damper are required to control the rotor dynamic response.

B. The existing turbine end bearing damper is inadequate. Examination of the hardware revealed evidence of motion of the squirrel cage within the housing. Design modifications are required to achieve desired damping characteristics.

C. Turbine wheel fits, measured after disassembly of the turbine, exceeded limits specified by the design drawings and contribute to the potential rotor unbalance problem. Further, balance shifts may occur during operation due to the loose wheel fits.

III. RECOMMENDATIONS

The following steps are recommended for solution of the rotor dynamics problem:

A. Redesign Turbine End Bearing Damper

- Provide more positive means of attachment of the damper cage to the bearing housing
- Eliminate or modify the turbine end damper seal to allow positive oil flow through the journal
- Increase land lengths of the damper at both ends
- The feasibility of incorporating these changes in the existing hardware should be determined

B. Reduce Rotor Unbalance

The existing turbine wheel-to-hub clearances should be reduced by plating and made as tight as possible, allowing for assembly/disassembly requirements.

C. Review Bearing Oil System Design

Conduct design review of the bearing oil system to insure adequate bearing life.

D. Conduct Additional Mechanical Tests

Design and build a special test rig to allow evaluation of a redesigned damper. This rig should be capable of testing the rotor assembly without the turbine casing and would be powered by directing air jets against the eighth stage turbine wheel. This would enable installation of instrumentation to measure shaft and damper motion and would also eliminate unbalance due to rotor disassembly/assembly after balancing.

IV. DISCUSSION

A. Rotor System Modeling

Rotating machinery dynamics analysis is conducted using a mathematical representation of the rotor system. For the Aerojet turbine, the principle system components affecting the dynamic behavior are (1) the turbine rotor, and (2) the rotor support system. Development of the model used for analysis is presented in this section.

1. Rotor Mathematical Model

A mathematical model of the rotor system was prepared (Figure 1). The model is constructed based on Aerojet drawings and represents the rotor as a system of concentrated and distributed masses and moments of inertia, and models shaft stiffness on an equivalent diameter basis.

For the Aerojet Turbine, the stiffness diameter at two locations, namely through the first seven turbine stages and in the region of the turbine end bearing spacer, is dependent upon a stackup of several individual pieces on both the turbine and shaft ends, and is a function of tie bolt tightening torque. To determine the correct stiffness diameters for the model, the rotor was experimentally tested to determine its lateral natural "ringing" frequencies. Two series of tests were conducted. The first series, for the shaft end, was made on a partial rotor assembly with the turbine end tie bolt and turbine wheels 1 - 7 removed. Several checks were made with repeated loosening and re-tightening of the shaft end tie bolt to the specified torque of 75 in.-lb to obtain an average natural frequency. The second test series was conducted on the fully assembled rotor to determine the natural frequency of the complete rotor assembly and, thereby, identify the turbine end stiffness contribution, loosening and re-tightening the turbine end tie bolt. The average natural frequencies were 1805 Hz (108,300 cpm) and 1273 Hz (76,380 cpm) for the partial and complete rotor assemblies, respectively.

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Mathematical Model of ERDA Steam Turbine ~~Rotor~~ Rotor Assembly

July 26, 1977

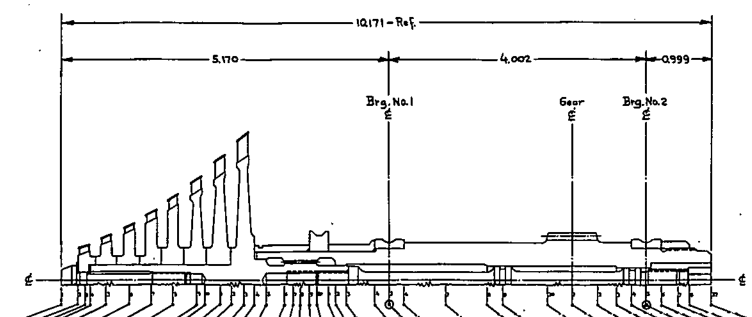
Notes:

1 - The data obtained from an actual rotor assembly were used in preparing this rotor model;

2 - It was found, that the measured total weight of this rotor assembly is 4.436 lbs.;

3 - The tabulated data of "Concentrated W" of turbine wheels represent the actual weights as measured;

4 - This rotor model is tuned to reflect the actual measured ringing frequency of 1273 CPS according to room temp. condition and with 75 in.lbs. applied tightening torque at both ends of the rotor assembly. This tuning represents the actual stiffening effect of the stacked-up components with axial compression.



Material Properties for Rotor Testing with 530°F Steam Inlet Condition:

1	2	3	4	5	6 through 11	Material No. (Ref. to Computer Input)
500	480	460	440	420	Same as below	Temperature of the Shaft - °F
Inconel 718					Same as below	Material of the Shaft
27.1	27.2	27.3	27.4	27.5	Same as below	$E - (10)^6$ psi.
0.296					Same as below	ρ - lbs./in.^{3}
7.97	7.99	8.01	8.03	8.05	Same as below	$G \times \alpha - (10)^6$ psi.

Station	1	2	3	4	5	6	7	8	9	10	11	12	13
Concentrated W - lbs.	—	0.0072	0.0438	—	0.0646	0.1067	0.1765	0.2505	0.3520	—	0.5544	—	0.6499
Concentrated I_p - lbs.in.^{2}	—	0.0001	0.0058	—	0.0144	0.0364	0.0802	0.1807	0.3674	—	0.8172	—	1.3210
Concentrated I_T - lbs.in.^{2}	—	0.0002	0.0031	—	0.0075	0.0186	0.0419	0.0914	0.1850	—	0.4108	—	0.6627
Distance between Stations - in.	0.254	0.117	0.074	0.260	0.352	0.359	0.340	0.358	0.100	0.259	0.157	0.210	0.174
O.D. for Stiffness - in.	0.400	0.506	0.630	0.713	0.713	0.713	0.925	0.928	0.925	0.925	0.925	0.931	1.038
O.D. for Weight - in.	0.400	0.296	0.456	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.863	0.975
I.D. for both Stiffness and Weight - in.	0.180	0.296	0.456	0.260	0.260	0.260	0.227	0.223	0.219	—	—	—	—
Material No. (Ref. to Computer Input)	1	1	1	2	2	3	3	4	4	5	5	6	6
Temperature of the Shaft - °F	900			830		680		550		440		400	
Material of the Shaft	Inconel 718												
$E - (10)^6$ psi.	25.3			25.6		26.3		26.9		27.4		27.6	
ρ - lbs./in.^{3}	0.296												
$G \times \alpha - (10)^6$ psi.	7.46			7.56		7.76		7.91		8.03		8.07	

Station	14	15	16	17	18	19	20	21	22	23	24	25	26
Concentrated W - lbs.	—	—	—	—	—	—	—	—	—	0.0643	—	—	—
Concentrated I_p - lbs.in.^{2}	—	—	—	—	—	—	—	—	—	0.0015	—	—	—
Concentrated I_T - lbs.in.^{2}	—	—	—	—	—	—	—	—	—	0.0189	—	—	—
Distance between Stations - in.	0.195	0.295	0.140	0.125	0.145	0.120	0.180	0.115	0.170	0.435	0.236	0.236	0.655
O.D. for Stiffness - in.	0.891	0.694	0.840	0.920	0.999	1.157	1.157	0.999	0.999	0.999	1.102	1.102	1.160
O.D. for Weight - in.	1.099	0.940	1.099	1.099	1.099	1.415	1.415	1.099	1.099	1.099	1.220	1.220	1.160
I.D. for both Stiffness and Weight - in.	—	0.276	0.285	0.285	0.434	0.583	0.710	0.660	0.461	0.500	0.500	0.500	0.500
Material No. (Ref. to Computer Input)	7	7	7	8	9	9	9	9	10	10	11	11	11
Temperature of the Shaft - °F	360			290					230		200		
Material of the Shaft	(Inconel 718)				Nitralloy 135 Mod.								
$E - (10)^6$ psi.	27.7			28.0	28.9				29.2		29.3		
ρ - lbs./in.^{3}	(0.296)				0.283								
$G \times \alpha - (10)^6$ psi.	8.12			8.17	8.33				8.42		8.45		

Station	27	28	29	30	31	32	33	34	35	36	37	38	39
Concentrated W - lbs.	—	—	0.0518	—	—	—	—	0.0385	—	—	0.0318	—	—
Concentrated I_p - lbs.in.^{2}	—	—	0.0008	—	—	—	—	0.0005	—	—	0.0018	—	—
Concentrated I_T - lbs.in.^{2}	—	—	0.0182	—	—	—	—	0.0085	—	—	0.0032	—	—
Distance between Stations - in.	0.655	0.240	0.690	0.375	0.375	0.300	0.240	0.236	0.236	0.265	0.180	0.318	—
O.D. for Stiffness - in.	1.160	1.160	1.160	1.375	1.375	1.160	1.160	0.985	0.985	0.954	0.937	0.920	—
O.D. for Weight - in.	1.160	1.160	1.160	1.375	1.375	1.160	1.160	1.220	1.220	1.200	1.200	0.920	—
I.D. for both Stiffness and Weight - in.	0.500	0.438	0.438	0.438	0.438	0.438	0.376	0.376	0.559	0.559	0.559	0.559	—
Material No. (Ref. to Computer Input)	11	11	11	11	11	11	11	11	11	11	11	11	11
Temperature of the Shaft - °F	(200)												
Material of the Shaft	(Nitralloy 135 Mod.)												
$E - (10)^6$ psi.	(29.3)												
ρ - lbs./in.^{3}	(0.283)												
$G \times \alpha - (10)^6$ psi.	(8.45)												

Figure 1

Using the mathematical rotor model, stiffness diameters at the turbine end and for the spacer section were then established so that the natural frequency of the model corresponded to the natural frequency of the actual rotor as tested. Partial and full rotor models were used in this analysis, duplicating the configurations tested.

2. Rotor Support Stiffness

The support stiffness affects the dynamic behavior of the rotor system. The support stiffness at each bearing location is composed of the stiffness of the bearing supporting the shaft and the stiffness of the pedestal, or mounting of the bearing. The subject rotor is rigidly mounted at the gear end bearing and flexibly mounted on a damper at the turbine end bearing as shown in Figure 2.

The stiffness of the bearing and damper have been determined as discussed below:

a. Bearing Stiffness - The bearings are Barden HJB ball bearings and operate at a nominal preload of 125 lbs up to the design speed of 60,000 rpm. The bearing stiffness depends on the preload and the speed.

   The bearing stiffness at the design speed vs. preload is shown in Figure 3. It may be seen that the stiffness is about 455,000 lb/in. for the nominal preload of 125 lbs.

   The bearing stiffness at the nominal preload vs. speed is shown in Figure 4. It may be seen that decreasing the speed from 60,000 rpm to 20,000 rpm increases the stiffness from 460,000 to 936,000 lb/in.

b. Damper Stiffness - The damper, shown in Figure 2, contains a flexible squirrel cage which is attached to the bearing housing and functions, presumably, as a guided cantilever beam. There is a nominal 3 mil radial clearance between the damper journal and bearing housing, and two Viton-70 O-rings are installed as shown.

