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SUMMARY RESULTS OF THE DOE FLYWHEEL DEVELOPMENT EFFORT

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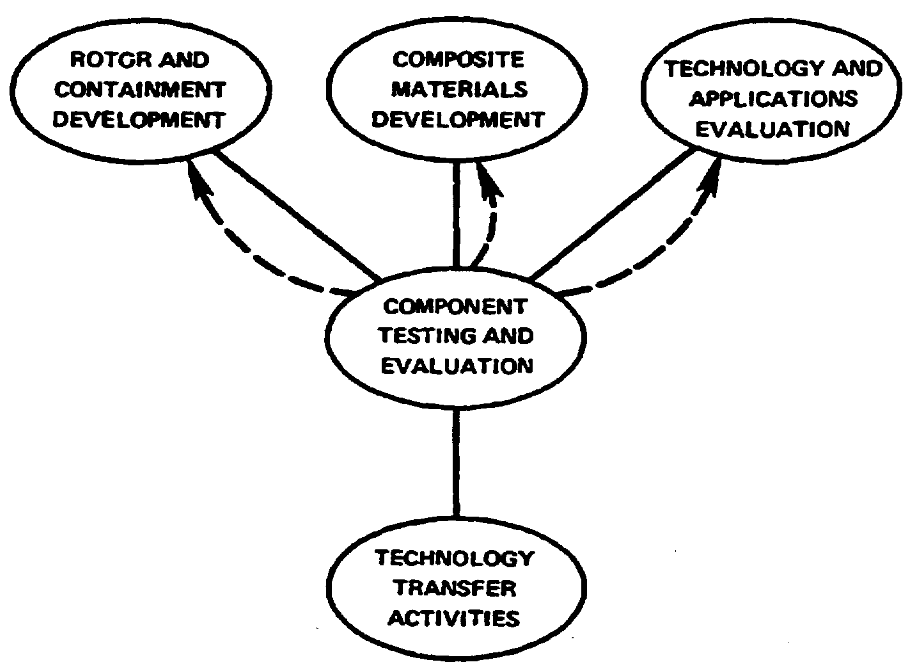
The technology and applications evaluation task focuses on defining performance and cost requirements for flywheels in the various areas of application. To date the DOE program has focused on automotive applications. The composite materials effort entails the testing of new commercial composites to determine their engineering properties. The rotor and containment development work uses data from these program elements to design and fabricate flywheels. The flywheels are then tested at the Oak Ridge Flywheel Evaluation Laboratory and their performance is evaluated to indicate possible areas for improvement. Once a rotor has been fully developed it is transferred to the private sector.

THE FIVE COMPONENTS OF FLYWHEEL DEVELOPMENT EFFORT ARE INTERACTIVE



The Oak Ridge National Laboratory is the lead center for the DOE flywheel effort. This includes program management functions as well as technical development in the area of testing. Fabricated rotors are supplied by the private sector. This is done to ease technology transfer once developmental activities have been completed.

THE MEST PROGRAM HAS INVOLVED PUBLIC AND PRIVATE SECTOR PARTICIPATION

- ORNL
  - MANAGES AND DIRECTS PROGRAM
  - TESTING OF FLYWHEELS IN OAK RIDGE FLYWHEEL EVALUATION LABORATORY (ORFEL)
  - DEVELOPMENT OF ADVANCED TESTING TECHNIQUES TO OBTAIN MORE COMPLETE DATA FROM TESTS
  - DEVELOPMENT OF NONDESTRUCTIVE INSPECTION TO PREDICT INCIPIENT FAILURE
- LLNL
  - ROTOR TEST DATA ANALYSIS EFFORTS
  - ENGINEERING DATA FOR NEW COMPOSITES
- PRIVATE SECTOR PARTICIPANTS SUPPLIED ROTORS
  - GENERAL ELECTRIC
  - GARRETT AIRESEARCH
  - AVCO
  - BROBECK
  - OWENS CORNING/LORD KINEMATICS

Three rotors were chosen for second generation testing activities. The disk/ring design uses an SMC α-ply layup disk with a wound graphite/epoxy ring. The subcircular rim wheel is composed of a 9 or 15 ring rim using a Kevlar/epoxy material with a graphite spoke system. The bidirectional weave wheel uses a fabric of Kevlar fibers in a helically wound configuration. After layup, the fabric is impregnated with resin.

