

EA030712

(USNA-EPRD-28

DESIGN DEVELOPMENT OF ADVANCED COMPOSITE FLYWHEELS

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June 1976

Period 1 July 1975-30 June 1976

Unlimited Distribution

Prepared for:
Naval Material Command
Navy Energy & Natural Resources R&D
MAT 032
Washington, D. C. 20360

Energy-Environment Study Group
U. S. Naval Academy
205 Rickover Hall
Annapolis, Maryland 21402

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 14 USNA-EPRD-28	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) DESIGN DEVELOPMENT OF <u>ADVANCED</u> COMPOSITE FLYWHEELS.		5. TYPE OF REPORT & PERIOD COVERED Final rept. 1 July 1975 - 1 June 1976
7. AUTHOR(s) Dr. Robert A. McCoy		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS U. S. Naval Academy Annapolis, Maryland 21402		8. CONTRACT OR GRANT NUMBER(s)
11. CONTROLLING OFFICE NAME AND ADDRESS Navy Energy & Natural Resources R&D MAT 03Z Washington, D. C. 20360		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62765N TF 57.572.001
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Energy-Environment Study Group U.S. Naval Academy, 205 Rickover Hall Annapolis, Maryland 21402		12. REPORT DATE 28 June 1976
		13. NUMBER OF PAGES 21 (12) 230
		15. SECURITY CLASS. (of this report) UNCLASSIFIED
16. DISTRIBUTION STATEMENT (of this Report) DISTRIBUTION STATEMENT A Approved for public release; Distribution Unlimited		18a. DECLASSIFICATION/DOWNGRADING SCHEDULE 16 TF 57-572 17 TF 57-572-041
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Advanced composites Energy storage devices		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report describes a research project to develop a highly efficient flywheel design based upon advanced filamentary composite materials. After analyzing the interrelationships between the specific energy, shape factor, strength-to-weight ratio, configuration, stress distribution, and fiber directions, the optimal flywheel configuration selected was a rounded tapered disk. Also a fabrication technique for this flywheel model was proposed. This technique employs a simple wrapping apparatus by which unidirectional prepreg fiber/epoxy tape is wound so that the fiber directions coincide with		

20. the major stresses within the flywheel when spinning.

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INTRODUCTION

One hundred years ago the U.S. Navy was using flywheel energy to propel its Howell torpedo. Today there are numerous naval applications of flywheels, both as energy storage devices as well as for gyroscopic control, associated with the operation of ships, submarines, submersibles, aircraft, aircraft catapults, rockets, and missiles. Thus, the U. S. Navy like most other technically oriented segments of today's society is keenly interested in the technological advancement in the area of flywheels.

In recent years it has been shown advantageous to make use of the very high specific strength (strength-to-density ratio) of advanced filamentary composite materials in the construction of flywheels with new and highly efficient configurations. The next logical step is the design development of such flywheels leading to the fabrication, testing, and evaluation of promising designs. Accordingly, the technical objectives of this project were the following:

1. Design analysis for advanced composite flywheels.
2. Detailed design for at least one of the most promising rotors of a type not previously built.
3. Develop fabrication techniques for construction of a model of the selected design.
4. Time permitting, construct a model and perform evaluation tests on it.

FLYWHEEL CONFIGURATIONS AND MATERIALS

In optimizing the design of flywheels, the selection of both the flywheel configuration and the materials used in its construction are of vital importance. The relation governing the kinetic energy stored in a spinning body is given in equation (1):

$$E = \frac{1}{2} I \omega^2 \quad (1)$$

where E = kinetic energy

I = polar mass moment of inertia

ω = rotational speed

Specific energy is the kinetic energy stored for unit weight of flywheel and is commonly used as the basis of flywheel optimization. Specific energy is related to the shape factor and strength-to-density ratio by equation (2). This relationship is derived in references 1 and 2.

$$S.E. = \frac{E}{W} = S \times \frac{\sigma}{\rho} \quad \text{when rotated at maximum allowable speed, where S.E. = specific energy.} \quad (2)$$

W = weight of flywheel

S = shape factor

σ = strength of flywheel material

ρ = density of flywheel material

¹Chang, G.C. "A Design Study of Advanced Flywheels for Spacecraft Applications," Memo CL-5-72, COMSAT Laboratories, Communications Satellite Corporation, Clarksburg, MD (1 Mar'72).

