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UNITED TECHNOLOGIES RESEARCH CENTER 8-kW PROTOTYPE WIND SYSTEM

FINAL TEST REPORT

K. K. HIGASHI

September 1981

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Prepared by
DOE Rocky Flats
Wind Systems Program

Operated by
Rockwell International Corporation
Energy Systems Group
P.O. Box 464
Golden, Colorado 80402-464

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For the:
UNITED STATES DEPARTMENT OF ENERGY
WIND TECHNOLOGY DIVISION
FEDERAL WIND ENERGY PROGRAM

DOE Contract DE-AC04-76DP03533

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SUMMARY

The United Technologies Research Center 8 kW prototype wind system underwent testing at the Rocky Flats Small Wind Systems Test Center from April 1980 through August 1980. During atmospheric testing, the machine survived wind speeds of 30.8 m/s (69 mph) without incurring damage and proved it was capable of meeting the design specification for power production (8 kW @ 9 m/s - 20 mph). Erratic cycling of the generator speed detector was the only operational problem encountered. Vibration tests indicated the first and second bending modes of the tower were excited during actual machine operation, but modifications were not required. Noise measurements revealed that sound pressure levels of the UTRC are within an acceptable range and should pose no barriers to machine use.

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LIST OF ABBREVIATIONS

A or amp	- ampere
ac	- alternating current
Btu	- British thermal units
CBR	- Composite Bearingless Rotor
cm	- centimeter
Cp	- power coefficient
dB	- decibel
dBA	- decibel, A-weighted
dc	- direct current
ft	- foot
hp	- horsepower
Hz	- Hertz
in.	- inch
kg	- kilogram
kVA	- kilovolt-ampere
kW	- kilowatt (1000 watts)
kWh	- kilowatt hour
lb	- pounds
LTDC	- Long Term Data Collection
m	- meter
mph	- miles per hour
m/s	- meters per second
RI	- Rockwell International
RF	- Rocky Flats
rpm	- revolutions per minute
SWECS	- Small Wind Energy Conversion System
V	- volt
W	- watt
WSTC	- Wind Systems Test Center
WTG	- wind turbine generator
°	- degrees

1.0 INTRODUCTION

The major objective of activities at the Rocky Flats Small Wind Systems Test Center (WSTC) is to assist the small wind energy conversion systems (SWECS) industry in the development of a sound technological base through research and testing. This final test report is designed to provide a complete presentation of the operational characteristics of the United Technologies Research Center (UTRC) prototype wind system and a summary of data and analytical results. Every effort has been made to ensure that data presented herein give an accurate representation of the performance of the UTRC unit during the test period. It is planned, at a later date, to test an additional UTRC unit which incorporates production-line design modifications.

Manufactured by the United Technologies Research Center, East Hartford, Connecticut, the prototype (Figure 1) was designed and fabricated for the U.S. Department of Energy (DOE) under a subcontract with Rockwell International (References 1 and 2). Basic design goals of the contract were to develop a wind system which had: 1) the capability of producing a minimum of 8 kW at a wind speed of 9 m/s (20 mph) at sea level; 2) a capital cost of \$750/kW (1978 dollars) based on output at 9 m/s; 3) a useful life of at least 25 years; 4) the ability to withstand severe weather conditions including maximum wind gusts of 74 m/s (165 mph); and 5) an on-line availability of 99%. Although the ability of the UTRC to meet some of the above objectives must be determined over a longer time, testing at the WSTC did show the capability to produce 8 kW at 9 m/s and an on-line availability of 99% during the test period.

2.0 TEST SPECIMEN

The UTRC 8 kW prototype is a horizontal-axis, two-bladed, propeller-type, variable pitch, downwind machine. The system can supply power through three generating modes (Table I). In Mode I, the generator is connected directly to a 60 Hz utility grid. Mode II is a generating mode

where the generator is interconnected with a utility grid in parallel with an auxiliary power supply. Mode III is a stand-alone generating system using a dc generator. In Modes I and II, the generator is a constant speed induction-type which uses the utility grid 60 Hz signal as a reference to maintain generator speed. All testing of the UTRC at Rocky Flats was accomplished under Mode I.

