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TEST PLAN
RESEARCH AND DEVELOPMENT **MASTER**
FOR
IMPROVED EFFICIENCY, SMALL STEAM TURBINE
PROJECT NO. 1380 PHASE II
REVISION A
December, 1981

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INTRODUCTION

Northern Research and Engineering Corporation together with Terry Steam Turbine Corporation is currently engaged in a development program aimed at demonstrating that a family of high efficiency radial inflow steam turbines (RIT) can be developed to meet the demands of the small (500 to 5,000 hp) steam turbine market, such that significant market penetration, hence significant savings in the nation's use of energy, will result. This effort is being funded under the auspices of the United States Department of Energy. Since market demands include great reliability as well as relatively low first costs resulting from parts standardization, the RIT must exhibit these attributes as well as high efficiency.

The program is being conducted in two phases. During Phase I, recently completed, the market for small steam turbines was examined and the family of radial inflow turbines best suited to penetrate the market was identified. Substantial energy savings due to such penetration were predicted (see Ref 1). In addition, a particular RIT configuration was selected to be designed, built and tested during the second phase of the program.

Investigation of market demands resulted in a definition of the ranges of operating steam conditions which will cover those of the vast majority of 500 hp to 5,000 hp steam turbine applications.

Inlet Pressure	50 - 650 psig
Inlet Temperature	420 - 820 deg F
Pressure Ratio	3.0 - 19.0 (Non Condensing Units)

A radial inflow turbine stage can be adapted to various demands by changing steam flow path geometry through the use of tip diameter and shroud line cuts of the turbine wheels. A parametric study, relating variations in efficiency with the number of wheels used to cover market demands, led to the selection of four turbine stages, each designed for a particular speed and range of volume flow rates (Q) such that most applications can be covered with various combinations of these stages operating

at close to optimum specific speed and driving a common bull gear/output shaft. These stages are defined as follows:

<u>Stage</u>	<u>A</u>	<u>B</u>	<u>C</u>	<u>D</u>
N (rpm)	70,000	52,500	39,375	29,531
Q/QA	1.0	1.778	3.163	5.623

where Q/QA is the ratio of the volume flow rate capability of a wheel to that of the primary "A" wheel.

A similar investigation of the trade off between the low first costs associated with standardization and the higher efficiencies resulting from custom design yielded a definition of four horsepower classes, i.e., modular high speed rotor designs.

<u>Class</u>	<u>Maximum Shaft Horsepower</u>
I	600
II	1,100
III	1,900
IV	2,500

The selection of a prototype configuration with two 600 shp turbine stages resulted from the determination during Phase I that the greatest potential for energy savings lies in the 500 to 1,000 hp range. The Stage I turbine will employ an A wheel; Stage II, a B wheel.

While the prototype has been designed mechanically for the range of steam conditions specified in Table I, a nominal design point was selected for aerodynamic design and baseline performance demonstrations.

Inlet Pressure	225 psig
Inlet Temperature	600 deg F
Exhaust Pressure	35 psig
Output Shaft Power	700 hp

The tests specified in this report fall into three categories:

- Component Testing
- Mechanical Rotating Testing
- Performance

The component and mechanical rotating tests are designed to assure the integrity of the machine prior to performance testing and verify the results of engineering analyses employed in its design. The performance tests are meant to demonstrate the predicted performance which has been the rationale for this program.

The schedule for the completion of these tests is shown in Figure 1.

COMPONENT TESTING

COMPONENT TESTINGA. Wheel Overspeed Testing

Purpose:

Assure the high speed integrity of the turbine wheels.
Identify areas of peak stress.

Requirements:

Both A (70,000 rpm) wheels - 1380D10000

Both B (52,500 rpm) wheels - 1380D10001

Components for complete Stage 1 and 2 Rotor Assemblies

Magnetic Speed Pick-up and Tachometer

Stress Coat

Calibration beam to be used for estimating magnitudes of strains

Spin Arbor

Responsible Group:

NREC Laboratory

Set-Up:

1. Fluorescent penetrant inspection per MIL-I-6866, Type I, Method B to be conducted by an outside testing laboratory. Testing laboratory to furnish test report.
Any indications of cracks or porosity to result in a nonconforming material report for engineering evaluation prior to continuing testing of the wheels in question.
2. Balance the wheel per NREC Specification 1380A10006.
3. Measure the outside diameter.
Primary set of wheels - Perform Step 4.
All spare wheels - Go on to Step 5.
4. Apply stress coat to entire wheel and calibration beam.
Be sure to place calibration beam in pit during test.
5. Set up balanced wheel/arbor assembly in spin pit.