ROTOR AND CONTAINMENT DEVELOPMENT ACTIVITIES INCLUDE

- DESIGN SPECIFICATIONS FOR ROTORS
  - PRESENT ROTOR DESIGNS SELECTED FOR EVALUATION INCLUDE
    HYBRID DISK/RING
    SUBCIRCULAR RIM
    BIDIRECTIONAL WEAVE
- DESIGN DATA FOR ROTOR/HUB ELASTOMERIC BOND
- COST ANALYSIS

The MEST Program was focused on automotive applications. Consistent with this application, flywheel development centered on rotors with a total stored energy of ≤ 1 kWh with values near 0.25 kWh being quite adequate for the application. Size constraints imposed by the automobile required a maximum diameter of about 0.6 m. The test facility was capable of supplying a maximum input power level of 3 kw to accelerate the flywheel.

PERFORMANCE PARAMETERS WERE SPECIFIED BY VARIOUS ASPECTS OF THE PROGRAM

- AUTOMOTIVE APPLICATION EMPHASIS
  - TOTAL STORED ENERGY ≤ 1 kWh
  - ROTOR SIZE OF ABOUT 0.6 m (2 ft)
- TESTING PROGRAM
  - INPUT POWER 3 kW MAXIMUM
- ENERGY DENSITY AT ULTIMATE SPEED OF 88 Wh/kg

The first generation wheels concentrated on rim and disk type designs. A variety of composite materials were used and the performance of the wheels varied greatly. This initial phase of testing concentrated on obtaining energy density data at the maximum wheel speed. The maximum speed is defined as that speed where a limiting failure mechanism is first observed. This includes material failures (e.g., cracks or fragments slung off the wheel), unacceptable imbalance, or radial runout in excess of 20 mils. The highest energy density obtained was 79.5 Wh/kg using a rim design.

FIRST GENERATION ROTORS SHOWED A WIDE VARIATION IN PERFORMANCE

MANUFACTURER	WHEEL TYPE	MATERIAL	ENERGY DENSITY AT MAXIMUM SPEED (Wh/kg)	ENERGY STORED (kWh)
ORNL	OVERWRAP	K49	49.3	0.56
BROBECK	RIM	SG/K49	63.7	0.71
GARRETT/ AIRESEARCH	RIM	K49/K29/SG	79.5	1.23
ROCKETDYNE	OVERWRAP RIM	G	39.6	2.13
APL–METGLASS	RIM	M	24.4	0.04
HERCULES	DISK (CONTOURED PIERCED)	G	37.4	0.85
AVCO	DISK (PIERCED)	SG	44.0	0.40
LLNL	DISK (TAPERED)	G	62.6	0.31
LLNL	DISK (FLAT)	SG	67.1	0.16
GE	DISK (SOLID)	SG/G	55.1	0.28
OWENS/LORD	DISK	SMG/G	27.8	0.36
		SMC/G	36.6	0.40
		SMC/G	25.0	0.28
		SMC	17.5	0.17

SG = S GLASS; K49 = KEVLAR 49; K29 = KEVLAR 29; G = GRAPHITE; M = METGLASS; SMC = S–GLASS SHEET MOLDING COMPOUND

During FY 1983 the advanced design wheels were tested. The disk and disk/ring designs successfully completed 10,000 cycle fatigue tests. Subsequent ultimate speed tests indicated energy densities higher than that achieved by similar wheels that had not been fatigued. The sub-circular rim design wheel did not successfully complete the cyclic fatigue test, failing at 2585 cycles. In addition, energy storage densities at ultimate speed were 26% below design specifications. The bidirectional weave design showed a very low energy storage density. This very low value may be attributable to poor resin impregnation during fabrication.

ADVANCED ROTORS HAVE UNDERGONE CYCLIC FATIGUE AND ULTIMATE SPEED TESTS

	FLYWHEEL DESIGN			
	DISK	DISK/RIM	SUBCIRCULAR RIM	BIDIRECTIONAL WEAVE
MATERIAL	SMC	SMC/G	K49	K49
COMPLETED 10,000 CYCLE TEST	YES	YES	NO[1]	
ULTIMATE ENERGY DENSITY (Wh/kg)	48.6[2]	63.5[2]	65.7	37.3
TOTAL STORED ENERGY (Wh)	517	644	622	416
SPEED AT FAILURE (rpm)	40,638	47,058	30,012	27,575

[1] ROTOR FAILED AT 2586 CYCLES

[2] ROTOR HAD PREVIOUSLY COMPLETED CYCLIC TEST

With cost constraints loosened (as opposed to automotive applications), a 2% strain graphite fiber becomes a very attractive candidate for space flywheel systems. Its ultimate tensile strength of 700 ksi or greater would make possible much higher energy densities. Use of this fiber with a flexible resin would permit the fabrication and operation of a thick rim design having an ID/OD ratio of 0.5 or less. This design could yield energy storage densities of 150 Wh/kg or greater.