²Biggs, F. "Flywheel Energy Systems," Report SAND 74-0113, Theoretical Division, Sandia Laboratories, Albuquerque, NM (Nov 1974).

Thus to optimize the specific energy, the flywheel must have a configuration with the largest shape factor possible and be made of material with the highest strength-to-density ratio possible. Because advanced composites have very high strength-to-density ratios, they are likely candidates for flywheels with relatively high specific energies. Composites containing Kevlar fibers look particularly promising. Kevlar fibers and similar ones under development by DuPont and Monsanto are members of a new generation of high strength aromatic polyamides, descendants of the nylon family. The strength-to-density ratio of Kevlar fiber composites is nearly six times that of high-strength maraging steel.²

Much literature has recently been published surveying the most promising configurations and materials along with their associated parameters (references 1-7). Some examples of disk, rim and bar type configurations and their shape factors are

¹Ibid.

²Ibid.

³Post, R.F. and S.F. Post, "Flywheels," Scientific American, pp. 17-23 (December 1973).

⁴Fullman, R.L., "Energy Storage by Flywheel," General Electric Research & Development Center, Schenectady, N.Y. (1975).

⁵Gilbert, R.R. et al, "Flywheel Feasibility Study and Demonstrations," Report LMSC-D007915, Ground Vehicle Systems, Lockheed Missiles and Space Company, Sunnyvale, CA (30 Apr 1971).

⁶Rabenhorst, "Potential Applications for the Superflywheel," presented at the Intersociety Energy Conversion Engineering Conference, Boston, MA (3-5 Aug 1971).

⁷Rabenhorst, D.W. "Primary Energy Storage and the Superflywheel," Report TG-1081, The Applied Physics Laboratory, Johns Hopkins University, Silver Spring, MD (Sept 1969).

shown in Figures 1 and 2. Depending upon the specific system of which the flywheel will be a part, tradeoffs among the flywheel parameters of specific energy (energy stored per unit of weight), specific volume (energy stored per unit of swept volume), and specific cost (energy stored per unit cost) must often be performed.

The attractive properties of the fiber composites for use in improved flywheels demand new approaches in flywheel design. Unidirectional fiber composites develop maximum strength in the direction in which the fibers are aligned. The strength perpendicular to the aligned directions is essentially only that of the bonding matrix, typically only 1 or 2 percent of the strength of the composite in the aligned direction. To employ fiber composites in the construction of flywheels to full effectiveness, it is imperative that the fibers be aligned according to the stress distribution set up within the flywheel while it is spinning. Stress distributions for several flywheel configurations assuming isotropic material properties are shown in Figures 3-7.

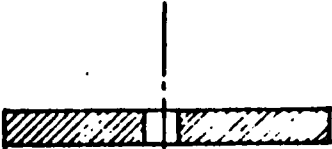
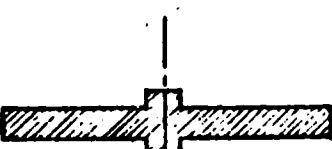
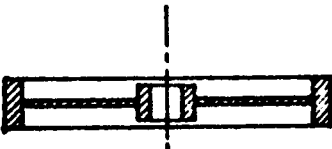
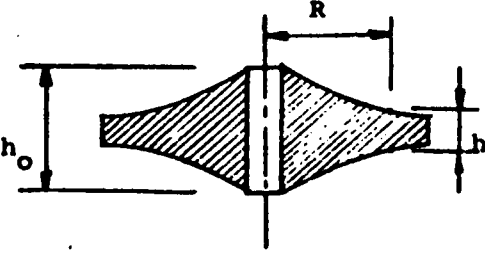
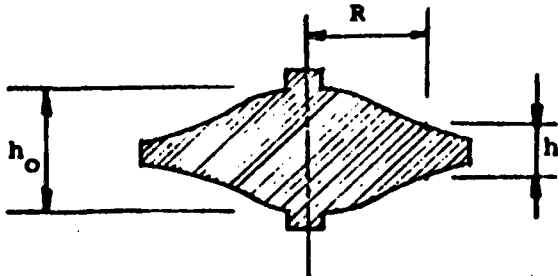
Type	Cross Section	Shape Factor
1. Plane Disk (with center hole)		0.317
2. Plane Disk (without center hole)		0.60
3. Conventional Rim Rotor		0.25 to 0.40
4. Stodola Rotor (hyperbolic disk) $h = h_o R^{-n}$ $n = \text{selected constant}$		0.30 to 0.60
5. Constant-Stress Disk (exponential) $h = h_o e^{-K}$ $K = \omega^2 R^2 / 2\sigma_w$		0.92