Procedure:

1. Overspeed test the wheels to the following speeds:

A Wheels (1380D10000) - 100,000 rpm

B Wheel (1380D10001) - 75,000 rpm

Hold test speed for a minimum of two minutes.

2. On those wheels which have been stress coated, identify areas of critical strains and note their location and principal strain directions on a print of the wheel drawing. Pertinent photographs to be taken as well.

The magnitude of the strains to be estimated.

3. Measure the outside diameter of each turbine wheel after testing. A maximum growth of 0.002 inches is acceptable.
 4. Outside testing laboratory to perform fluorescent penetrant inspection after testing and furnish a test report.
- No indications of cracks or porosity are acceptable.

COMPONENT TESTINGB. 1 - Preliminary Wheel Blade Excitation

Purpose:

To provide an illustration of blade mode shapes to indicate the optimum locations and orientations for strain gages in subsequent testing.

Requirements:

Spare B Wheel
Shaker Table
Adapter
Stress coat

Responsible Group:

NREC Laboratory

Set-up:

1. Balance the wheel per NREC Specification 1380A10006.
2. In the QC room, apply stress coat to the entire wheel.
3. Mount wheel to shaker table using adaptor.

Procedure:

Sweep the 0 to 10,000 Hz frequency range.

Examine the disk, full blades and splitters to establish mode shapes for subsequent specification of strain gage placement.

COMPONENT TESTING

B. 2 - Wheel Blade Excitation

Purpose:

Determine the natural frequencies of the turbine wheel blades.

Confirm results of finite element analyses. Identify wheel speeds which should be avoided.

Requirements:

Spare B wheel

Shaker table with amplifier

Tape recorder

Oscilloscope

Frequency Analyzer

Strain gages

Responsible Group: Terry Corporation

Set-Up:

Final selection of strain gages and their location and orientation to be specified based on the results of the preliminary excitation tests.

To include one gage on the backface of the disk for determination of disk natural frequencies.

Mount wheels to shaker table.

Procedure:

A frequency sweep from 0 to 10,000 Hz (or to 20,000 Hz if circumstances permit) is to be made such that a graph of frequency vs. amplitude can be plotted.

COMPONENT TESTING

B. 3 - Wheel Blade Impulse Testing

Purpose:

Determine blade natural frequencies and associated mode shapes.

Verify results of shaker table testing and finite element analysis.

Requirements:

Spare B wheel

Eddy current proximity probe and holding fixture

Testing hammer with force gauged tip

Modal analysis electronic hardware

Responsible Group:

Terry Corporation

Set-Up:

Mount eddy current proximity probe to sense motion of a blade on a B (52,500 rpm) wheel. Use instrumented hammer to excite the specific blade being monitored.

Procedure:

1. Determine test piece natural frequencies by impacting the piece and viewing spectral content of probe output.
2. Build a model, much like a Finite Element grid model, and store it in the modal analysis system.
3. Strike the test piece with the testing hammer at predetermined points of high vibratory response to provide excitation and response information for the model.
4. Use the modal analysis system to develop mode shapes and display them in hard copy form.

COMPONENT TESTINGC. Hydrostatic Test

Purpose:

Assure the integrity of the steam flowpath.

Requirements:

1st Stage Scroll

1st Stage Shroud

2nd Stage Scroll

2nd Stage Shroud

Nozzle Vanes

Crossover Piping

Fixtures for sealing the inlet flange, the exhaust flange, and the rotor bores on the inboard side of the scroll.

Dial indicators

Responsible Group:

NREC Laboratory

Set-Up:

The following segments of steam flowpath casing, which together comprise the entire flowpath, are to be tested independently:

- The 1st Stage Scroll and Shroud
- The 2nd Stage Scroll and Shroud
- The fabricated crossover piping structure

Install fixtures to seal each assembly at the inlet flanges, the exhaust flanges and the rotor bores at the inboard side of the scrolls. Be sure to include nozzle vanes in the assembly of the shroud to the scroll.

Procedure:

Fill the assembled segments of the casing with water in such a manner so as to preclude the possibility of air pockets remaining in them during hydrostatic testing. Nitrogen to be used as the medium for application of the test pressure.