Figure 1
UTRC 8 kW Prototype

TABLE 1
DESIGN PERFORMANCE SPECIFICATIONS

	<u>Generating Modes I and II</u>	<u>Generating Mode III</u>
Number of Blades	2	2
Blade Material	Fiberglass	Fiberglass
Blade Chord	0.381 m	0.381 m
Twist and Taper	0	0
Airfoil Series	23112	23112
Pre-Cone	8°	8°
Solidity	0.0568	0.0568
Static Blade Pitch	16°	16°
Rotor Diameter	9.45 m	9.45 m
Rated Wind Speed	9 m/s	9 m/s
Rotor Tip Speed @ V_{RATED}	53.3 m/s	53.3 m/s
Blade Pitch @ V_{RATED}	2°	0°
Rotor Power Output @ V_{RATED}	11.1 kW	13.0 kW
Generator Power Output @ V_{RATED}	9.5 kW	12.2 kW
Cut-In Wind Speed	3.36 m/s	3.0 m/s
Cut-Out Wind Speed	22.9 m/s	22.9 m/s
Gearbox Ratio	1:17	1:17
Annual Electrical Power Output @ $V_{\text{MEAN}} = 5 \text{ m/s}$	20,000 kWh	20,000 kWh

A major feature of the UTRC 8 kW is a flexbeam that employs the specialized features of the Composite Bearingless Rotor (CBR). Developed initially for helicopter applications, the CBR evolved as a result of the unique application of fiber-reinforced composite materials. The nonisotropic nature of unidirectional composites (graphite epoxy) yields a structure that is decidedly softer in torsion and stronger in the axial direction. By utilizing this material in a flexbeam that serves as an interface between the blades and rotor hub, torsional deflections can be achieved to satisfy the pitch angle change requirements of a wind turbine rotor, while at the same time providing stiffness in the in-plane and out-of-plane directions to satisfy operational rotor frequency requirements (Figure 2).

The flexbeam is pre-twisted 16 degrees (defined for WSTC purposes as a 16° deflection of the leading edge from the plane of rotation into the wind) to allow the rotor to self-start and is connected to a pendulum by a steel flexstrap. Blade pitch angle is automatically varied by centrifugal forces acting on each pendulum. For example, as rpm increases the pendulums move toward the plane of rotation and, through the flexstrap, provide a moment to the blades which untwists the flexbeam. This decreases blade pitch until at the rotor design speed of 106 rpm, the blade has reached the optimum angle for power output. From this point on, the induction generator acts as an external governing device to maintain a constant rotor speed since the generator rotational speed is determined by the utility line frequency to which it is connected.

If the induction generator should disconnect from the utility due to a utility failure under high wind conditions, overspeed is controlled by blade stall at a specific combination of wind speed and rpm. At approximately 240 rpm or over twice the design rotor rpm, the pendulums are essentially in the plane of rotation and produce a blade pitch angle of approximately -5 degrees. This angle, in combination with the aerodynamic angle produced by wind speed, is sufficient to stall the blades. At this point, rotor speed is reduced to approximately 180 rpm and will remain at this level until the wind speed drops or utility power is brought back on-line.

Rotor aerodynamic speed is increased by a 1:17 gearbox and converted to electrical power by a 20 hp (15 kW), 3-phase, induction generator connected to a 240 Vac utility line. Generator synchronous speed is 1800 rpm which corresponds to a rotor speed of 106 rpm. A speed detector picks up a signal from a 64-tooth gear on the generator and is preset to connect the generator to the utility when rotor speed reaches 111 rpm. Disconnection occurs when rotor speed drops below 106 rpm. As a result, the generator will remain connected to the utility (when in a generating mode) at all wind speeds once cut-in is achieved and rotor speed is above 106 rpm.

Figure 2

UTRC Pendulum and Flexbeam

3.0 TEST OBJECTIVES

The immediate objectives of atmospheric testing were to establish system power curves and verify the degree to which performance met the specifications set forth in the development contract (see Section 1.0). In order to accomplish these objectives, the UTRC was instrumented for long term data collection (LTDC) using parameters defining system performance characteristics: power output, wind speed, wind azimuth, rotor rpm and yaw angle. Additional test objectives were to determine rotor pitch schedule, tower resonance/vibration modes, power coefficient, annual power output and obtain noise measurements from the machine during actual operation.

