ROTATING ASSEMBLY WORKING GROUP SUMMARY

Dr. Satish V. Kulkarni, Lawrence Livermore National Laboratory

Chairman

INTRODUCTION

The output of this working group is represented by this summary report. It follows a format similar to that previously employed in Department of Energy (DOE) programs and shall address the following items (Figure 1):

1. Task goals
2. Rationale
3. Strategy
4. Key pacing issues

The goals associated with the central task need to be identified to provide the necessary focus for the program. The rationale for the program and the strategy for accomplishing the work need to be defined. During the course of the effort several key issues will have to be addressed to insure development success.

The table (Table 1) at the end of this summary identifies the 17 persons who made up this panel and developed these recommendations.

CONCLUSIONS AND RECOMMENDATIONS

The panel addressed the issues associated with such areas as rotor design and dynamics, rotor materials and fabrication, safety, nondestructive testing, and system operational loads and environment. Recommendations arising from the working group deliberations are presented in the following material.

1. Task Goals

The primary objective of this development effort should be (Figure 2) to demonstrate the feasibility of a fail-safe flywheel system comprised of units having a useful energy capacity of 5 kilowatt-hours per unit. This system concept should be expandable to meet power requirements of 50-200 kilowatts. A system energy density of 20 watt-hours/kilogram or more should be achieved, with an operational life requirement of 5-10 years. A key pacing issue (Figure 3) attendant to this program goal is the question of whether the flywheel system should provide attitude control and energy storage simultaneously, or whether it should accommodate energy storage functions only. It is recommended that a system study be conducted to determine the impact of this role combination and to resolve this issue.

2. Rationale

Recent studies (Figure 4) conducted by Boeing, NASA, and others have shown the concept of flywheel energy storage to be highly competitive with other more conventional system approaches such as batteries. Three of the major advantages of flywheel systems are longer operational life, higher electrical efficiency, and higher system energy density. The use of composite material flywheels is important for realizing these advantages.

3. Strategy

A significant amount of technology is available as a result of programs sponsored by the Department of Energy (DOE), the Department of Transportation (DOT), and the U.S. Army (Figure 5). Every attempt should be made to capitalize on the results of these efforts, especially in the areas of composite materials utilization and flywheel design. Improvements to that data base should be made to optimize the system design and performance capability. In that vein, therefore, a list of published reports on these topics should be generated by personnel at the Lawrence Livermore National Laboratory and at the Oak Ridge National Laboratory, as well as at the other cognizant facilities, and distributed to the participants of this conference.

Having a knowledge of the state of the technology in composite materials, it is then possible to make use of that engineering data base in the definition of candidate rotor designs (Figure 6). One issue which must be pursued at the onset of any flywheel program is to develop an understanding of the time-dependent behavior of composites and, therefore, assess their long-term performance. In parallel with these efforts, there is a need to screen and support the development of new materials for future upgrading of flywheel systems.

In determining a plausible multiyear development program, some critical issues (Figure 7) surfaced. These consisted of questions dealing with matrix and material fiber aspects, as well as engineering design data.

4. Fiber Issues

In keeping with a technology ready date of 1987, consideration should be given to designing with existing fibers, since they are well characterized (Figure 8). Characterization of composite materials is a time- and money-consuming task. Therefore, it is possible to utilize such materials as T-300 or Celion-6000 graphite fibers, or even possibly Kevlar-49 or S2 glass. At the same time, efforts should be initiated to obtain data on higher strength fibers such as AS6, IM6, T-700, T-800, or improved Kevlar.

5. Matrix Issues

Some data are available in the literature which indicate that matrix materials can withstand temperatures of 350°F with, however, operational capability degradation. Thus, an important step (Figure 9) is to define some test effort on these materials to determine what is the acceptable operational temperature range for the desired performance levels. Other materials which warrant investigation are the flexible resins, such as urethanes, because of their advantages when used in multiring flywheels. Again, there exists some concern on the temperature stability of these materials primarily because of the lack of available data. Some promising candidate materials for use in high-speed rotors are the metal matrices, such as boron/aluminum. These materials offer some advantages in terms of long-term durability, balance stability, and performance capability at higher temperatures.

6. Engineering Design Data Issues

Additional information is required on these and other materials because the currently available data base is restricted to a terrestrial environment, as opposed to a space environment, where the operational loads and conditions are drastically different (Figure 10). Other areas of concern in the use of composite materials are the effects of radiation on the material properties. In addition, the poor transverse load-carrying capacity of these materials may severely impact some rotor designs and applications. Solutions to the transverse strength question range from "live with it," to "expend a lot of time and money to get a small delta improvement." If the former approach is selected, it is deemed advisable to determine some design values to compensate for the considerable data scatter which exists in the literature regarding transverse strength.