Per Section VIII, Division 1 of the ASME Code, the requisite hydrostatic test pressure is equal to 1-1/2 times the maximum allowable working pressure, multiplied by a factor obtained by dividing the maximum allowable stress for the material* at room temperature by the corresponding stress value at steam temperature. The scrolls and shrouds are cast steel, Grade WCB and the crossover piping structure is 309 stainless steel. Since the maximum inlet conditions are 650 psig and 750 deg F the first stage scroll and shroud test pressure is calculated as follows:

$$\text{Hydrostatic Test Pressure} = 1.5 (650.) \left(\frac{17.5}{14.8} \right) = 1153 \text{ psig}$$

The scroll and shroud structure which is used for the second stage in this prototype may, in another application, function as the first stage. Thus, this segment of the casing will also be qualified for the 650 psig, 750 deg F inlet conditions. The maximum allowable working pressure of the crossover piping is 400 psig.

$$\text{Hydrostatic Test Pressure} = 1.5 (400) \left(\frac{16.}{12.8} \right) = 750 \text{ psig}$$

Test duration to be a minimum of 30 minutes. No visible leakage to be permitted. Dial indicators to be situated to measure:

- . Any deformation or increase in the diameter of of the scrolls
- . The change in axial position of the shrouds relative to the inboard surfaces of their corresponding scrolls.

* Maximum allowable stresses obtained from ASME Code.

- . . The deflection of the OD of the first stage discharge plenum.
- . The axial deflection of the outboard end of the discharge plenum.

MECHANICAL ROTATING TESTING

MECHANICAL ROTATING TESTING

A. Rotordynamics

Purpose:

To minimize the chances for mechanical failure of the machine, it will be spun up to 115 percent of rated speed under no load before performance testing. Critical speeds will be identified as will the onset of any non-synchronous instabilities such as oil whip.

Furthermore, it is under lightly loaded conditions that the likelihood of oil whip occurring in the operating speed range is theoretically greatest.

Note that shaft vibrations will be continuously monitored during all other testing of the turbine as well.

Requirements:

Assembled machine complete with lube system, governor valve, actuator, electronic governor and trip and throttle valve.

High speed rotors to be two plane balanced to a residual unbalance of 20×10^{-6} inches each plane, per NREC Specification 1380A10006.

Instrumentation per Table II

Multi channel T/C indicator

Bull gear to be two plane balanced to within 0.16 oz-inch.

Responsible Group:

Instrumentation - NREC

Performance of Test - Terry Corporation

Set-up:

Turbine to be piped into steam supply system.

Procedure:

After a one hour warm-up period at an output shaft speed of approximately 50 rpm, a sweep of the speed range 0 to 4,000 rpm is to be made with no load on the turbine. Shaft vibrations to be continuously observed and critical speeds noted. Oil temperatures and supply pressure to be monitored as well.

The performance of the trip and throttle valve is to be checked until satisfactory response is assured

PERFORMANCE TESTING

PERFORMANCE TESTING

A. Speed Lines

Purpose:

1. Generate curves of variation of the throttle steam rate with turbine shaft output at 1/2, 3/4 and rated speeds. Comparison of the actual steam rate with the theoretical steam rate will yield turbine efficiency.
2. Determine gross turbine (wheel) output as well as shaft output to separate turbine (thermodynamic) efficiency from mechanical.
3. Assess component performance

Requirement:

Fully assembled, instrumented prototype unit
Instrumentation per Table III and Figure 2
Eaton Dynamatic Model 1519-2-WIG Dynamometer
Scanni Valve

Responsible Group:

Instrumentation - NREC
Performance of Test - Terry Corporation

Set-up:

Fully assembled (including governor valve, actuator, electronic governor, lube system) and instrumented turbine to be piped into steam supply system and coupled to dynamometer.

Provision for auto shutdown in case of a loss of oil pressure or overspeed to be supplied by Terry's test laboratory.

Procedure:

Testing to be preceded by a one hour (minimum) warm-up period at an output shaft speed of 200 rpm. The matrix of tests identified on Table IV and Figure 3 to be run in the numbered sequence. Testing to begin and end with testing at the nominal design point (Test 1). Each speed line to be initiated at the design power with the throttle full open.

Turbine temperatures and pressures to be read at five-minute intervals with at least two readings taken after the exhaust temperature has stabilized. Shaft vibrations and oil pressures and temperatures to be monitored.

Condensate output of the test condenser to be weighed to provide turbine exhaust flow. Gland seal condensate to be measured as well.