4.0 TEST CONFIGURATION AND POWER LOAD

Rocky Flats atmospheric testing of the UTRC 8 kW was conducted with the machine mounted on a Schedule 10 steel pipe tower (pipe 10.75 in. dia.) located at Tower Pad 3.4. Since the prevailing winds at the WSTC are from the northwest, the R. M. Young anemometer was mounted on a separate tower 14.32 m (47 ft) northwest of the machine (Figure 3). Both the anemometer and rotor axis were at a height of 16.76 m (55 ft).

When being tested in mode I, the UTRC was designed to provide 240 Vac, three-phase, 60 Hz power for tie-in to a utility. For testing at Rocky Flats, interconnection was with the Public Service Company of Colorado utility grid.

Figure 3
UTRC Anemometer Location

5.0 INSTRUMENTATION - ATMOSPHERIC TESTING

All instrumentation used for atmospheric testing of the UTRC 8 kW was owned by DOE. The following is a list of instrumentation used:

<u>Instrumentation</u>		
<u>Parameter</u>	<u>Instrument and Manufacturer</u>	<u>Location</u>
Wind Speed/Direction	Anemometer, Model 8002 Propvane, R. M. Young Company	Separate Tower (see Figure 3)
Generator RPM	Magnetic Pickup & Frequency to Voltage Converter, Elektro Model 3015-117, Elektro, Inc.	Generator Shaft
Power	Watt Transducer, Model PC5-53, Ohio Semitronics, Inc.	WTG Shed
Yaw	Rotary Variable Differential Transducer, Model 3371, Beckman Instruments	Base of Yaw Column

Data Collection

1. Rockwell International microprocessor.
2. Data General NOVA 3/12 computer.
3. Data General Eclipse S/250 computer.

6.0 CALIBRATION

All instrumentation was calibrated following specifications described in the WSTC procedures manual (see Reference 3).

7.0 TEST METHODS

Long Term Data Collection (LTDC)

LTDC is characterized by testing 24 hours a day, 7 days a week, 365 days a year. Data collected during LTDC fall into two categories. System

performance parameters (the first category) include rotor rpm, power output (i.e., watts, Btu, or shaft hp), machine yaw and blade pitch angle. Input to the SWECS (the second category) includes wind velocity and direction.

Methods used to collect vibration data and noise measurements from the UTRC are described in Appendices A and B, respectively.

8.0 TEST RESULTS

Atmospheric Testing (Quantitative)

Figures 4 through 11 represent data collected during testing at Rocky Flats and are, respectively: power vs wind speed, adjusted to standard-day sea level conditions; power vs wind speed, uncorrected; blade pitch vs rpm; rpm vs wind speed; blade pitch vs wind speed; power coefficient vs wind speed; tip speed ratio vs wind speed; and power coefficient vs tip speed ratio. The power curve adjustment to standard-day conditions (Figure 4) was based on temperature and barometric pressure differential between Rocky Flats and sea level standard-day.

Comparison between the RF adjusted power curve and the manufacturer's power curve (Figure 4) indicates that at rated wind speed (9 m/s) the UTRC produced 8.3 kW, while 9.5 kW were predicted. Although 8.3 kW is lower than predicted power output, it does meet the 8 kW design requirement specified in the development contract. The maximum adjusted output (16.1 kW) is significantly higher than the predicted maximum output (12 kW) and can be attributed to a mass reduction in the pendulum control system prior to testing at RF. Since the blade pitch angle is dependent on the pendulum acting under the influence of centrifugal forces as rpm varies, less mass produces a smaller pitch angle change and results in higher power at lower wind speeds and delays blade stall to a higher wind speed. The effect of this mass reduction can be clearly seen when comparing RF measured and manufacturer predicted blade pitch vs rotor speed (Figure 6).