To improve the understanding of the time-dependent behavior of composites, especially in a cyclic load environment, it is recommended that testing of existing DOE rotors be again undertaken. Steps to effect accelerated testing of these devices should also be evaluated. Data obtained from these test programs will be instrumental in the definition of life prediction methodologies.

7. Flywheel Development Issues

The development of the flywheel (Figure 11) must be initiated by a thorough study to define the requirements associated with this device. An answer to such questions as "should the storage device also incorporate the capability of satisfying the control tasks as well as the power system functions?" and "should the energy storage function be the dominating item in the design of the flywheel?" must be provided. Once these and other questions have been satisfactorily addressed, it is then possible to define candidate flywheel concepts. Such definition must emphasize fail-safe designs but must also examine the need and advisability of containment. In addition, an assessment of scalability of the design must also be conducted. The development of the rotor must be performed in concert with the other elements of the storage system and not as an independent item in order to insure the attainment of the desired performance. To effect a timely system development, a two-phase program should be undertaken. Phase I should initiate 2-3 competitive system programs which would result in prototype storage units for thorough laboratory evaluations. The results of these tests would then be used in a final selection of the "optimum" design. Phase II would then produce a final system design, followed by fabrication and evaluation at the system level, which may include flight testing should test results so indicate the need.

8. Rotor Fabrication Issues

One issue (Figure 12) raised by papers presented in the formal session was that an investigation should be conducted which will lead to improvements in filament wound single- or multiple-ring rotor fabrication. In addition, new concepts for attaching the motor/generator and suspension bearing components to the rotor must be developed. These developments are necessary to permit the attainment of the energy density and operational life postulated for this storage concept.

9. Testing

In terms of testing and evaluation of rotors, two categories were identified (Figure 13). These consisted of nondestructive inspection and evaluation, and spin testing. Nondestructive inspection will be instrumental in minimizing resources expenditures by allowing for the identification of manufacturing flaws in the rotor prior to the costly spin test program. Furthermore, the establishment of appropriate nondestructive inspection techniques (Figure 14) will facilitate the evaluation of the impact of handling damage or service-induced damage accumulation on system performance. One of the critical items which must be identified to make the nondestructive inspection and evaluation program successful is an accept/reject criteria definition.

10. Rotor Dynamics

Rotor failures are frequently preceded by system dynamic instabilities resulting from rotor imbalance. However, not all rotor instabilities lead to failures or are caused by mass imbalances. It is therefore necessary to define methodologies for recognizing the differences and thus improve our understanding of rotor and rotor system dynamics (Figure 15). In the case of the advanced storage systems where magnetic suspensions will be utilized, the impact of the unique characteristics of these suspensions on the rotor systems dynamics must be thoroughly investigated and understood.

11. Spin Testing

To reduce the cost burden on the overall development program (Figure 16), an evaluation of the suitability of existing DOE spin test facilities for conducting the test effort associated with this program is required. Should upgrading of these facilities be necessary, then the extent of these modifications and their attendant costs should be defined. In conducting a credible spin-testing effort for these storage devices, it is recommended that a good representation of the cyclic and environmental load spectrum be incorporated into the test setup, along with improved sensing capability for detecting onset of rotor failure based on changes in rotor balance and/or dynamic characteristics.

Safety issues (Figure 17) associated with this storage concept can be addressed during the design task by producing a non-burst or fail-safe design. Such a design would accommodate large safety margins and/or planned failure mechanisms such as the Rocketdyne mechanical fuse. Definition of the approach to be employed in addressing safety management in space applications must be generated.

12. Other Issues

Other issues which will have a significant impact on the evolution of this system concept (Figure 18) are the loads to which these devices will be subjected. Among these are the launch loads which are being quoted in the vicinity of 100g and the thermal loads posed by operating temperatures in the range of 85°C. It is recommended that some consideration be given to utilizing metallic rotors in the interim period until all the issues raised in the working group deliberations can be resolved.

TABLE 1

ROTATING ASSEMBLY WORKING GROUP

PANEL MEMBERSHIP

NAME	ORGANIZATION
J. A. Kirk	University of Maryland
R. R. Rice	NASA-JSC
F. C. Younger	Brobeck Corporation
J. P. Joyce	NASA-LeRC
B. Wiest	Sperry-Space Systems
P. Burke	Bendix-Guidance Systems
J. Bloomer	Boeing Aerospace Corp.
B. P. Gupta	Lord Corporation
A. J. Hannibal	Lord Corporation
W. W. Anderson	NASA-LaRC
A. A. Robinson	ESA-ESTEC, Netherlands
S. O'Dea	C. S. Draper Laboratory
W. O. Wilkinson	Johns Hopkins U., A.P.L.
A. P. Coppa	G. E.-Space Systems
B. R. Ginsberg	Rockwell Intl., Rocketdyne
S. V. Kulkarni	LLNL
C. Haldeman	MIT Lincoln Laboratories

PRESENTATION OUTLINE

- TASK GOALS
- RATIONALE
- STRATEGY
- KEY PACING ISSUES
  - IDENTIFICATION OF TECHNOLOGY TASKS

Figure 1

TASK GOALS

DEMONSTRATE THE FEASIBILITY OF A FAIL-SAFE FLYWHEEL SYSTEM HAVING A USEFUL ENERGY CAPACITY OF ABOUT 5 kW-hr, A SYSTEM ENERGY DENSITY OF APPROXIMATELY 20 W-hr/kg, AND A LIFETIME OF 5-10 YEARS.