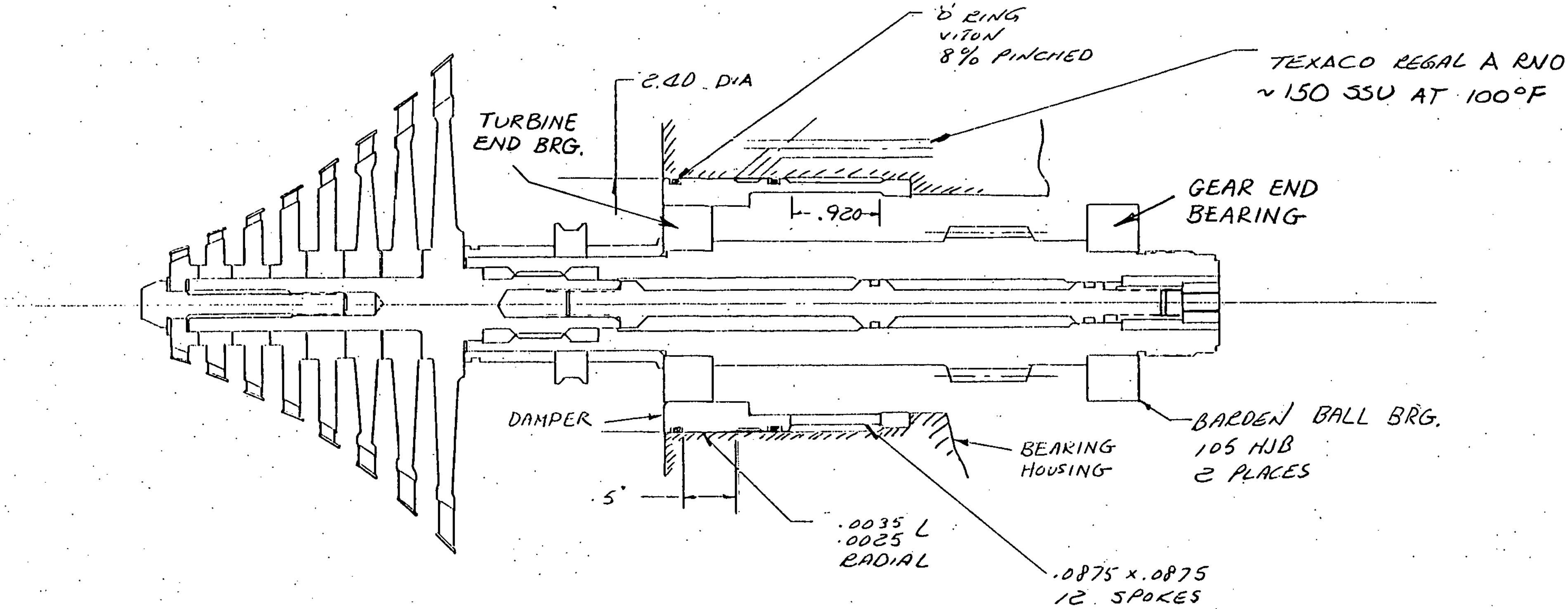


Figure 2. Turbine-End Bearing Damper

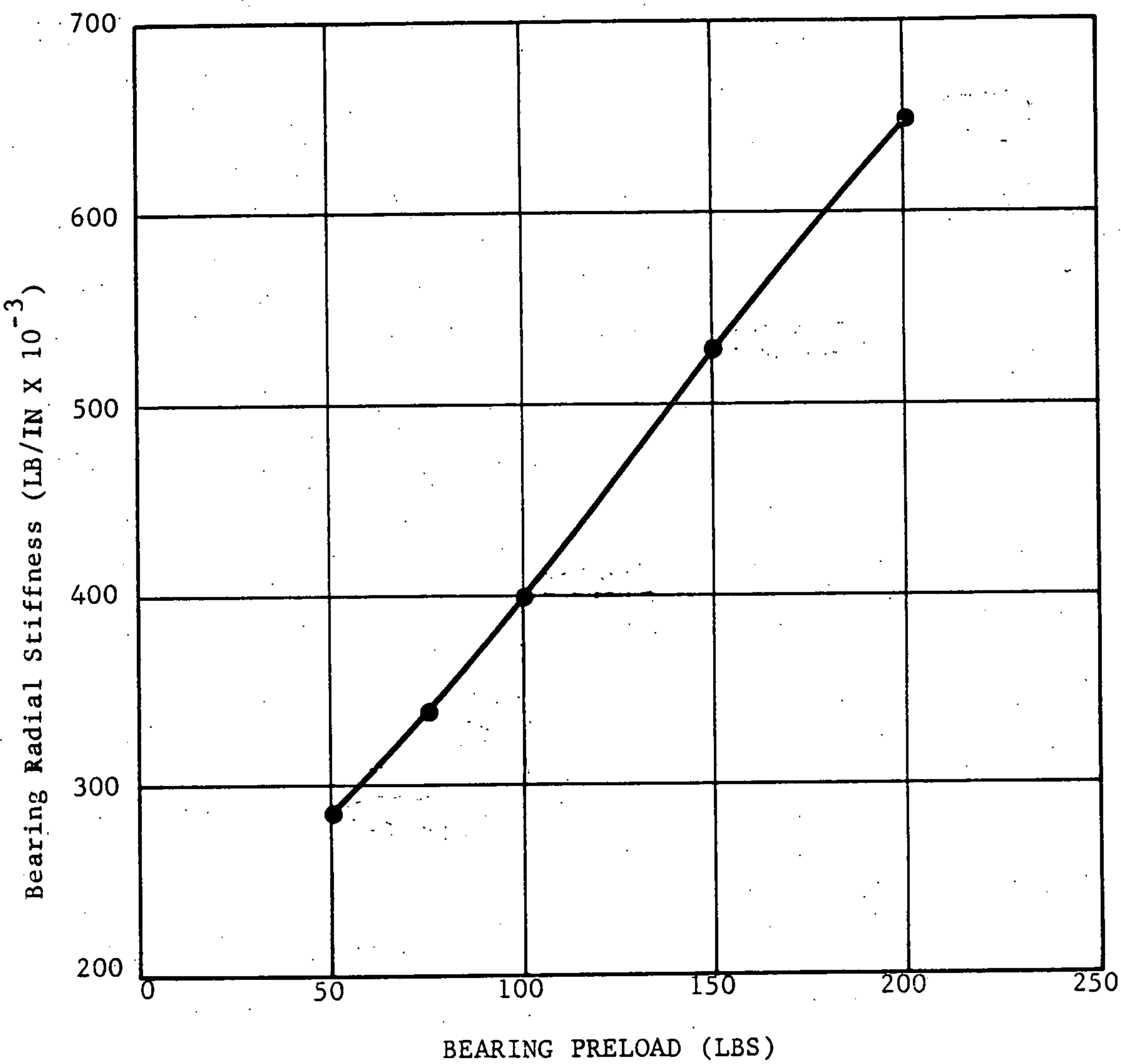


Figure 3. Barden Bearing 105HJB
Radial Stiffness At
60,000 RPM

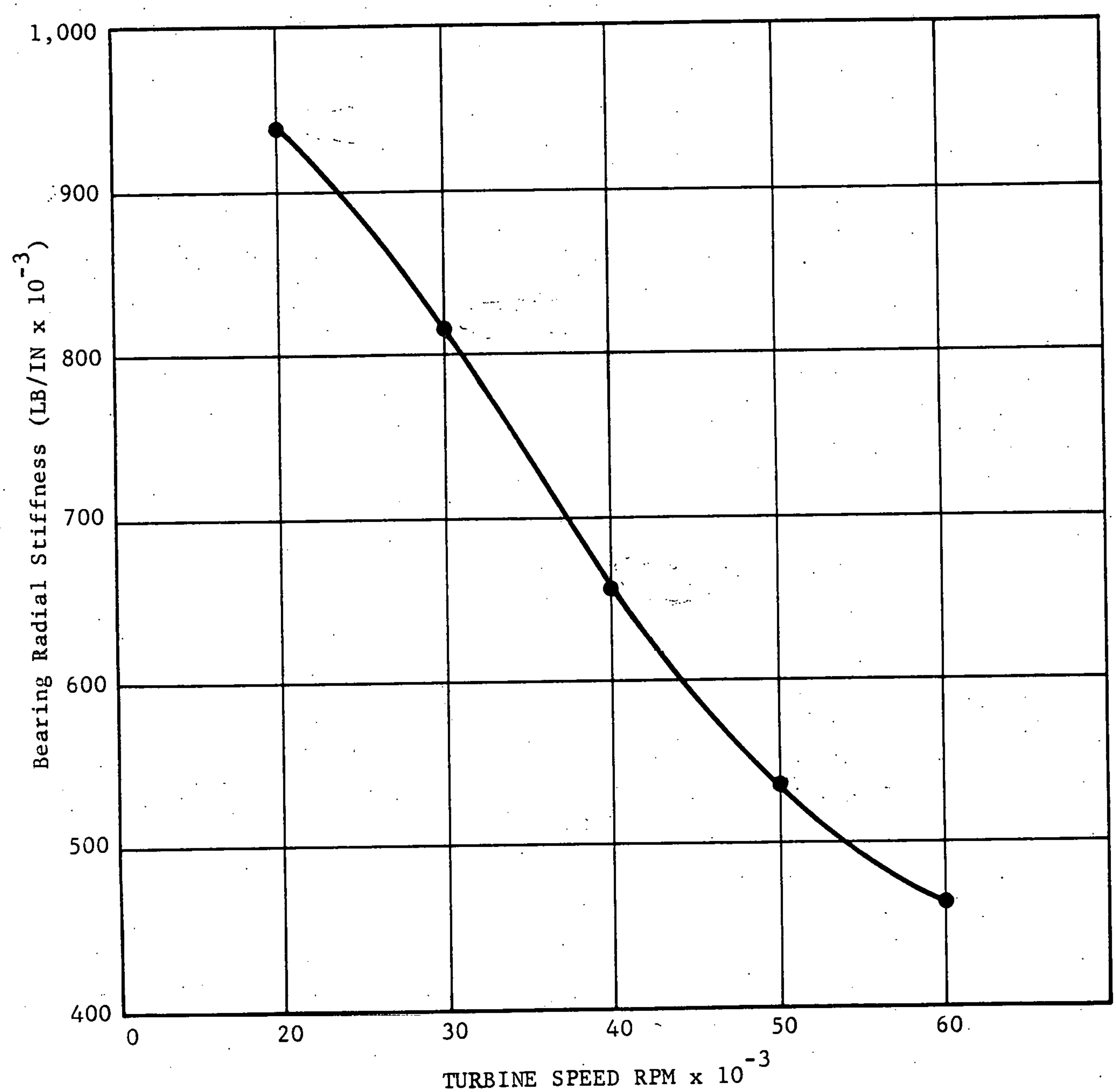


Figure 4. Barden Bearing 105HJB
Radial Stiffness At
125 LB Preload

The oil film between the journal and housing provides the damping effect. The damper stiffness consists of the cage and O-ring stiffnesses, which are additive. The oil film contributes very little to the damper stiffness and can be ignored.