The rpm vs wind speed curve (Figure 7) would seem to indicate that the rotor did not attain synchronous speed until winds reached 8 m/s, although Figures 4 and 5 show power being generated at 4 m/s. This is due to the fact that Figure 7 represents an rpm average as a result of using the "Method-of-Bins" analysis in which all data for a given wind speed are binned, then averaged (e.g., zero rpm values are binned with normal range values collected under operating conditions). Figure 7 also serves, along with Figure 8 (blade pitch vs wind speed), to verify the UTRC CBR concept. As can be seen in these two figures, rpm and blade pitch are relatively constant at wind speeds above 8 m/s, indicating that the pitch schedule was maintained in the manner predicted.

Figures 9 and 10 show system power coefficient (C_p) and tip speed ratio vs wind speed, respectively. The "dip" at approximately 7 m/s in Figure 10 is the result of superimposing several curves to create average values. The reason for the two different peak tip speed ratios has not yet been conclusively defined.

Figure 11 represents a RF measured system power coefficient (C_p) vs tip speed ratio and shows the UTRC attained a peak C_p of 0.27 at a tip speed ratio of 8.5. The tip speed ratio value closely agrees with the manufacturer's predicted ratio (8.0 to 8.5). Also shown is the manufacturer's predicted rotor power coefficient with a peak value of 0.41. If both coefficients are assumed to be correct, this infers a combined generator/gearbox efficiency of approximately 66% at the power level associated with peak rotor C_p . Although dynamometer tests were not conducted on the UTRC, previous RF dynamometer test experience with three-phase systems has shown a typical generator/gearbox efficiency of 80-85% at rated output. However, the peak C_p is associated with a power level less than half of rated power. Consequently, it is reasonable to expect a generator/gearbox efficiency well below the rated value. Actual dynamometer tests are required to determine the partial power generator/gearbox efficiency so that measured system C_p can be accurately correlated with predicted rotor C_p .

Figure 4 - Adjusted Power vs Wind Speed

Figure 5 - Unadjusted Power vs Wind Speed

Figure 6 - Blade Pitch vs RPM

Figure 7 - RPM vs Wind Speed

Figure 8 - Blade Pitch vs Wind Speed

Figure 9 - System Power Coefficient vs Wind Speed

Figure 10 - Tip Speed Ratio vs Wind Speed

Figure 11 - Power Coefficient vs Tip Speed Ratio

TABLE II
MEASURED CHARACTERISTICS OF THE UTRC 8 kW PROTOTYPE
(Adjusted to Sea Level)

Cut-In Wind Speed.....	3.5 m/s (7.8 mph)
Cut-Out Wind Speed.....	None
Survived Wind Speed.....	31 m/s (69.3 mph)
Output @ 9 m/s (20 mph).....	8.3 kW

TABLE III
ESTIMATED ANNUAL ENERGY PRODUCTION
(Using a Rayleigh Wind Distribution)

Average Wind Velocity		Annual Energy Output
(m/s)	(mph)	(kWh)
3.58	8	7,300
4.47	10	15,800
5.36	12	26,400
6.26	14	32,800
7.15	16	49,000

NOTE: The annual energy output is based on the adjusted Rocky Flats power curve for the UTRC 8 kW. The power curve is superimposed on the Rayleigh Wind Distribution (velocity duration curve) generating a power duration curve which is then integrated over time to obtain energy. Data contained in Table III are adjusted to sea level.

Figure 12
Annual Energy Output - RF Adjusted vs Predicted

Atmospheric Testing (Qualitative)

While undergoing testing at Rocky Flats, the UTRC prototype was exposed to wind speeds of 30.8 m/s (69 mph) without incurring a machine failure. In fact, a minor operational problem with the speed detector was the only machine deficiency encountered. The speed detector, by measuring generator rpm, connects the generator to the utility grid when the preset cut-in rpm is reached. If during light winds the generator drops below synchronous speed, a dropout time delay is activated to allow disconnection from the utility if synchronous speed is not reattained. If synchronous speed is reached, the delay is reset and normal operation continues.