ADVANCED FIBERS COULD SIGNIFICANTLY INCREASE STORAGE DENSITIES

- THE 2% STRAIN GRAPHITE FIBER DEVELOPED BY HERCULES PROMISES TO GIVE A 700 ksi ULTIMATE TENSILE STRENGTH
- IT HAS NOT BEEN INVESTIGATED FOR TERRESTRIAL APPLICATIONS BECAUSE AT $30/lb IT IS TOO COSTLY
- FOR SPACE APPLICATIONS, WHERE WEIGHT OR VOLUME IS A PREMIUM, THE MATERIAL–RELATED STORAGE COST IS NOT UNREASONABLE
- WE ESTIMATE THAT THE USE OF THE 2% STRAIN GRAPHITE IN A THICK RIM DESIGN COULD RESULT IN AN ENERGY DENSITY OF 150 Wh/kg AT ULTIMATE SPEED

Spin testing of flywheels is a very important component of the DOE program. The testing program is designed to confirm failure modes of the flywheel as well as determine how a material performs in a specific design.

SPIN TESTING IS A CRITICAL COMPONENT OF FLYWHEEL DEVELOPMENT

- CONFIRM MATERIAL PERFORMANCE AS USED IN A SPECIFIC DESIGN
- CONFIRM FAILURE MODE
- GENERATE DATA CONCERNING EFFECTS OF CYCLING ON WHEEL
  - FATIGUE
  - RELAXATION
- LOOK FOR CRITICAL RESONANCES IN DESIGN

The Oak Ridge Flywheel Evaluation Laboratory represents the state of the art for spin testing flywheels. High speed balancing before the test insures that material limits will be reached during the test. Radial runouts of the arbor, hub, and wheel are monitored continuously during the test and can be used to indicate if something is going wrong with the flywheel during the test. Other parameters measured during the test include flywheel temperature, axial runout, and vacuum.

THE ORFEL FACILITY OFFERS UNIQUE INSTRUMENTATION AND DATA ANALYSIS CAPABILITIES NOT AVAILABLE IN OTHER FACILITIES

- BEFORE TEST ACTIVITIES INCLUDE
  - HIGH SPEED (UP TO 30,000 rpm) BALANCING
  - COMPUTATION OF WHIRL FREQUENCIES
  - DETERMINATION OF FORCE RESONANCE FREQUENCY
- DURING THE TEST THE FOLLOWING PARAMETERS ARE MONITORED
  - FLYWHEEL TEMPERATURE VIA PYROMETRY
  - RADIAL RUNOUT OF ARBOR, HUB AND WHEEL
  - AXIAL RUNOUT TO DETERMINE TILT OF WHEEL
  - VACUUM
- CRITICAL PARAMETERS SUCH AS WHIRL AND FORCED RESONANCE ARE ALSO ANALYZED DURING THE TEST USING AN ON-LINE COMPUTER AND FREQUENCY SPECTRUM ANALYZER

It would be useful if a technique was available to predict incipient failure of the flywheel while in service. To this end ORNL has begun investigations concerning non-contact strain measurement and nondestructive inspection. These techniques show promise but have not been developed to the point where they are a useful diagnostic tool.

PRELIMINARY INVESTIGATIONS HAVE BEEN MADE FOR OTHER MEASUREMENT TECHNIQUES

- NON–CONTACT STRAIN MEASUREMENT
  - USES CHANGE IN DIFFRACTION ANGLE OF A LASER–ILLUMINATED DIFFRACTION GRATING, BONDED TO FLYWHEEL AS INDICATOR OF STRAIN
  - COMMERCIAL GRATINGS (14,000 LINE/INCH) YIELDED RESOLUTIONS NOT ADEQUATE FOR THE LOW STRAIN (~ 0.7%) MATERIALS USED
  - RESOLUTION MAY BE ADEQUATE FOR 2% STRAIN MATERIAL
- NDI
  - ULTRASONIC DETECTION OF MICROCRACKING IN THE MATRIX
  - PRELIMINARY RESULTS SHOWED FREQUENCY ATTENUATION INCREASES MONOTONICALLY WITH STRAIN HISTORY
  - NOT YET ABLE TO USE TECHNIQUE TO PREDICT INCIPIENT FAILURE