The damper cage stiffness was calculated to be about 25,000 lbs/in. The O-rings have a significant radial stiffness dynamically. MTI test data on similar O-rings indicate that the dynamic stiffness of the two rings will be on the order of 20,000 lbs/in. at operating speed. The total damper stiffness will then be on the order of 45,000 lbs/in.

It should be noted here that the static stiffness of the O-rings could be as low as 5,000 lbs/in. As noted in the summary of results section, there are indications that the damper cage is moving inside the bearing housing. The resulting decreased stiffness, now more dependent on the O-rings, could result in the damper bottoming out and becoming ineffective under steady state gear loads.

B. Rotor Dynamics Analysis

The mathematical rotor model and support system characteristics developed in the preceding sections were utilized to evaluate rotor system dynamics.

1. Rotor Critical Speed

Undamped critical speed calculations were performed for a range of support stiffness values for both the gear end and turbine end (damper mounted) bearings. The gear end bearing support stiffness is a function only of the bearing stiffness and was varied to cover the 450,000 lb/in. to 900,000 lb/in. range determined in Section IV.A.2.a. The support stiffness at the turbine end bearing is composed of the bearing and damper stiffnesses. The bearing and damper are in series, and the damper stiffness is dominant, since it is an order of magnitude smaller. With a design damper stiffness of 45,000 lb/in. and a bearing stiffness of 450,000 lb/in., the resulting support stiffness at the turbine end bearing will be about 40,000 lb/in. A range of 10,000 to 100,000 lb/in.

was evaluated to adequately encompass the probable stiffness range. The critical speed map thus generated is presented in Figure 5. The following should be noted:

- Safe operation will be achieved at design speed of 60,000 rpm. However, acceleration through the first critical speed is required to reach design speed. The second critical speed is well above design speed.
- Gear end bearing stiffness has essentially no influence on critical speed.
- Bearing preload has little influence on critical speed, since turbine end support stiffness is dominated by the damper stiffness.
- For a turbine end bearing support stiffness in the range of 10,000 to 100,000 lb/in., the first critical speed would be between 6,000 and 17,000 rpm.

Aerojet turbine testing experience indicates that the first critical speed was higher than would be anticipated for the calculated turbine end bearing support stiffness. This further indicates the possibility of the damper bottoming out, since the critical speed with damper flexibility eliminated would be close to 30,000 rpm.

The first critical speed mode shape, a near rigid conical mode, is shown in Figure 6 for a range of turbine end bearing support stiffness. The mode shapes indicate that the turbine end bearing damper would be more effective at the lower value of damper stiffness.

2. <u>System Stability Analysis</u>

A stability study of the rotor-bearing-damper system was made in order to establish the range of damping which is required in the fluid film damper for stabilizing the system or avoiding a subsynchronous whirl problem while operating at the design speed of 60,000 rpm.

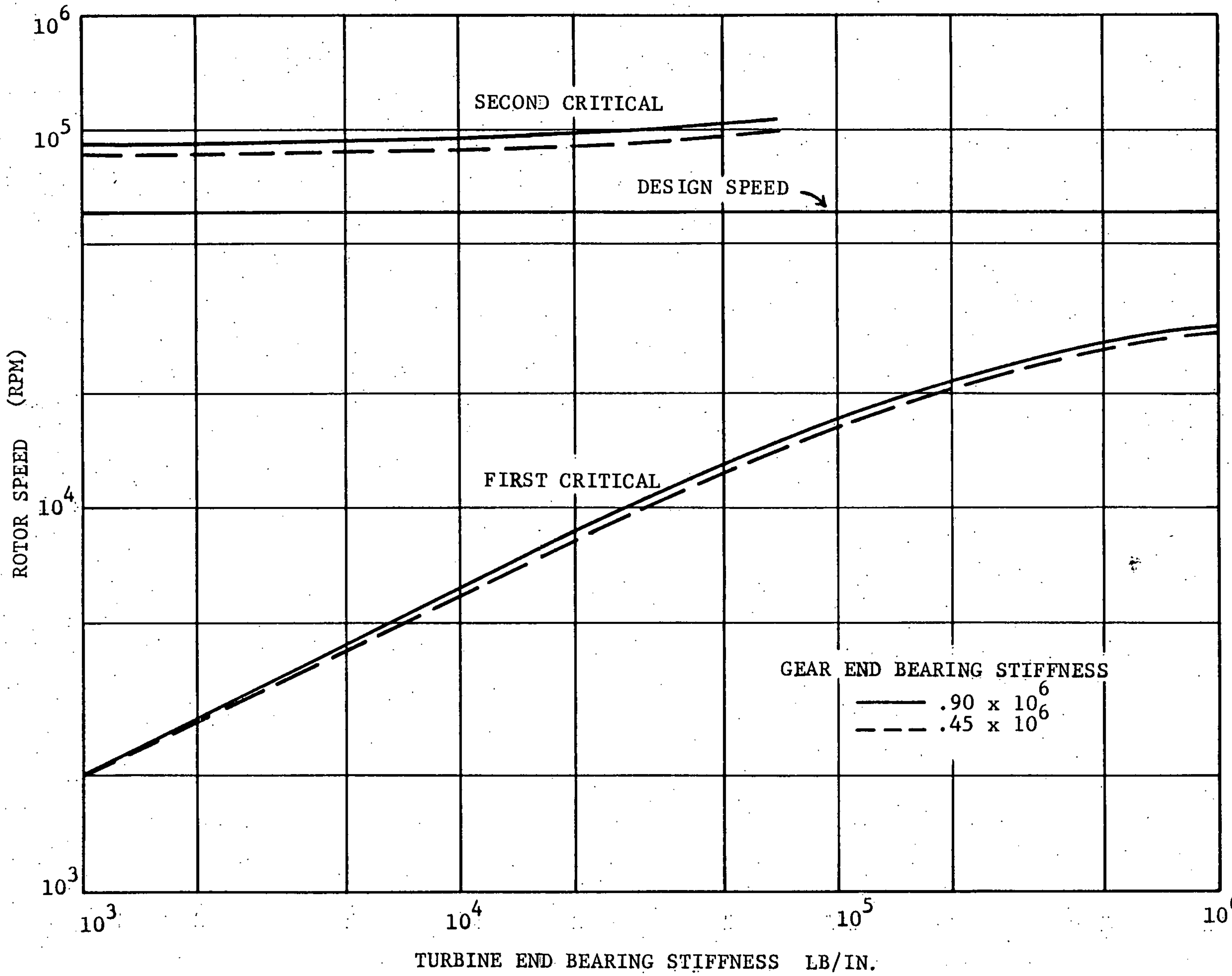


Fig. 5. ERDA Steam Turbine Critical Speed Map

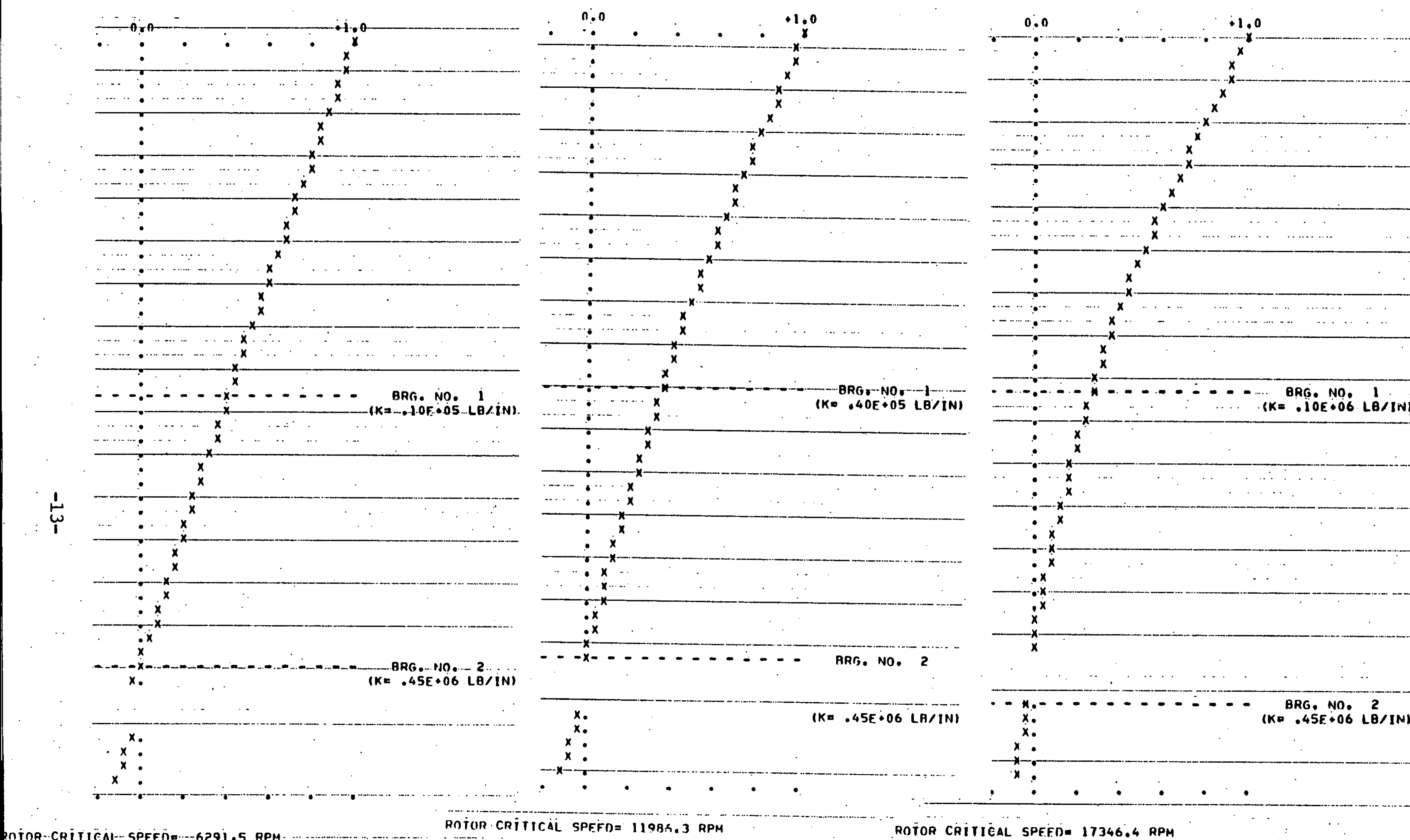


Figure 6. Undamped 1st Critical Mode Shape
(Varying Support Stiffness at Turbine End Bearing)

The results of the study are presented in Figure 7. In Figure 7, the vertical axis is the log decrement which is an index of stability, and the horizontal axis is the damping coefficient B. For the present rotor system with a large overhang, the log decrement should be more than 0.5 for acceptable stability.

Figure 7 indicates that the optimal, or most stable, damping is about 20 to 70 lb-sec/in. for damper stiffness of 100,000 lbs/in., and it may be seen that less damping is required for decreasing damper stiffness. From the geometry of the damper and the fluid properties, a damping of about 10 lb-sec/in. was calculated for the current design. The exact value depends somewhat on the oil temperature, and the O-rings may contribute an additional 1 or 2 lb-sec/in. If this theoretical uncavitated damping is achieved and the damper is functioning as designed, a log decrement of about .8 will result which indicates that the system would be adequately damped.