A sample data sheet for this and the stage testing is illustrated in Figure 4.

B. Stage Performance Map

Purpose:

Accurately assess radial inflow turbine stage performance over a wide range of speeds and pressure ratios.

Requirements:

Fully assembled, instrumented prototype turbine minus the
2nd Stage
Instrumentation as in Speed Line Testing less that specified
for the 2nd stage
Eaton Dynamic Model 1519-2-W1G Dynamometer
Scanni Valve

Responsible Group:

Terry Corporation

Set-up:

First stage only to be piped into the steam supply system.
The second stage rotor to be removed from the turbine and
covers installed over the bores in the gear case and cover.
As in speed line testing, provisions to be made for auto
shutdown in case of loss of oil pressure or overspeed.

Procedure:

Testing to be preceeded by a one hour (minimum) warm-up period
at an output shaft speed of 200 rpm. The test points identified
in the matrix shown on Table V are to be run by initiating
each speed line at the lowest specified pressure ratio and
reducing the back pressure to obtain higher pressure ratios.

The back pressure to be reduced to yield pressure ratios greater than 3.5 if necessary to reach the point where the work per pound of steam no longer increases (i.e., lbm/hp hr. no longer decreases) with an increase in pressure ratio. However, the exhaust must not be less than the minimum specified in Table V. Each test point to be held until the turbine exhaust steam temperature reaches a steady state.

Turbine temperatures and pressures to be read at five-minute intervals with at least two readings taken after the exhaust temperature has stabilized. Shaft vibrations and oil pressures and temperatures to be monitored.

TABLES

TABLE I
PROTOTYPE TURBINE OPERATING LIMITS

	<u>Output Shaft</u>	<u>1st Stage Rotor</u>	<u>2nd Stage Rotor</u>
Rated Horsepower	1100 at 3600 rpm	600 at 70,000 rpm	600 at 52,500 rpm
Max. Allowable Operating Speed, rpm	3600	70,000	52,500
Maximum Continuous Speed, rpm	3780	73,500	55,125
Overspeed Trip Speed, rpm	4140	80,500	60,375

Maximum Inlet Conditions 650 psig - 750 deg F

Maximum Exhaust Pressure 200 psig

Maximum Allowable
Working Pressure, psig

Stage 1 Inlet Scroll and Shroud	650
Crossover Piping Structure	400
Stage 2 Inlet Scroll and Shroud	650

TABLE IIROTORDYNAMICS TEST INSTRUMENTATION SCHEDULE

Oil Supply Pressure Tap

Oil Supply Temperature Thermocouple

One Thermocouple at Each Bearing to Measure Exit Oil Temperatures

Proximitors at Each Pinion for Speed Pickup

Two (x & y) Proximitors at Each High Speed Bearing

Two (x & y) Proximitors at the Output Side Bullgear Bearing

One Accelerometer on the Outboard Side of Each Bearing Shell

TABLE III
PERFORMANCE TEST INSTRUMENTATION SCHEDULE

Static Pressure Taps

P_1	Ambient
P_2	Upstream of Throttle
$P_3 - P_6$	Downstream of Throttle
P_7	Stage 1 Nozzle Inlet (Scroll Exit)
P_8	Stage 1 Nozzle Exit
P_9	Stage 1 Rotor Exit
P_{10}	Stage 1 Wheel Backface at Hub
P_{11}	Downstream of Stage 1 Labyrinth Seal
P_{12}, P_{13}	Stage 1 Diffuser Exit
P_{14}	Stage 2 Nozzle Inlet (Scroll Exit)
P_{15}	Stage 2 Nozzle Exit
P_{16}	Stage 2 Rotor Exit
P_{17}	Stage 2 Wheel Backface at Hub
P_{18}	Downstream of Stage 2 Labyrinth Seal
$P_{19} - P_{22}$	Exhaust Pressure
P_{23}	Oil Supply

Thermocouples

$T_1 - T_4$	Upstream of Throttle
T_5, T_6	Downstream of Throttle
T_7, T_8	Stage 1 Discharge
$T_9 - T_{12}$	Turbine Exit
T_{13}	Oil Temperature In
T_{14}	Oil Temperature Out
$T_{15} - T_{21}$	Oil Temperatures at the Exit of Each Bearing