RF investigation of the speed detector revealed that several factors were causing the contactor to operate erratically in light winds. It was determined that a high (1900 rpm) cut-in speed, failure of reset

circuitry to allow a dropout time delay during initial startup, and a low dropout time delay (1.5 sec.) were the major causes of the speed detector problems. In addition, these problems were compounded by temperature sensitivity of the analog components. In order to achieve necessary consistency, temperature sensitive components were replaced with equivalent parts of a more stable design, a circuit was added which reset the dropout time delay when cut-in was achieved, and the dropout time delay was increased to 4 seconds. Following these modifications, much of the speed detector's erratic cycling was eliminated. It was, however, recommended to the manufacturer that use of a digital or microprocessor-controlled speed detector and lowering of machine cut-in speed be investigated.

Results of Vibration Testing

Vibration tests (modal analyses) were performed on the following UTRC components or configurations: each individual blade, the flexbeam, each blade when attached to the flexbeam, the machine (without blades) mounted on the tower, and the machine fully installed and operational (accelerometers mounted on tower). The method used for collection of vibration data is described in Appendix A.

Test results showed that vibration modes of all components/configurations tested were within an acceptable frequency range, with the exception of the first (Figure 13) and second (Figure 14) bending modes of the tower during actual machine operation. Excitation of these two modes was visually observed at the top of the tower during rotor startup (first mode - 1.8 Hz) and at the point where tower sections were bolted together (second mode - 9.0 Hz). Table IV shows higher tower frequencies under operating conditions than those found with the blades and pendulum removed. One possible reason for the difference is the existence of thrust loads at the tower top (created by rotating blades) and gyroscopic forces transmitted to the tower.

UTRC representatives were present during the tests and after discussions with RF personnel, it was decided excitation of the first mode was not serious due to occurrence during initial start up when rotor rpm was

low. Excitation of the second mode was observed in two situations: (1) if the machine was unloaded (i.e., a power outage); and (2) when the machine synchronized with the utility grid, thereby creating a "hammer-type" vibration input. However, it was decided that the amplitudes were such that the machine could continue to operate in its original configuration during short-term testing at the WSTC. Second mode excitation did necessitate implementation of a routine schedule of examination for tightness of tower flange bolts, but no loosening was observed during the test period. Second generation UTRC design specifications did include a lower generator cut-in speed and use of a shorter tower to change natural frequencies to minimize dynamic response.

Figure 13
UTRC Autospectrum - Tower Top

Figure 14
UTRC Autospectrum - Middle of Tower

TABLE IV
SUMMARY OF MEASURED UTRC PREDOMINANT MODES OF VIBRATION

<u>Component/Configuration</u>	<u>Predominant Mode</u>
Blade #1 (Cantilevered, w/o flexbeam)	1.4 Hz - First Mode Bending 9.0 Hz - Second Mode Bending 25.0 Hz - Third Mode Bending 46.0 Hz - Fourth Mode Bending 22.0 Hz - First Mode Torsional 68.0 Hz - Second Mode Torsional
Blade #2 (Cantilevered, w/o flexbeam)	1.5 Hz - First Mode Bending 9.4 Hz - Second Mode Bending 25.4 Hz - Third Mode Bending 46.5 Hz - Fourth Mode Bending 23.0 Hz - First Mode Torsional 68.3 Hz - Second Mode Torsional
Flexbeam - Side #1	14.0 Hz - First Mode Bending 85.0 Hz - First Mode Edgewise
Flexbeam - Side #2	13.6 Hz - First Mode Bending 85.0 Hz - First Mode Edgewise
Blade #1 (with flexbeam)	0.7 Hz - First Mode Bending 2.3 Hz - First Mode Edgewise
Blade #2 (with flexbeam)	0.7 Hz - First Mode Bending 2.3 Hz - First Mode Edgewise
System (without blades & pendulum)	1.5 Hz - First Mode Bending 8.8 Hz - Second Mode Bending
System (while operating - accelerometers mounted on tower)	1.8 Hz - First Mode Bending * 9.0 Hz - Second Mode Bending *

* Excited during normal operation

Results of Noise Measurements

During manufacturer checkout of the UTRC at RF, excessive rotor noise was noticed. There are several possible causes for the noise, but it is beyond the scope of this report to address them adequately. To correct the problem, the manufacturer installed serrated aluminum tape on the out-board six feet of the upwind surface of the blade at the 3/4 chord point. This modification significantly reduced the noise level.