The first forward natural mode shape for the damper stiffnesses of 10,000, 30,000, and 100,000 lbs/in. and a damping of 10 lb-sec/in. is shown in Figure 8.

3. Unbalance Response

A summary of unbalance due to measured clearance, thermal and centrifugal growth at the wheel hubs is shown in Table 1. In the worst situation, the estimated unbalance of the rotor could be .017 oz-in., which is ten (10) times the assembled unbalance estimated by Aerojet. This value has been used to calculate steady state unbalance response in the speed range of 4,000 to 60,000 rpm in increments of 2,000 rpm.

Bearing and damper stiffness values selected in previous sections were again used in this analysis. A damping value of 10 lb-sec/in. was used, and one calculation was made with a damping of 70 lb-sec/in. and a damper stiffness of 100,000 lbs/in. to verify that acceptable dynamic performance can be obtained

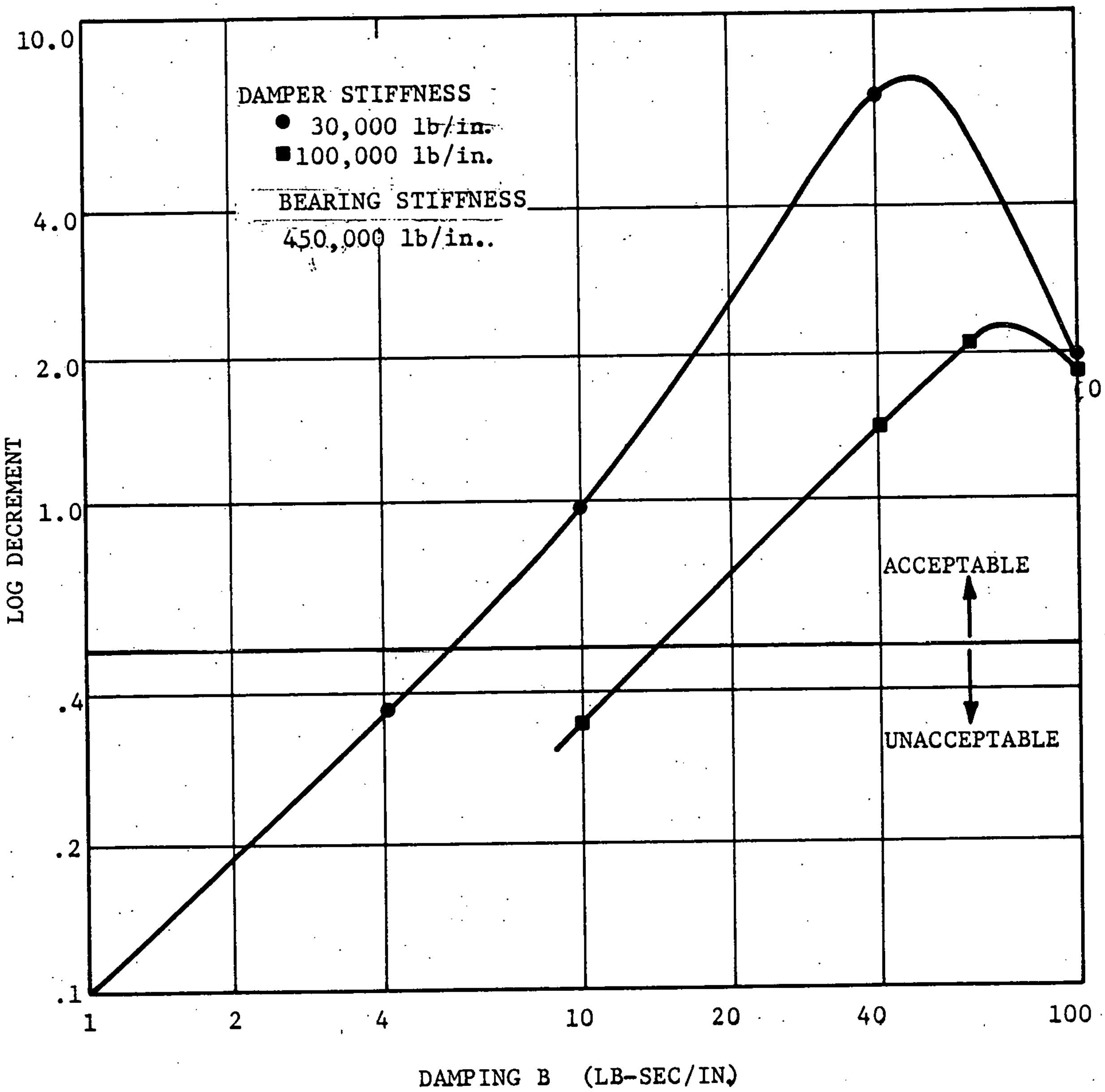


Figure 7. System Stability at 60,000 RPM
(First Forward Mode)

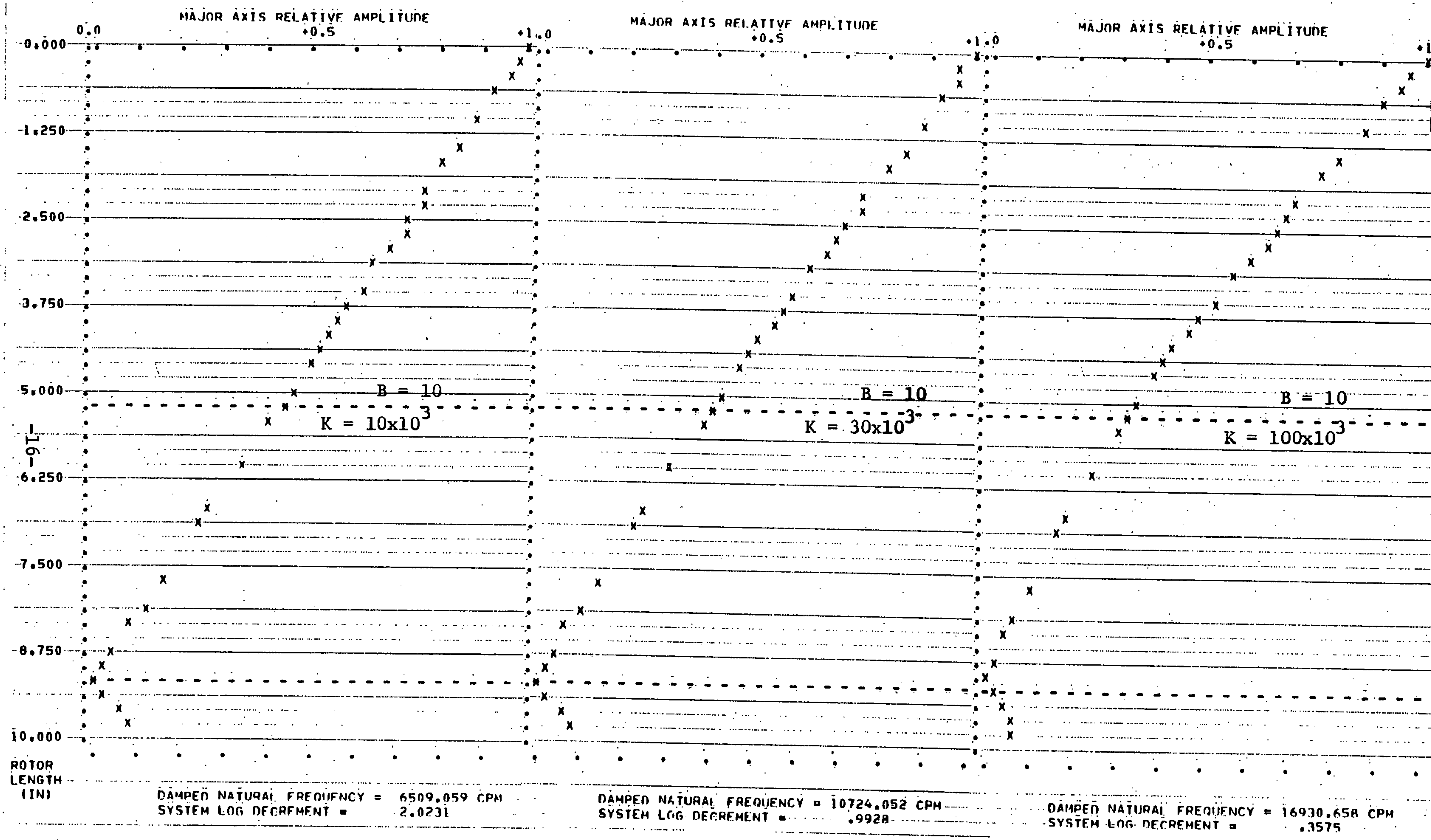


Figure 8: Damped 1st Forward Mode Shape
(Varying Support Stiffness at Turbine End Bearing)

TABLE 1A

ERDA Steam Turbine Rotor Dynamics Analysis

Detailed Calculation of Unbalances

Due to Loose Turbine Wheels at Cold Assembly Condition

a	b	c	d	e	f	g	h	i	j	k	l	m=gxl	n=hxl	o=kxl	p
Stage No.	Model	Sta. No.	Total W of Turbine Wheel lbs.	Machined I.Dia. of Wheel in.	Machined O.D.of Shaft in.	Maximum Machined Radial Clearance in.	Minimum Machined Radial Clearance in.	Inspected I.D.of the Wheel in.	Inspected O.D.of the Shaft in.	Actual Measured Radial Clearance in.	Total W of Turbine Wheel oz.	Max. Cold Design Unbalance oz.in.	Min. Cold Design Unbalance oz.in.	Actual Cold Unbalance oz.in.	Material of the Wheel
1	C	3	0.0438	0.5001 / 0.5002		0.00015	0.00005	0.5002	0.4998	0.0002	0.7008	0.000105	0.000035	0.000140	Inconel 625
2	D	5	0.0646	0.5001 / 0.5002		0.00015	0.00005	0.5003		0.00025	1.0336	0.000155	0.000052	0.000258	Inconel 625
3	E	6	0.1067	0.5001 / 0.5002		0.00015	0.00005	0.5003		0.0002	1.7072	0.000256	0.000085	0.000341	Inconel 625
4	F	7	0.1641	0.5001 / 0.5002	0.5000 / 0.4999	0.00015	0.00005	0.5003	0.4999	0.0002	2.6256	0.000394	0.000131	0.000525	Inconel 625
5	G	8	0.2505	0.5001 / 0.5002		0.00015	0.00005	0.5005		0.0003	4.0080	0.000601	0.000200	0.001202	Inconel 718
6	H	9	0.3520	0.5001 / 0.5002		0.00015	0.00005	0.5006	0.4998	0.0004	5.6320	0.000845	0.000282	0.002253	Inconel 718
7	I	11	0.5544	0.5001 / 0.5002		0.00015	0.00005	0.5010		0.0006	8.8704	0.001331	0.000444	0.005322	Inconel 718
TOTAL			1.5361								24.5776	0.003687	0.001229	0.010041	