Figure 2

TASK GOALS- KEY PACING ISSUE

SHOULD THE SPACE FLYWHEEL SYSTEM PROVIDE AC/ES OR ES ALONE?

- INVESTIGATE THE IMPACT OF A COMBINED AC/ES FUNCTION ON THE DESIGN OF AN ES FLYWHEEL SYSTEM
- (TRADE-OFF OF A DUAL PURPOSE AC/ES FLYWHEEL SYSTEM VS. SINGLE PURPOSE ES OR AC SYSTEM)

Figure 3

RATIONALE

RECENT ASSESSMENTS (E.G., BOEING, NASA,....) SHOW THAT FLYWHEEL ENERGY STORAGE SYSTEMS IN SPACE OFFER ADVANTAGES OVER COMPETITIVE SYSTEMS SUCH AS BATTERIES, FUEL CELLS,....

- LONGER LIFE
- HIGHER ELECTRICAL EFFICIENCY
- HIGHER SYSTEM ENERGY DENSITY
  - COMPOSITE MATERIAL FLYWHEELS ARE IMPORTANT FOR REALIZING THESE ADVANTAGES

Figure 4

STRATEGY

- UTILIZE EXISTING MATERIALS/FLYWHEEL DESIGN TECHNOLOGY DEVELOPED TO DATE
  (DOE, UMTA, U.S. ARMY, ETC.)
  - MAKE IMPROVEMENTS/MODIFICATIONS AS NECESSARY
- MAKE A LIST OF ALL DOE REPORTS AND SEND TO PARTICIPANTS

Figure 5

OBJECTIVES FOR MATERIALS TASK

- TO USE ESTABLISHED ENGINEERING DATA BASE ON MATERIALS APPLICABLE TO THE CANDIDATE ROTOR DESIGNS
- TO ENHANCE OUR UNDERSTANDING OF THE TIME-DEPENDENT BEHAVIOR OF COMPOSITES AND ASSESS THEIR LONG-TERM PERFORMANCE
- TO SCREEN AND SUPPORT THE DEVELOPMENT OF NEW MATERIALS FOR FUTURE UPGRADING OF FLYWHEELS

Figure 6

CRITICAL ISSUES IN MULTIYEAR PLAN

- MATRIX
- FIBER
- ENGINEERING DESIGN DATA

Figure 7

ISSUES WITH FIBERS

- FOR THE 1987 TECHNOLOGICAL READINESS DEMONSTRATION, CONSIDER EXISTING FIBERS (T-300, CELION-6000, GRAPHITE, KEVLAR-49, S2-GLASS) WHICH ARE WELL CHARACTERIZED
- SIMULTANEOUSLY DEVELOP PRELIMINARY DATA BASE FOR HIGHER STRENGTH FIBERS (AS6, IM6, T-700,T-800 GR, IMPROVED KEVLAR, ETC.)

Figure 8

ISSUES WITH MATRICES

- ESTABLISH OPERATIONAL TEMPERATURE RANGE FOR THE CURRENTLY USED EPOXIES TO OBTAIN DESIRED PERFORMANCE LEVELS
- FLEXIBLE RESINS SHOULD BE INVESTIGATED BECAUSE OF THE ADVANTAGES ASSOCIATED WITH THEIR USE IN FILAMENT WOUND RINGS
  - ASCERTAIN THEIR SAFE OPERATING TEMPERATURES
- INVESTIGATE APPLICABILITY OF METAL MATRIX COMPOSITES (BORON/AL,....)