Following installation of the tape, noise measurements were taken at two different locations (relative to tower location): (1) at the base of the tower, and (2) at a location 21.94 m (72 feet) across the wind (in the plane of the rotor) from the operating machine. Winds during the tests were from the west and with turbulence typical of near-neutral atmospheric

stability. The ground in this test was dry, flat and covered with small rocks and sparse prairie grasses. A discussion of instrumentation and techniques used during these tests is contained in Appendix B.

Figure 15 shows a number of familiar noise levels to allow subjective comparison with test results. These levels are expressed in terms of decibels (dB), a logarithmic scale (a 10 dB increase is perceived as a doubling of noise level). The human ear does not respond equally to sound at all frequencies. Therefore, sound level meters are used which are capable of filtering the noise measured to simulate human response. Noise levels measured in this manner are expressed on an A-weighted scale denoted as dBA. Thus the sound pressure levels reflected in test results contained herein, being A-weighted, closely match levels that would be heard by humans.

Figures 16 and 17 show the UTRC sound pressure level as a function of hub-height wind speed. Figure 16 indicates that at the base of the UTRC tower the noise level varied from 52 to 61 dBA, and the average (or equivalent) noise level was 58 dBA. At a distance of 72 ft from the tower the noise level ranged between 49 and 52 dBA (Figure 17), with an overall average noise level of 50 dBA. The noise levels at higher wind speeds (> 8 m/s) are only slightly greater than the background wind noise even in open, smooth terrain. Noise levels presented in Figures 16 and 17 are free of discrete tones but do contain harmonics of a two-per-rotor-revolution blade impulse sound. An in-depth discussion of SWECS noise measurements can be found in Reference 4.

Figure 15
Familiar Noise Levels

Figure 16

Sound Pressure Level of the UTRC 8 kW (Base of Tower)

Figure 17

Sound Pressure Level of the UTRC 8 kW (72 ft. Distance Across-Wind)

Conclusions/Recommendations

The UTRC met the design specification for power production, survived wind speeds of 30.8 m/s (69 mph), and had an on-line availability of 99% during the test period. The machine actually produced a higher than predicted maximum output due to a mass reduction in the pendulum control system prior to RF testing. The only operational problem found was with the generator speed detector, and use of a digital or microprocessor-controlled detector is recommended for future machines.

Vibration test results showed that the first and second bending modes of the tower were excited during actual operation. Excitation of the first mode was not considered serious since it was observed at rotor speeds well below synchronous speed; and although excitation of the second mode did cause some concern, it was not considered serious enough to modify the existing tower configuration. Routine inspection of the tower flange bolts, which was the only precaution taken, failed to disclose any loosening of the bolts during the test period.

Noise measurements indicated the UTRC sound pressure levels were within an acceptable range. A major contributor to this fact was the manufacturer's installation of a serrated tape over the smooth, handcrafted blades at the 3/4-blade chord point. This modification significantly reduced the noise levels. Future production blades will have a rougher finish and should produce lower noise levels without the use of tape.

It is recommended that a production version of the UTRC 8 kW be tested at the WSTC. Such testing would verify the value of design changes made to the machine and its tower configuration. One major design change made to the production version is replacement of the three-phase generator with a single-phase generator. This will allow easier interconnection with utilities in rural or remote market areas.

9.0 RESPONSIBLE PERSONNEL

The following individuals were associated with the UTRC test program and functioned in the capacities listed below:

<u>Name</u>	<u>Company</u>	<u>Function</u>
M. C. Cheney	United Technologies Research Ctr.	Advisor to RF
B. Goepner	United Technologies Research Ctr.	Advisor to RF
T. Murrin	United Technologies Research Ctr.	Advisor to RF
I. B. Allen	Rockwell International Corp.	Site Engineer
J. F. Boland	Rockwell International Corp.	Program Monitor
K. K. Higashi	Rockwell International Corp.	Test Engineer
G. B. Buckley	Rockwell International Corp.	Electrical Engineer
D. A. Chamberlain	Rockwell International Corp.	Data Engineer

10.0 REFERENCES

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4. "Measurement and Assessment of the Noise Produced by Small Wind Energy Systems," A. C. Hansen, Rocky Flats Wind Systems Program, Proceedings of the Fifth Biennial Conference on Wind Energy Systems, October 1981. SERI/CP-635-1340. (Available from NTIS.)