* Note: Shaft Material Inconel 718

TABLE 1B

ERDA Steam Turbine Rotor Dynamics Analysis
Detailed Calculation of Unbalances of Loose Turbine Wheels
Due to Steady State Operation of 1000°F Steam Inlet and 60,000 RPM Speed

a	b	c	q	r	s	t	u	v	w	x	y	z	Case A	Case B	Case C	
Stage No.	Model	Sta. No.	Avg. Op. Temp. °F	ΔT (q-70) °F	Δα Therm. Coeff. Difference in./in./°F$(10)^{-6}$	Radial Clearance at change Temp. (r)(s)(0.250) in.	E of Shaft at Temp. $(10)^6$ psi	Radial Clearance Change Due to Shaft at Speed in.	E of Wheel at Temp. $(10)^6$ psi	Radial Clearance Change Due to Wheel at Speed in.	Total Radial Clearance Change at Temp. & Speed in.	Total Unbalance Due to "y" oz.in.	Total Max. Unbalance as Designed oz.in.	Total Min. Unbalance as Designed oz.in.	Total Actual Unbalance oz.in.	Poison's Ratio ν
1	C	3	900	830	0.455	-0.000094	25.3	-0.000009	25.7	0.000030	-0.000073	-0.000051	0.000054	-0.000016	0.000089	0.305
2	D	5	840	770	0.480	-0.000092	25.6	-0.000009	26.0	0.000070	-0.000031	-0.000032	0.000123	0.000020	0.000226	0.303
3	E	6	760	690	0.507	-0.000087	25.9	-0.000009	26.4	0.000110	0.000014	0.000024	0.000280	0.000109	0.000365	0.301
4	F	7	680	610	0.530	-0.000081	26.3	-0.000009	26.8	0.000150	0.000060	0.000158	0.000552	0.000289	0.000683	0.300
5	G	8	610	540	-----	---------	26.6	-0.000009	26.6	0.000250	0.000241	0.000966	0.001567	0.001166	0.002168	0.272
6	H	9	520	450	-----	---------	27.0	-0.000009	27.0	0.000330	0.000321	0.001808	0.002653	0.002090	0.004061	0.275
7	I	11	440	370	-----	---------	27.4	-0.000009	27.4	0.000470	0.000461	0.004089	0.005420	0.004533	0.009411	0.278
											TOTALS →	0.006962	0.010649	0.008191	0.017003	

even at high damper stiffness if optimal high damping levels are achieved. The result is shown in Tables 2 through 5, and a summary of vibration amplitudes in the range of the first damped critical speed is shown in the following table:

TABLE	DAMPER		MAX. RADIAL RESPONSE AT				COMMENTS	
No.	Stiffness lbs/in.	Damping lb-sec/in.	Approx. Speed RPM	1st Wheel mil	Turbine End Brg. mil	Damper mil	Static Load Capacity	Dynamic Performance
2	10,000	10	6,000	.79	.33	.45	inadequate (damper too soft)	good
3	30,000	10	10,000	1.69	.63	.84	damper close to marginal but acceptable	marginal but acceptable
4	100,000	10	16,000	5.45	1.58	1.81	good	unacceptable
5	100,000	70	22,000-24,000	1.37	.33	.25	good	acceptable

The following observations should be made from this analysis:

- At high levels of damper stiffness (100,000 lb/in.) and design levels of damping (10 lb-sec/in.), vibration amplitudes become very large. The first turbine wheel dynamic deflections are on the order of the present labyrinth seal design clearance and deflections at the damper are 60 percent of nominal clearance.
- With damper stiffness and damping at design values, rotor performance appears to be acceptable.
- A very soft damper would exhibit very good dynamic performance, but would provide inadequate static load capability as it would bottom out under the gear load.

In addition to the dynamic deflections tabulated above, additional deflections are caused by steady state gear loads.

A damper with a static stiffness of 30,000 lbs/in., (or close to the design value) would deflect about 1 mil under a representative gear load of 30 lbs. The resulting deflection at the first turbine wheel would be about 2 mils. These static deflections, when added to the dynamic deflections calculated above, identify the total motion experienced at both locations. The resulting total deflection indicates that the damper design is somewhat marginal, and that modifications should be made to insure that the damper functions as designed and to minimize the potential rotor unbalance response.

C. Design Modifications

1. Damper Modifications

The present damper design has several weaknesses which may have caused the apparent unsatisfactory performance of the existing rotor system, and which should be modified to insure acceptable operation. The desired modifications are discussed below:

- The means by which the damper cage is attached to the housing appears to be inadequate. There is evidence that the cage is moving in the housing and, therefore, not providing the conventional "guided cantilever" support to the squeeze film journal. The cage and housing both have a similar burnished appearance, as if the two have been working against each other. If this is the case, there is very little to oppose the gear load. With a static stiffness of 5,000 lbs/in. for the O-rings, even a 15 lb gear load may bottom out the damper. A more positive method for holding the cage in the housing should be designed.

- The damper squeeze film, located between the two O-rings, is marginally short. Since damping at this L/D is roughly proportional to L^3, a 25 percent increase in length would have a substantial benefit in damping and permit a reduction of the supply pressure needed to eliminate cavitation in the film. Part of the length is consumed by a wide oil supply groove which could be made shorter and deeper, thus providing increased film length.

TABLE 2

Damping = 10 lb-sec/in. Stiffness = 10×10^3 lb/in.

FORCE TRANSMITTED TO FOUNDATION BY PEDESTAL, PEDESTAL MOTION AND MAXIMUM RELATIVE ECCENTRICITY

	STATION 25			STATION 35		
	FORCE	MOTION		FORCE	MOTION	
SPEED RPM	MAJOR AXIS	MAJOR AXIS	MAX REL ECC.	MAJOR AXIS	MAJOR AXIS	MAX REL ECC.
4000.	.131E+01	.121E-03	.286E-05	.523E+00	.523E-08	.116E-05
6000.	.377E+01	.451E-03	.806E-05	.141E+01	.154E-07	.312E-05
8000.	.418E+01	.326E-03	.880E-05	.147E+01	.207E-07	.327E-05
10000.	.400E+01	.276E-03	.831E-05	.136E+01	.193E-07	.303E-05
12000.	.405E+01	.252E-03	.834E-05	.138E+01	.194E-07	.307E-05
14000.	.426E+01	.240E-03	.872E-05	.149E+01	.206E-07	.332E-05
16000.	.456E+01	.234E-03	.931E-05	.168E+01	.224E-07	.374E-05
18000.	.492E+01	.231E-03	.100E-04	.194E+01	.246E-07	.431E-05
20000.	.533E+01	.229E-03	.109E-04	.226E+01	.273E-07	.502E-05
22000.	.578E+01	.230E-03	.119E-04	.264E+01	.303E-07	.587E-05
24000.	.627E+01	.232E-03	.130E-04	.310E+01	.338E-07	.687E-05
26000.	.679E+01	.234E-03	.142E-04	.362E+01	.378E-07	.802E-05
28000.	.736E+01	.238E-03	.155E-04	.421E+01	.422E-07	.933E-05
30000.	.798E+01	.242E-03	.170E-04	.489E+01	.489E-07	.108E-04
32000.	.864E+01	.247E-03	.186E-04	.566E+01	.566E-07	.125E-04
34000.	.936E+01	.253E-03	.203E-04	.653E+01	.653E-07	.145E-04
36000.	.101E+02	.260E-03	.223E-04	.752E+01	.752E-07	.166E-04
38000.	.110E+02	.267E-03	.245E-04	.863E+01	.863E-07	.191E-04
40000.	.119E+02	.276E-03	.269E-04	.989E+01	.989E-07	.219E-04
42000.	.129E+02	.286E-03	.295E-04	.113E+02	.113E-06	.250E-04
44000.	.140E+02	.297E-03	.325E-04	.130E+02	.130E-06	.286E-04
46000.	.152E+02	.309E-03	.358E-04	.148E+02	.148E-06	.327E-04
48000.	.165E+02	.322E-03	.395E-04	.169E+02	.169E-06	.374E-04
50000.	.180E+02	.338E-03	.437E-04	.194E+02	.194E-06	.428E-04
52000.	.197E+02	.355E-03	.484E-04	.222E+02	.222E-06	.489E-04
54000.	.215E+02	.374E-03	.538E-04	.254E+02	.254E-06	.561E-04
56000.	.236E+02	.396E-03	.599E-04	.292E+02	.292E-06	.643E-04
58000.	.259E+02	.421E-03	.669E-04	.336E+02	.343E-06	.739E-04
60000.	.285E+02	.449E-03	.749E-04	.387E+02	.412E-06	.851E-04

* ERDA UNBALANCE RESPONSE ANALYSIS * JULY 19, 1977 * M. CHEN * CASE 1

RESPONSE SUMMARY TABLE
MAJOR SEMI-AMPLITUDE (IN.) VS.
SPEED AND STATION NO.

STA. NO.	UNBALANCE (OZ-IN.)
3	.8900E-04
5	.2260E-03
6	.3650E-03
7	.6830E-03
8	.2168E-02
9	.4061E-02
11	.9411E-02

	STATION								
RPM	1	7	13	18	25	28	33	35	37
4000.	.301E-03	.252E-03	.202E-03	.170E-03	.124E-03	.748E-04	.136E-04	.117E-05	.165E-04
6000.	.790E-03	.660E-03	.530E-03	.447E-03	.326E-03	.197E-03	.361E-04	.314E-05	.431E-04
8000.	.787E-03	.659E-03	.530E-03	.447E-03	.327E-03	.198E-03	.367E-04	.329E-05	.430E-04
10000.	.673E-03	.563E-03	.454E-03	.384E-03	.281E-03	.171E-03	.321E-04	.305E-05	.366E-04
12000.	.608E-03	.510E-03	.413E-03	.350E-03	.257E-03	.157E-03	.299E-04	.308E-05	.330E-04
14000.	.570E-03	.479E-03	.389E-03	.331E-03	.244E-03	.150E-03	.291E-04	.334E-05	.309E-04
16000.	.546E-03	.460E-03	.375E-03	.320E-03	.237E-03	.146E-03	.290E-04	.376E-05	.294E-04
18000.	.528E-03	.446E-03	.366E-03	.313E-03	.233E-03	.145E-03	.294E-04	.433E-05	.284E-04
20000.	.515E-03	.436E-03	.359E-03	.310E-03	.232E-03	.144E-03	.302E-04	.504E-05	.275E-04
22000.	.504E-03	.428E-03	.355E-03	.307E-03	.232E-03	.145E-03	.312E-04	.590E-05	.267E-04
24000.	.494E-03	.421E-03	.352E-03	.307E-03	.233E-03	.147E-03	.325E-04	.690E-05	.260E-04
26000.	.485E-03	.415E-03	.349E-03	.307E-03	.235E-03	.149E-03	.341E-04	.805E-05	.253E-04
28000.	.477E-03	.410E-03	.348E-03	.307E-03	.238E-03	.152E-03	.359E-04	.938E-05	.246E-04
30000.	.469E-03	.405E-03	.347E-03	.309E-03	.241E-03	.156E-03	.380E-04	.109E-04	.239E-04
32000.	.461E-03	.400E-03	.346E-03	.311E-03	.245E-03	.160E-03	.403E-04	.126E-04	.232E-04
34000.	.453E-03	.395E-03	.346E-03	.314E-03	.250E-03	.165E-03	.430E-04	.145E-04	.224E-04
36000.	.445E-03	.390E-03	.346E-03	.317E-03	.256E-03	.171E-03	.460E-04	.167E-04	.216E-04
38000.	.436E-03	.385E-03	.347E-03	.321E-03	.262E-03	.177E-03	.494E-04	.192E-04	.208E-04
40000.	.428E-03	.381E-03	.347E-03	.325E-03	.269E-03	.184E-03	.532E-04	.220E-04	.201E-04
42000.	.421E-03	.376E-03	.348E-03	.330E-03	.278E-03	.192E-03	.575E-04	.252E-04	.194E-04
44000.	.414E-03	.371E-03	.349E-03	.336E-03	.287E-03	.201E-03	.624E-04	.288E-04	.189E-04
46000.	.408E-03	.366E-03	.350E-03	.342E-03	.297E-03	.211E-03	.679E-04	.329E-04	.186E-04
48000.	.404E-03	.362E-03	.352E-03	.349E-03	.308E-03	.222E-03	.742E-04	.376E-04	.189E-04
50000.	.403E-03	.359E-03	.354E-03	.357E-03	.321E-03	.235E-03	.814E-04	.430E-04	.199E-04
52000.	.407E-03	.356E-03	.356E-03	.365E-03	.335E-03	.249E-03	.895E-04	.492E-04	.218E-04
54000.	.416E-03	.355E-03	.359E-03	.375E-03	.351E-03	.265E-03	.989E-04	.563E-04	.248E-04
56000.	.435E-03	.357E-03	.362E-03	.386E-03	.370E-03	.283E-03	.110E-03	.646E-04	.291E-04
58000.	.465E-03	.363E-03	.365E-03	.397E-03	.390E-03	.304E-03	.122E-03	.743E-04	.348E-04
60000.	.509E-03	.374E-03	.369E-03	.410E-03	.412E-03	.328E-03	.136E-03	.855E-04	.421E-04