TABLE III. (Continued)PERFORMANCE TEST INSTRUMENTATION SCHEDULEProximitys

N_1	Speed Pickup, Stage 1 Pinion
N_2	Speed Pickup, Stage 2 Pinion
$V_1 - V_8$	High Speed Rotor Bearing Two Planes (x & y) per Bearing
V_9, V_{10}	Bullgear Bearing, Output Side Two Planes
V_{11}, V_{12}	Axial Position of High Speed Rotors at the Thrust Collar

Accelerometers

$A_1 - A_4$	Outboard Side of High Speed Bearing Shells
-------------	---

TABLE IV
MATRIX OF TESTS FOR
DEVELOPMENT OF PERFORMANCE SPEED LINES

25

1st Stage Scroll Inlet Pressures, P_4 are as shown on Matrix
Turbine Inlet Temperature, $T_1 = 600$ deg F for all tests.
Turbine Exhaust Pressure, $P_{12} = 35$ psig for all tests.

Rated Speed = 3600 rpm 3/4 Speed = 2700 rpm 1/2 Speed = 1800 rpm

Nominal Design Point Power 687 SHP	1 225 psig	5 220 psig	9 256 psig
3/4 Power 515 SHP	2 193 psig	6 183 psig	10 205 psig
1/2 Power 344 SHP	3 159 psig	7 144 psig	11 155 psig
1/4 Power 172 SHP	4 118 psig	8 104 psig	12 103 psig

TABLE V

MATRIX OF TESTS TO DEVELOP STAGE 1 PERFORMANCE MAP

Corrected Speed, Percent of Design	Inlet Conditions		Actual Wheel Speed, rpm	Test Exhaust Pressures, psig							Max. Work, Except Pressure to be No Less Than
	Pressure, psig	Temperature, deg F		P/p	1.5	1.75	2.0	2.5	3.0	3.5	
60	185	600	42,000		120	100	85	65	52	42	15
70	185	600	49,000								
80	185	600	56,000								
90	185	600	63,000								
100	185	600	70,000		120	100	85	65	52	42	15
110	65	506	73,500		38	31	25	17	12	8	0

FIGURES

CONTRACT TITLE: IMPROVED EFFICIENCY SMALL STEAM TURBINE		CONTRACT NO.: DE-AC03-79ET15426	DATE OF PLAN: SEPTEMBER, 1981	REV A 12/4/81
CONTRACTOR: NORTHERN RESEARCH AND ENGINEERING CORP. 39 Olympia Avenue Woburn, Massachusetts 01801		TEST PLAN	NREC PROJECT NO: 1380	

TEST	AUG	SEPT	OCT	NOV	DEC	JAN, 82	FEB	MAR	APR
	8 15 22 29	5 12 19 26	3 10 17 24 31	7 14 21 28	5 12 19 26	2 9 16 23 30	6 13 20 27	6 13 20 27	3 10 17 24 1
I-A WHEEL OVERSPEED									
I-B1 PRELIMINARY WHEEL BLADE EXCITATION									
I-B2 TURBINE WHEEL SHAKER									
I-B3 TURBINE WHEEL IMPULSE									
I-D HYDROSTATIC									
II ROTORDYNAMICS									
III-A SPEED LINES									
III-B STAGE PERFORMANCE MAP									

FIGURE 1 - TEST PLAN SCHEDULE

FIGURE 2 - STATIC TAP LOCATIONS - STAGE 1

FIGURE 2 (Continued) - STATIC TAP LOCATIONS - STAGE 2

FIGURE 3 - IDENTIFICATION OF TESTS OF PROTOTYPE TURBINE - ANTICIPATED PERFORMANCE

Run No. _____ Date _____ Ambient Pressure _____

Temperature _____

Time													
N ₂													
N ₁													
P ₂													
P ₃													
P ₄													
P ₅													
P ₆													
P ₇													
P ₈													
P ₉													
P ₁₀													
P ₁₁													
P ₁₂													
P ₁₃													
P ₁₄													
P ₁₅													
P ₁₆													
P ₁₇													
P ₁₈													

FIGURE 4 - PERFORMANCE TEST DATA SHEET

Run No. _____ Date: _____ Ambient Pressure: _____

Temperature: _____

Time												
T ₁												
T ₂												
T ₃												
T ₄												
T ₅												
T ₆												
T ₇												
T ₈												
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T ₁₈												
T ₁₉												
T ₂₀												
T ₂₁												

FIGURE 4 - (CONTINUED) PERFORMANCE TEST DATA SHEET