APPENDIX A
VIBRATION TESTING METHOD - UTRC 8 kW

The type of structural dynamics testing applied to the UTRC 8 kW is referred to as modal analysis. Basically, modal analysis is the process of characterizing the dynamic properties of an elastic structure by identifying its modes of vibration.

The technique used for vibration testing of the UTRC is commonly known as impact testing. The structure being tested is excited with a hammer that has a load cell attached to it. This allows a series of input forces and associated responses (output) to be measured by an accelerometer and accurately recorded and stored by a digital analyzer. Once a set of frequency responses relating to points of structural interest have been measured and recorded, the digital signal analyzer calculates and plots natural frequencies, damping factors and characteristic mode shapes for predominant modes of vibration. The results are then compared with predicted resonance frequencies in order to identify potential vibration problems.

Table V lists instrumentation used during vibration testing at Rocky Flats, and Figure 18 is a conceptual schematic of the vibration testing system.

TABLE V
INSTRUMENTATION - VIBRATION TESTING

<u>Instrument</u>	<u>Manufacturer</u>	<u>Model No.</u>
Load Cell	PCB Piezotronics, Inc.	086B20/20BA03
Charge Amplifier	PCB Piezotronics, Inc.	482A10
Accelerometer	Endevco, Dynamic Instr. Div.	2262C-25
Signal Conditioning	Cyber Systems, Inc.	9320
Calculator	Hewlett-Packard Company	9825A
Plotter	Hewlett-Packard Company	9872A
Digital Analyzer	Hewlett-Packard Company	5420A
Digital Oscilloscope	Nicolet Scientific Corp.	201

Figure 18
Conceptual Schematic of Vibration Test System

APPENDIX B
NOISE MEASUREMENT METHOD - UTRC 8 kW

Both SWECS and background noise levels are highly dependent upon wind speed. Thus it was necessary to devise a method for determining the average noise level at several different wind speeds. The "Method-of-Bins" is an acceptable method for determining average values of a dependent variable for an arbitrary number of discrete independent variable intervals (or bins). DC voltages proportional to dBA and wind speed were played from the FM recorder into a Hewlett-Packard A/D converter and computer system. The computer sampled each channel approximately twice per second and performed the "Method-of-Bins" analysis. In addition to the average sound pressure level at each wind speed, the minimum and maximum pressure levels were determined and the average level for the entire test was calculated by the digital computer system. This latter value provided a calibration check on the entire recording, playback, and analysis operation by comparing the sound level meter average pressure level with the computed average. The two values always agreed within ± 1 dBA and typically showed a difference less than ± 0.6 dBA.

Sound measurement and recording instruments used in the UTRC tests are all portable, battery-operated units which meet or exceed all applicable ISO and ANSI standards for accuracy. A Bruel and Kjaer (B&K) Model 2218 Precision Integrating Sound Level Meter was used. The meter contains an integrating microprocessor for continuous calculation of average dB level. In addition to analog and digital readouts of noise level, ac and dc output voltages are available for recording and analysis. The meter was always used with the "fast" time constant. A B&K Model 4165, 1/2-inch, free-field condenser microphone was attached to the meter with a 30 m shielded cable. The microphone has a frequency response of 3 Hz to 20 kHz (± 2 dB). Both "A" and linear filtering networks are available in the meter.

The sound level meter was calibrated using a B&K Model 4220 Pistonphone calibrator. Calibration was performed for each measurement series even though no drift in calibration was ever observed.

A B&K Model 7003 FM analog tape recorder was used to record all noise data for later detailed analysis. The recorder is a four-channel unit with frequency response from dc to 10 kHz (± 1 dB). Simultaneous recordings were made of wind speed, direct noise, dc voltage proportional to sound pressure level, and a voice track for test identification.