TABLE 3

Damping = 10 lb-sec/in. Stiffness = 30×10^3 lb/in.

FORCE TRANSMITTED TO FOUNDATION BY PEDESTAL, PEDESTAL MOTION AND MAXIMUM RELATIVE ECCENTRICITY

	STATION 25			STATION 35		
	FORCE	MOTION		FORCE	MOTION	
SPEED RPM	MAJOR AXIS	MAJOR AXIS	MAX REL ECC.	MAJOR AXIS	MAJOR AXIS	MAX REL ECC.
4000.	.100E+01	.331E-04	.221E-05	.416E+00	.416E-08	.925E-06
6000.	.290E+01	.947E-04	.634E-05	.117E+01	.117E-07	.259E-05
8000.	.798E+01	.256E-03	.172E-04	.307E+01	.307E-07	.682E-05
10000.	.188E+02	.838E-03	.401E-04	.684E+01	.888E-07	.152E-04
12000.	.153E+02	.472E-03	.321E-04	.522E+01	.677E-07	.116E-04
14000.	.117E+02	.350E-03	.240E-04	.370E+01	.437E-07	.823E-05
16000.	.101E+02	.295E-03	.205E-04	.300E+01	.357E-07	.666E-05
18000.	.947E+01	.267E-03	.188E-04	.263E+01	.331E-07	.584E-05
20000.	.919E+01	.251E-03	.179E-04	.245E+01	.327E-07	.543E-05
22000.	.916E+01	.242E-03	.176E-04	.241E+01	.336E-07	.535E-05
24000.	.927E+01	.237E-03	.175E-04	.250E+01	.353E-07	.554E-05
26000.	.949E+01	.234E-03	.177E-04	.271E+01	.377E-07	.601E-05
28000.	.980E+01	.234E-03	.181E-04	.304E+01	.408E-07	.674E-05
30000.	.102E+02	.234E-03	.187E-04	.348E+01	.444E-07	.772E-05
32000.	.106E+02	.237E-03	.194E-04	.404E+01	.487E-07	.894E-05
34000.	.112E+02	.240E-03	.203E-04	.470E+01	.537E-07	.104E-04
36000.	.117E+02	.244E-03	.214E-04	.547E+01	.596E-07	.121E-04
38000.	.124E+02	.249E-03	.226E-04	.636E+01	.664E-07	.141E-04
40000.	.131E+02	.255E-03	.241E-04	.738E+01	.743E-07	.163E-04
42000.	.140E+02	.262E-03	.258E-04	.855E+01	.855E-07	.189E-04
44000.	.149E+02	.270E-03	.277E-04	.989E+01	.989E-07	.219E-04
46000.	.159E+02	.280E-03	.299E-04	.114E+02	.114E-06	.252E-04
48000.	.170E+02	.290E-03	.325E-04	.132E+02	.132E-06	.290E-04
50000.	.182E+02	.302E-03	.354E-04	.151E+02	.151E-06	.334E-04
52000.	.196E+02	.316E-03	.387E-04	.174E+02	.174E-06	.385E-04
54000.	.212E+02	.331E-03	.425E-04	.201E+02	.201E-06	.443E-04
56000.	.230E+02	.349E-03	.468E-04	.232E+02	.232E-06	.510E-04
58000.	.250E+02	.368E-03	.518E-04	.267E+02	.267E-06	.588E-04
60000.	.272E+02	.391E-03	.575E-04	.309E+02	.312E-06	.679E-04

* ERDA UNBALANCE RESPONSE ANALYSIS * JULY 19, 1977 * M. CHEN * CASE 2

RESPONSE SUMMARY TABLE
MAJOR SEMI-AMPLITUDE (IN.) VS.
SPEED AND STATION NO.

STA. NO.	UNBALANCE (OZ-IN.)
3	.8900E-04
5	.2260E-03
6	.3650E-03
7	.6830E-03
8	.2168E-02
9	.4061E-02
11	.9411E-02

	STATION								
RPM	1	7	13	18	25	28	33	35	37
4000.	.961E-04	.786E-04	.611E-04	.501E-04	.353E-04	.207E-04	.322E-05	.929E-06	.527E-05
6000.	.274E-03	.224E-03	.174E-03	.143E-03	.101E-03	.592E-04	.932E-05	.260E-05	.150E-04
8000.	.737E-03	.604E-03	.470E-03	.387E-03	.273E-03	.160E-03	.255E-04	.685E-05	.404E-04
10000.	.169E-02	.139E-02	.108E-02	.892E-03	.630E-03	.372E-03	.599E-04	.153E-04	.924E-04
12000.	.133E-02	.109E-02	.856E-03	.707E-03	.501E-03	.296E-03	.487E-04	.116E-04	.727E-04
14000.	.976E-03	.802E-03	.630E-03	.522E-03	.371E-03	.220E-03	.371E-04	.826E-05	.531E-04
16000.	.812E-03	.668E-03	.527E-03	.438E-03	.313E-03	.187E-03	.322E-04	.669E-05	.440E-04
18000.	.722E-03	.596E-03	.472E-03	.393E-03	.282E-03	.169E-03	.301E-04	.586E-05	.390E-04
20000.	.666E-03	.551E-03	.438E-03	.367E-03	.265E-03	.160E-03	.293E-04	.546E-05	.359E-04
22000.	.628E-03	.521E-03	.417E-03	.351E-03	.255E-03	.155E-03	.293E-04	.537E-05	.336E-04
24000.	.600E-03	.499E-03	.401E-03	.340E-03	.249E-03	.152E-03	.297E-04	.557E-05	.319E-04
26000.	.578E-03	.482E-03	.391E-03	.333E-03	.245E-03	.151E-03	.306E-04	.604E-05	.306E-04
28000.	.560E-03	.469E-03	.383E-03	.328E-03	.244E-03	.152E-03	.318E-04	.677E-05	.294E-04
30000.	.545E-03	.458E-03	.377E-03	.325E-03	.244E-03	.153E-03	.334E-04	.776E-05	.283E-04
32000.	.531E-03	.448E-03	.372E-03	.324E-03	.245E-03	.155E-03	.352E-04	.898E-05	.273E-04
34000.	.518E-03	.439E-03	.369E-03	.324E-03	.248E-03	.158E-03	.373E-04	.104E-04	.263E-04
36000.	.506E-03	.432E-03	.366E-03	.324E-03	.251E-03	.162E-03	.397E-04	.122E-04	.253E-04
38000.	.495E-03	.424E-03	.364E-03	.326E-03	.255E-03	.167E-03	.425E-04	.141E-04	.243E-04
40000.	.484E-03	.417E-03	.363E-03	.328E-03	.260E-03	.172E-03	.456E-04	.164E-04	.233E-04
42000.	.473E-03	.411E-03	.362E-03	.331E-03	.266E-03	.178E-03	.492E-04	.190E-04	.223E-04
44000.	.463E-03	.404E-03	.361E-03	.335E-03	.273E-03	.185E-03	.532E-04	.219E-04	.213E-04
46000.	.453E-03	.398E-03	.361E-03	.339E-03	.281E-03	.193E-03	.578E-04	.253E-04	.204E-04
48000.	.443E-03	.391E-03	.362E-03	.344E-03	.290E-03	.203E-03	.630E-04	.292E-04	.198E-04
50000.	.435E-03	.385E-03	.363E-03	.350E-03	.301E-03	.213E-03	.688E-04	.336E-04	.194E-04
52000.	.429E-03	.380E-03	.364E-03	.357E-03	.312E-03	.225E-03	.755E-04	.386E-04	.197E-04
54000.	.425E-03	.375E-03	.365E-03	.365E-03	.325E-03	.238E-03	.832E-04	.445E-04	.208E-04
56000.	.427E-03	.371E-03	.367E-03	.374E-03	.340E-03	.253E-03	.920E-04	.512E-04	.230E-04
58000.	.434E-03	.369E-03	.369E-03	.384E-03	.357E-03	.270E-03	.102E-03	.591E-04	.265E-04
60000.	.451E-03	.370E-03	.372E-03	.395E-03	.376E-03	.290E-03	.114E-03	.682E-04	.315E-04

TABLE 4

Damping = 10 lb-sec/in. Stiffness = 100×10^3 lb/in.