Figure 9

ENGINEERING DATA DESIGN ISSUES

- DESIGN DATA FOR THE EXISTING COMPOSITE MATERIALS HAVE BEEN GENERATED. HOWEVER, ADDITIONAL DATA ARE REQUIRED FOR THE LOADING AND ENVIRONMENT IN SPACE APPLICATIONS
  - LOAD/THERMAL CYCLING
  - EFFECT OF RADIATION
- WHAT ABOUT POOR TRANSVERSE PROPERTIES OF COMPOSITES?
  - LIVE WITH THEM?
  - DETERMINE DESIGN VALUES TO INCLUDE DATA SCATTER?
- UTILIZE EXISTING DOE ROTORS TO EVALUATE CYCLIC LIFETIMES
  - DATA WILL BE USEFUL FOR SPACE FLYWHEEL DESIGN
- DEVELOP LIFE PREDICTION METHODOLOGY BY ANALYZING MATERIALS AND SPIN TEST DATA

Figure 10

ISSUES FOR FLYWHEEL DEVELOPMENT

- DEFINE DESIGN REQUIREMENTS (AC/ES, ES ONLY .....)
  - ES FUNCTION SHOULD DOMINATE?
- DEFINE CANDIDATE FLYWHEEL CONCEPTS
  - EMPHASIZE FAIL-SAFE DESIGN
  - ASSESS FEASIBILITY OF SCALE-UP
- COMPOSITE ROTOR DEVELOPMENT SHOULD BE PART OF AN OVERALL SYSTEMS PROGRAM AND NOT AN INDEPENDENT ACTIVITY
- INITIATE 2-3 COMPETITIVE SYSTEMS PROGRAMS (PHASE I)
- NO. OF PROTOTYPES IN PHASE I TO BE DETERMINED BY TEST PROGRAM/RESOURCES (PROOF-OF-CONCEPT, CYCLIC TESTS IN SIMULATED CONDITIONS,....)
- IN PHASE II SELECT ONE OR TWO OF THE DESIGNS FOR THE COMPLETE PROTOTYPE SYSTEM WHICH COULD BE FLIGHT TESTED

Figure 11

ROTOR FABRICATION ISSUES

- INVESTIGATE IMPROVEMENTS IN FILAMENT WOUND (SINGLE/MULTIPLE) RING FABRICATION
- INVESTIGATE CONCEPTS FOR ATTACHING M/G AND BEARING COMPONENTS TO FLYWHEEL

Figure 12

TEST AND EVALUATION OF ROTORS

KEY ACTIVITIES

- NONDESTRUCTIVE INSPECTION AND EVALUATION (NDI AND NDE)
- SPIN TESTING

Figure 13

NONDESTRUCTIVE INSPECTION AND EVALUATION ISSUES

- MANUFACTURING DEFECTS, HANDLING DAMAGE, AND SERVICE-INDUCED DAMAGE ACCUMULATION NEED TO BE DETECTED

- APPROPRIATE NDI TECHNIQUES MUST BE IDENTIFIED

- ACCEPT/REJECT CRITERIA SHOULD BE DEVELOPED
  - METHODOLOGY SHOULD BE DEVELOPED FOR PROOF TESTING OF FLYWHEELS

Figure 14

ROTOR AND ROTOR SYSTEMS DYNAMICS ISSUES

- MANY ROTOR FAILURES ARE PRECEDED BY SYSTEM DYNAMIC INSTABILITIES DUE TO IMBALANCE
- OUR UNDERSTANDING OF COMPOSITE ROTOR AND SYSTEMS DYNAMICS IS INADEQUATE
- UNIQUE CHARACTERISTICS OF SUSPENSION SYSTEM SHOULD BE CONSIDERED
- ROTOR DYNAMICS STUDIES TO DATE HAVE BEEN COMPILED AND PRESENTED IN A UNIFIED MANNER

Figure 15

SPIN-TESTING ACTIVITY ISSUES

- UTILIZE EXISTING DOE FACILITIES (APL, Y-12,...) AS FAR AS POSSIBLE
- DEFINE NEEDS FOR UPGRADING THOSE FACILITIES (FOR HIGHER ENERGY CAPACITY ROTORS AND PERTINENT SUSPENSION SYSTEMS)
- THE FAILURE MODE OF ROTORS MUST BE CORRECTLY IDENTIFIED
- EFFECTS OF DIFFERENT SUSPENSION SYSTEMS AND SHIFT IN BALANCE DURING TESTING NEED TO BE INVESTIGATED
- DYNAMIC INSTABILITIES SHOULD BE DETECTED BEFORE THEY PRECIPITATE FAILURE
- SPIN TESTING SHOULD BE PERFORMED IN A SIMULATED REAL LIFE LOAD SPECTRUM AND ENVIRONMENT DURING PHASE I
  - WHAT ARE THE FIXED OPERATING COSTS?

Figure 16

SAFETY ISSUES

- DESIGN ROTOR FOR NON-BURST MODE
  - INITIAL FAILURE SHOULD BE OF A BENIGN NATURE AND DETECTABLE
- HOW DO WE ADDRESS SAFETY MANAGEMENT IN SPACE APPLICATIONS?

Figure 17

OTHER ISSUES

- LAUNCH LOADS (APPROXIMATELY 100g)
- SPACE ENVIRONMENT (APPROXIMATELY 850C)
  - TOO SEVERE
- USE METALLIC ROTORS IN THE INTERIM (PHASE I)
- MATERIAL COST IS A NON-ISSUE

Figure 18