FORCE TRANSMITTED TO FOUNDATION BY PEDESTAL, PEDESTAL MOTION AND MAXIMUM RELATIVE ECCENTRICITY

	STATION 25			STATION 35		
	FORCE	MOTION		FORCE	MOTION	
SPEED RPM	MAJOR AXIS	MAJOR AXIS	MAX. REL ECC.	MAJOR AXIS	MAJOR AXIS	MAX. REL ECC.
4000.	.902E+00	.901E-05	.200E-05	.382E+00	.382E-08	.848E-06
6000.	.222E+01	.222E-04	.491E-05	.930E+00	.930E-08	.207E-05
8000.	.455E+01	.453E-04	.100E-04	.188E+01	.188E-07	.417E-05
10000.	.880E+01	.875E-04	.193E-04	.356E+01	.356E-07	.791E-05
12000.	.177E+02	.176E-03	.385E-04	.699E+01	.699E-07	.155E-04
14000.	.435E+02	.430E-03	.940E-04	.167E+02	.167E-06	.371E-04
16000.	.131E+03	.181E-02	.282E-03	.488E+02	.689E-06	.108E-03
18000.	.601E+02	.590E-03	.128E-03	.214E+02	.214E-06	.475E-04
20000.	.384E+02	.376E-03	.807E-04	.131E+02	.131E-06	.290E-04
22000.	.304E+02	.296E-03	.632E-04	.983E+01	.983E-07	.218E-04
24000.	.265E+02	.257E-03	.543E-04	.807E+01	.807E-07	.179E-04
26000.	.243E+02	.234E-03	.491E-04	.692E+01	.692E-07	.153E-04
28000.	.229E+02	.220E-03	.457E-04	.607E+01	.607E-07	.135E-04
30000.	.221E+02	.211E-03	.435E-04	.540E+01	.540E-07	.120E-04
32000.	.217E+02	.205E-03	.419E-04	.485E+01	.485E-07	.107E-04
34000.	.214E+02	.202E-03	.408E-04	.438E+01	.438E-07	.969E-05
36000.	.214E+02	.201E-03	.401E-04	.399E+01	.403E-07	.884E-05
38000.	.216E+02	.200E-03	.396E-04	.372E+01	.430E-07	.823E-05
40000.	.218E+02	.201E-03	.393E-04	.358E+01	.463E-07	.792E-05
42000.	.222E+02	.203E-03	.393E-04	.362E+01	.502E-07	.801E-05
44000.	.227E+02	.206E-03	.394E-04	.388E+01	.549E-07	.858E-05
46000.	.233E+02	.210E-03	.396E-04	.438E+01	.605E-07	.967E-05
48000.	.240E+02	.215E-03	.400E-04	.510E+01	.670E-07	.113E-04
50000.	.248E+02	.220E-03	.406E-04	.604E+01	.746E-07	.133E-04
52000.	.258E+02	.226E-03	.414E-04	.719E+01	.837E-07	.159E-04
54000.	.269E+02	.234E-03	.423E-04	.857E+01	.945E-07	.189E-04
56000.	.281E+02	.242E-03	.435E-04	.102E+02	.107E-06	.224E-04
58000.	.295E+02	.252E-03	.449E-04	.121E+02	.123E-06	.266E-04
60000.	.311E+02	.263E-03	.466E-04	.143E+02	.143E-06	.314E-04

* ERDA UNBALANCE RESPONSE ANALYSIS * JULY 19, 1977 * M. CHEN * CASE 3

RESPONSE SUMMARY TABLE
MAJOR SEMI-AMPLITUDE (IN.) VS.
SPEED AND STATION NO.

STA. NO.	UNBALANCE (OZ-IN.)
3	.8900E-04
5	.2260E-03
6	.3650E-03
7	.6830E-03
8	.2168E-02
9	.4061E-02
11	.9411E-02

RPM	STATION 1	7	13	18	25	28	33	35	37
4000.	.393E-04	.308E-04	.223E-04	.172E-04	.110E-04	.587E-05	.405E-06	.852E-06	.217E-05
6000.	.964E-04	.756E-04	.548E-04	.423E-04	.271E-04	.144E-04	.103E-05	.208E-05	.533E-05
8000.	.196E-03	.154E-03	.112E-03	.862E-04	.553E-04	.295E-04	.211E-05	.419E-05	.108E-04
10000.	.378E-03	.296E-03	.215E-03	.166E-03	.107E-03	.570E-04	.420E-05	.795E-05	.208E-04
12000.	.752E-03	.590E-03	.429E-03	.332E-03	.214E-03	.115E-03	.886E-05	.156E-04	.414E-04
14000.	.183E-02	.144E-02	.105E-02	.812E-03	.523E-03	.282E-03	.230E-04	.372E-04	.100E-03
16000.	.545E-02	.428E-02	.313E-02	.244E-02	.158E-02	.852E-03	.736E-04	.109E-03	.299E-03
18000.	.245E-02	.193E-02	.141E-02	.110E-02	.716E-03	.389E-03	.358E-04	.477E-04	.134E-03
20000.	.154E-02	.121E-02	.892E-03	.698E-03	.455E-03	.249E-03	.244E-04	.292E-04	.841E-04
22000.	.119E-02	.942E-03	.695E-03	.546E-03	.358E-03	.197E-03	.206E-04	.219E-04	.651E-04
24000.	.102E-02	.803E-03	.595E-03	.469E-03	.310E-03	.172E-03	.191E-04	.180E-04	.553E-04
26000.	.908E-03	.719E-03	.535E-03	.424E-03	.281E-03	.157E-03	.187E-04	.154E-04	.492E-04
28000.	.836E-03	.662E-03	.496E-03	.395E-03	.264E-03	.149E-03	.189E-04	.135E-04	.451E-04
30000.	.783E-03	.622E-03	.468E-03	.375E-03	.252E-03	.144E-03	.194E-04	.120E-04	.421E-04
32000.	.743E-03	.592E-03	.448E-03	.361E-03	.245E-03	.141E-03	.203E-04	.108E-04	.397E-04
34000.	.711E-03	.568E-03	.433E-03	.351E-03	.240E-03	.139E-03	.214E-04	.973E-05	.377E-04
36000.	.685E-03	.548E-03	.421E-03	.344E-03	.237E-03	.139E-03	.228E-04	.888E-05	.361E-04
38000.	.663E-03	.532E-03	.411E-03	.339E-03	.236E-03	.140E-03	.244E-04	.826E-05	.346E-04
40000.	.643E-03	.518E-03	.404E-03	.335E-03	.237E-03	.142E-03	.263E-04	.795E-05	.332E-04
42000.	.625E-03	.506E-03	.398E-03	.333E-03	.238E-03	.145E-03	.284E-04	.805E-05	.318E-04
44000.	.609E-03	.495E-03	.394E-03	.332E-03	.240E-03	.148E-03	.308E-04	.862E-05	.305E-04
46000.	.594E-03	.484E-03	.390E-03	.332E-03	.244E-03	.152E-03	.335E-04	.971E-05	.292E-04
48000.	.579E-03	.475E-03	.387E-03	.334E-03	.248E-03	.157E-03	.366E-04	.113E-04	.278E-04
50000.	.565E-03	.466E-03	.384E-03	.335E-03	.253E-03	.162E-03	.400E-04	.134E-04	.264E-04
52000.	.550E-03	.457E-03	.383E-03	.338E-03	.259E-03	.169E-03	.439E-04	.159E-04	.250E-04
54000.	.536E-03	.449E-03	.382E-03	.342E-03	.266E-03	.176E-03	.483E-04	.190E-04	.236E-04
56000.	.522E-03	.440E-03	.381E-03	.346E-03	.274E-03	.185E-03	.533E-04	.226E-04	.222E-04
58000.	.508E-03	.432E-03	.381E-03	.351E-03	.283E-03	.194E-03	.589E-04	.267E-04	.210E-04
60000.	.495E-03	.423E-03	.381E-03	.357E-03	.294E-03	.205E-03	.654E-04	.316E-04	.202E-04

TABLE 5

Damping = 70 lb-sec/in.   Stiffness = 100×10^3 lb/in.

FORCE TRANSMITTED TO FOUNDATION BY PEDESTAL, PEDESTAL MOTION AND MAXIMUM RELATIVE ECCENTRICITY

	STATION 25			STATION 35		
	FORCE	MOTION		FORCE	MOTION	
SPEED RPM	MAJOR AXIS	MAJOR AXIS	MAX REL ECC.	MAJOR AXIS	MAJOR AXIS	MAX REL ECC.
4000.	.898E+00	.862E-05	.199E-05	.381E+00	.381E-08	.846E-06
6000.	.218E+01	.200E-04	.483E-05	.917E+00	.917E-08	.204E-05
8000.	.429E+01	.370E-04	.948E-05	.179E+01	.179E-07	.397E-05
10000.	.758E+01	.625E-04	.167E-04	.312E+01	.312E-07	.694E-05
12000.	.125E+02	.113E-03	.275E-04	.511E+01	.511E-07	.114E-04
14000.	.196E+02	.185E-03	.430E-04	.794E+01	.794E-07	.176E-04
16000.	.289E+02	.265E-03	.632E-04	.116E+02	.116E-06	.257E-04
18000.	.387E+02	.307E-03	.846E-04	.155E+02	.178E-06	.343E-04
20000.	.463E+02	.268E-03	.101E-03	.184E+02	.247E-06	.408E-04
22000.	.500E+02	.264E-03	.109E-03	.198E+02	.279E-06	.438E-04
24000.	.509E+02	.251E-03	.111E-03	.200E+02	.279E-06	.444E-04
26000.	.504E+02	.234E-03	.110E-03	.197E+02	.264E-06	.438E-04
28000.	.495E+02	.217E-03	.108E-03	.193E+02	.246E-06	.429E-04
30000.	.487E+02	.202E-03	.106E-03	.190E+02	.230E-06	.420E-04
32000.	.480E+02	.188E-03	.104E-03	.186E+02	.216E-06	.413E-04
34000.	.474E+02	.177E-03	.103E-03	.184E+02	.204E-06	.407E-04
36000.	.471E+02	.167E-03	.102E-03	.182E+02	.195E-06	.403E-04
38000.	.469E+02	.158E-03	.102E-03	.181E+02	.188E-06	.400E-04
40000.	.468E+02	.151E-03	.102E-03	.180E+02	.182E-06	.399E-04
42000.	.468E+02	.145E-03	.102E-03	.180E+02	.180E-06	.398E-04
44000.	.468E+02	.147E-03	.102E-03	.180E+02	.180E-06	.398E-04
46000.	.469E+02	.147E-03	.102E-03	.180E+02	.180E-06	.398E-04
48000.	.471E+02	.147E-03	.103E-03	.181E+02	.181E-06	.399E-04
50000.	.474E+02	.147E-03	.103E-03	.182E+02	.182E-06	.401E-04
52000.	.476E+02	.146E-03	.104E-03	.183E+02	.183E-06	.403E-04
54000.	.480E+02	.145E-03	.104E-03	.184E+02	.184E-06	.405E-04
56000.	.483E+02	.144E-03	.105E-03	.185E+02	.185E-06	.408E-04
58000.	.487E+02	.143E-03	.106E-03	.187E+02	.187E-06	.412E-04
60000.	.491E+02	.142E-03	.107E-03	.189E+02	.189E-06	.415E-04

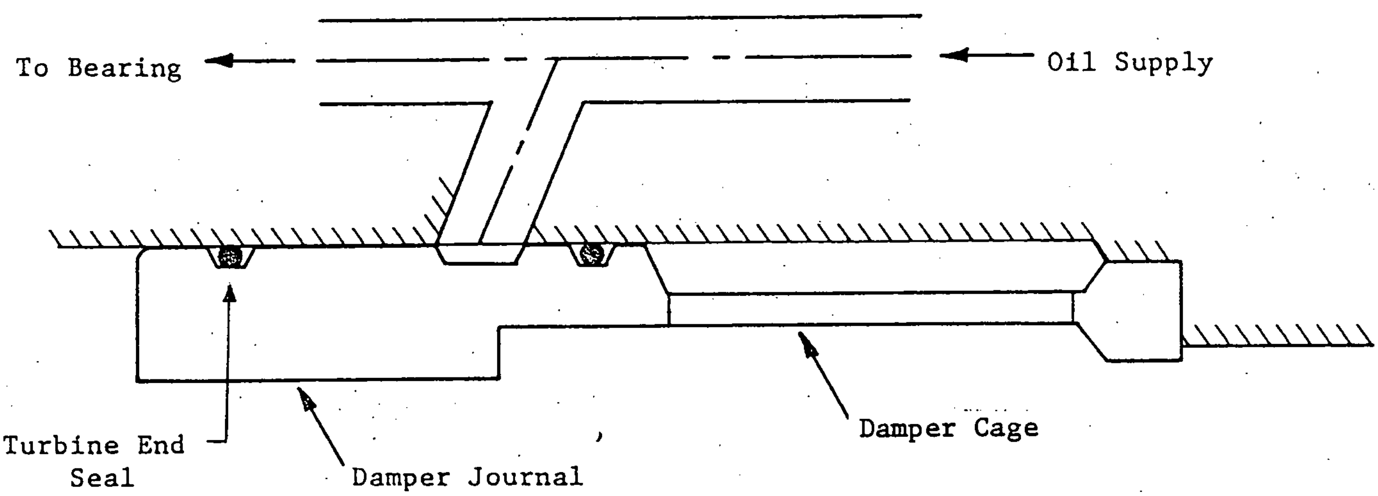
* ERDA UNBALANCE RESPONSE ANALYSIS * JULY 19, 1977 * M. CHEN * CASE 4

RESPONSE SUMMARY TABLE
MAJOR SEMI-AMPLITUDE (IN.) VS.
SPEED AND STATION NO.

STA. NO.	UNBALANCE (OZ-IN.)
3	.8900E-04
5	.2260E-03
6	.3650E-03
7	.6830E-03
8	.2168E-02
9	.4061E-02
11	.9411E-02

	STATION								
RPM	1	7	13	18	25	28	33	35	37
4000.	.380E-04	.297E-04	.215E-04	.165E-04	.105E-04	.561E-05	.430E-06	.850E-06	.210E-05
6000.	.888E-04	.693E-04	.500E-04	.384E-04	.245E-04	.130E-04	.113E-05	.205E-05	.491E-05
8000.	.167E-03	.130E-03	.934E-04	.715E-04	.454E-04	.241E-04	.237E-05	.399E-05	.921E-05
10000.	.280E-03	.217E-03	.156E-03	.119E-03	.752E-04	.399E-04	.448E-05	.697E-05	.155E-04
12000.	.437E-03	.339E-03	.241E-03	.184E-03	.116E-03	.615E-04	.784E-05	.114E-04	.242E-04
14000.	.649E-03	.501E-03	.356E-03	.270E-03	.169E-03	.898E-04	.128E-04	.177E-04	.359E-04
16000.	.908E-03	.699E-03	.494E-03	.373E-03	.233E-03	.123E-03	.196E-04	.259E-04	.501E-04
18000.	.116E-02	.889E-03	.624E-03	.470E-03	.292E-03	.155E-03	.271E-04	.345E-04	.641E-04
20000.	.133E-02	.101E-02	.707E-03	.530E-03	.327E-03	.173E-03	.331E-04	.410E-04	.733E-04
22000.	.137E-02	.104E-02	.725E-03	.541E-03	.332E-03	.176E-03	.364E-04	.440E-04	.759E-04
24000.	.134E-02	.102E-02	.702E-03	.521E-03	.318E-03	.169E-03	.376E-04	.446E-04	.743E-04
26000.	.128E-02	.966E-03	.664E-03	.491E-03	.298E-03	.158E-03	.377E-04	.440E-04	.711E-04
28000.	.122E-02	.915E-03	.626E-03	.461E-03	.278E-03	.148E-03	.374E-04	.431E-04	.678E-04
30000.	.116E-02	.869E-03	.591E-03	.434E-03	.260E-03	.138E-03	.371E-04	.422E-04	.648E-04
32000.	.111E-02	.830E-03	.562E-03	.410E-03	.245E-03	.130E-03	.368E-04	.415E-04	.622E-04
34000.	.107E-02	.797E-03	.537E-03	.391E-03	.231E-03	.123E-03	.366E-04	.409E-04	.601E-04
36000.	.104E-02	.769E-03	.515E-03	.374E-03	.220E-03	.117E-03	.365E-04	.405E-04	.584E-04
38000.	.101E-02	.745E-03	.497E-03	.360E-03	.211E-03	.112E-03	.365E-04	.402E-04	.570E-04
40000.	.988E-03	.725E-03	.482E-03	.348E-03	.202E-03	.108E-03	.366E-04	.400E-04	.559E-04
42000.	.968E-03	.707E-03	.468E-03	.337E-03	.195E-03	.105E-03	.367E-04	.400E-04	.550E-04
44000.	.951E-03	.692E-03	.457E-03	.328E-03	.189E-03	.101E-03	.369E-04	.400E-04	.542E-04
46000.	.936E-03	.679E-03	.447E-03	.320E-03	.184E-03	.988E-04	.371E-04	.400E-04	.537E-04
48000.	.923E-03	.667E-03	.438E-03	.313E-03	.179E-03	.965E-04	.374E-04	.401E-04	.532E-04
50000.	.912E-03	.657E-03	.430E-03	.307E-03	.175E-03	.946E-04	.377E-04	.403E-04	.529E-04
52000.	.903E-03	.648E-03	.423E-03	.302E-03	.171E-03	.929E-04	.381E-04	.405E-04	.526E-04
54000.	.895E-03	.640E-03	.416E-03	.297E-03	.168E-03	.916E-04	.385E-04	.407E-04	.525E-04
56000.	.887E-03	.633E-03	.411E-03	.293E-03	.165E-03	.904E-04	.389E-04	.410E-04	.524E-04
58000.	.881E-03	.626E-03	.406E-03	.289E-03	.163E-03	.895E-04	.394E-04	.414E-04	.524E-04
60000.	.876E-03	.620E-03	.401E-03	.285E-03	.161E-03	.888E-04	.399E-04	.417E-04	.524E-04

- Supply of oil to a groove at one end of the damper, as shown in the following sketch, makes the damper film a "dead end" due to the positive flow path provided to the bearing. Air could readily be trapped in the damper film. Elimination of the turbine end damper seal would have the benefit of allowing a positive oil flow through the damper journal. A careful check of the relative resistance of the film and bearing supply passages would be required in order to insure the oil supply to the bearing.



- Damper concentricity is an important factor. Errors in concentricity and the depth of the O-ring grooves may have an impact on the assembled concentricity of the damper journal and a significant impact on the damping, since damping varies with C^3.

2. <u>Turbine Modifications</u>

From the foregoing discussions, it has been concluded that rotor unbalance must be minimized to control dynamic response even with a revised damper design. Inspection of the turbine revealed excessively loose fits between the turbine wheels and rotor shaft. These clearances can be reduced by plating and should be made as tight as possible to improve rotor balance and prevent balance shifts during operation.

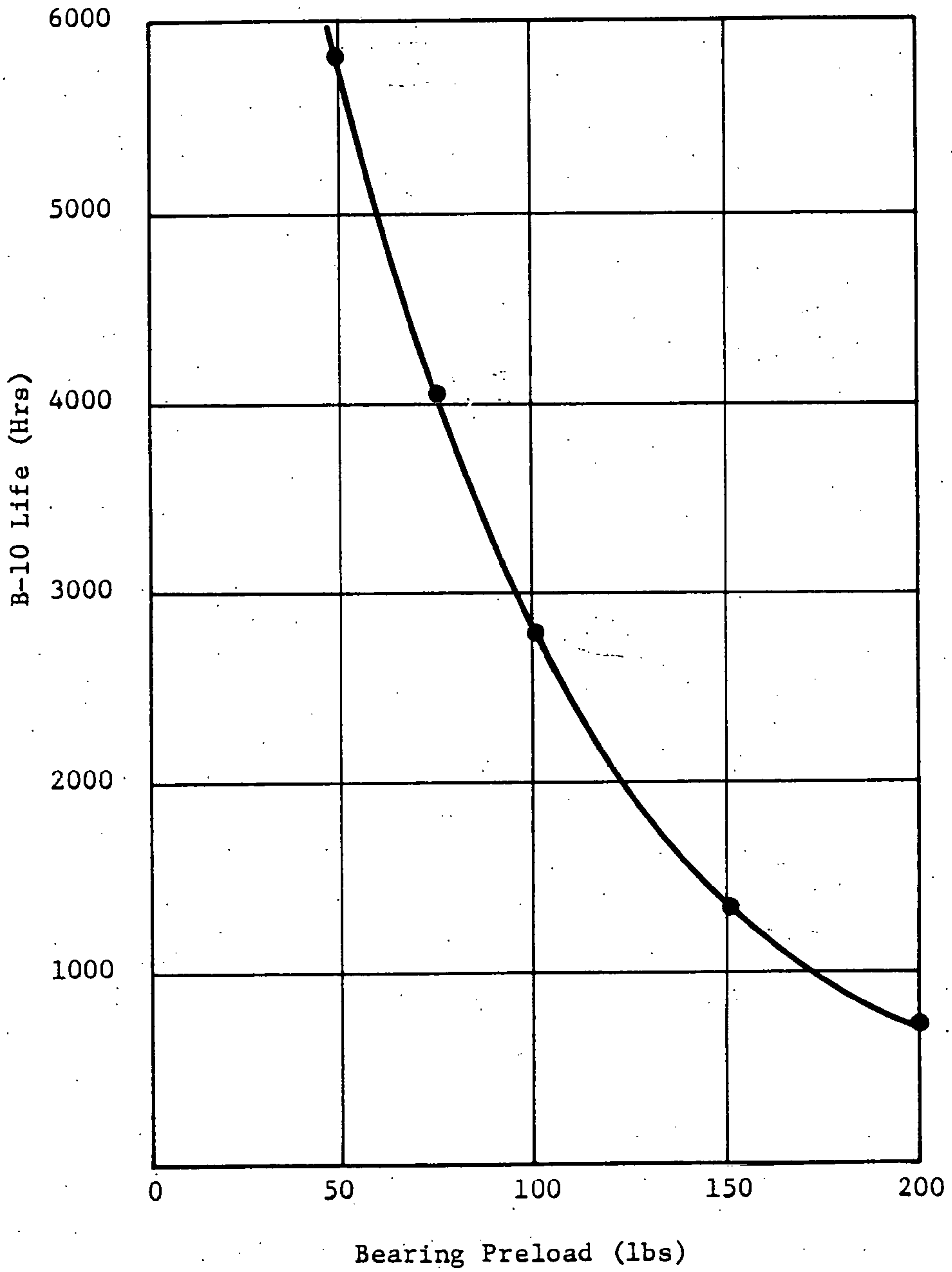


Figure 9. Barden Bearing 105 HJB
B-10 Life at 60,000 rpm

D. Bearing Oil System

The following changes should be considered to obtain a unit with a longer life.

In Figure 9, it may be seen that the B-10 fatigue life of the bearing at design speed and with the nominal preload of 125 lbs is 2,000 hours. This calculation is pessimistic and does not account for possible improvements in the bearing fatigue life, which could be realized by the utilization of modern vacuum cleaned materials. Optimal bearing lubrication was assumed, however, and there is concern that the oil drain system from one side of each bearing may be inadequate. With the bearing being in danger of running flooded and subject to overheating, it is recommended that proper oil drains be provided. As the redesign of the damper requires a review of the oil system, this additional task should be included.