Figure 1. Conventional Flywheels¹

¹Ibid

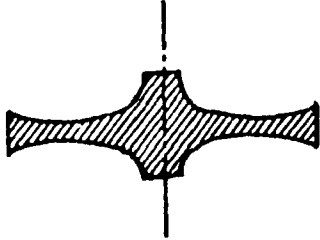
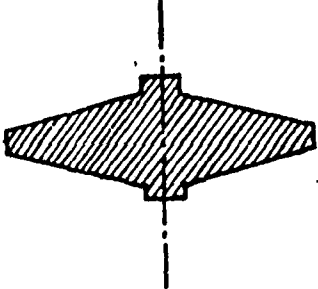
<u>Type</u>	<u>Section or Sketch</u>	<u>Shape Factor</u>
6. Modified Constant-Stress Disk		0.93
7. Truncated Conical Disk		0.80
8. Thin-Rim Rotor		0.50
9. Shaped Bar		0.50
10. Thin Rod		0.33
11. Rod-Mass Rotor		0.33 (max.)

Figure 2. Some Advanced Flywheels ¹

¹Ibid.

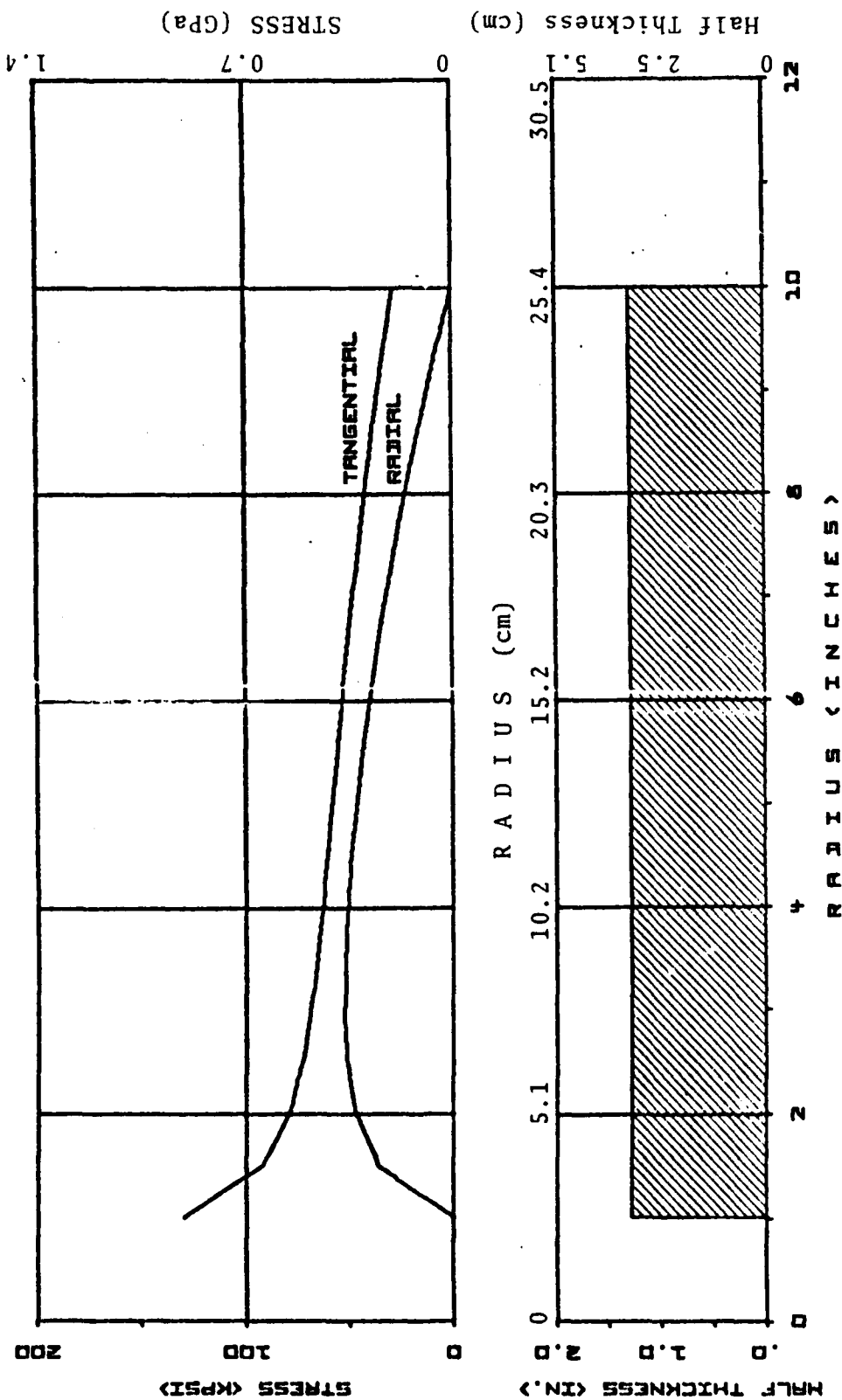


Figure 3. Stress Plots for a Pierced Disc Flywheel⁵

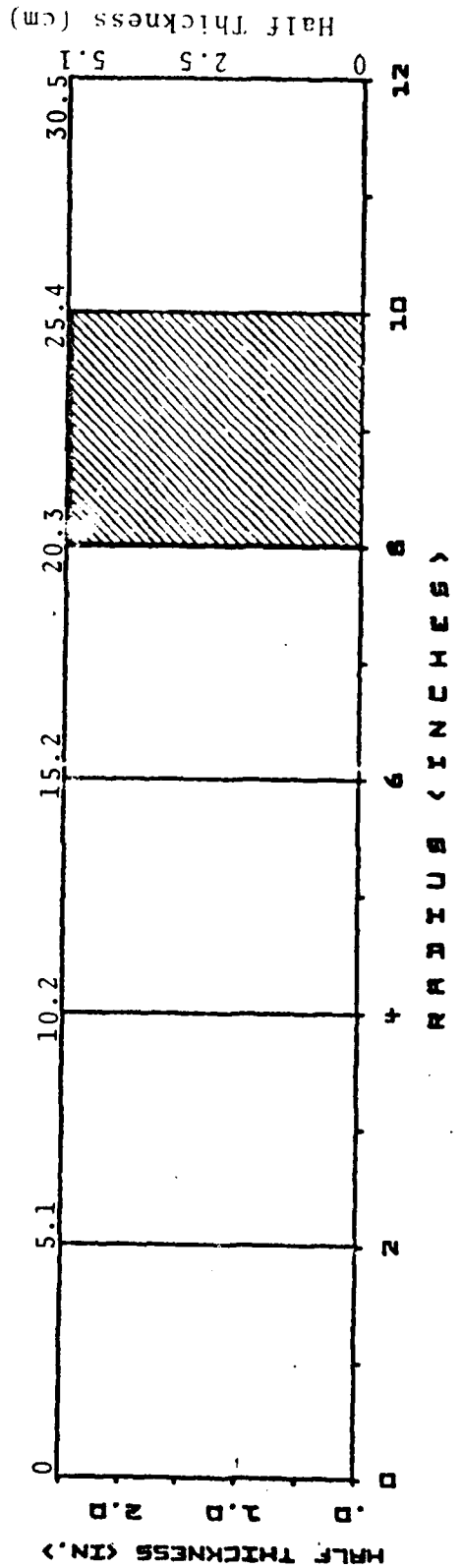
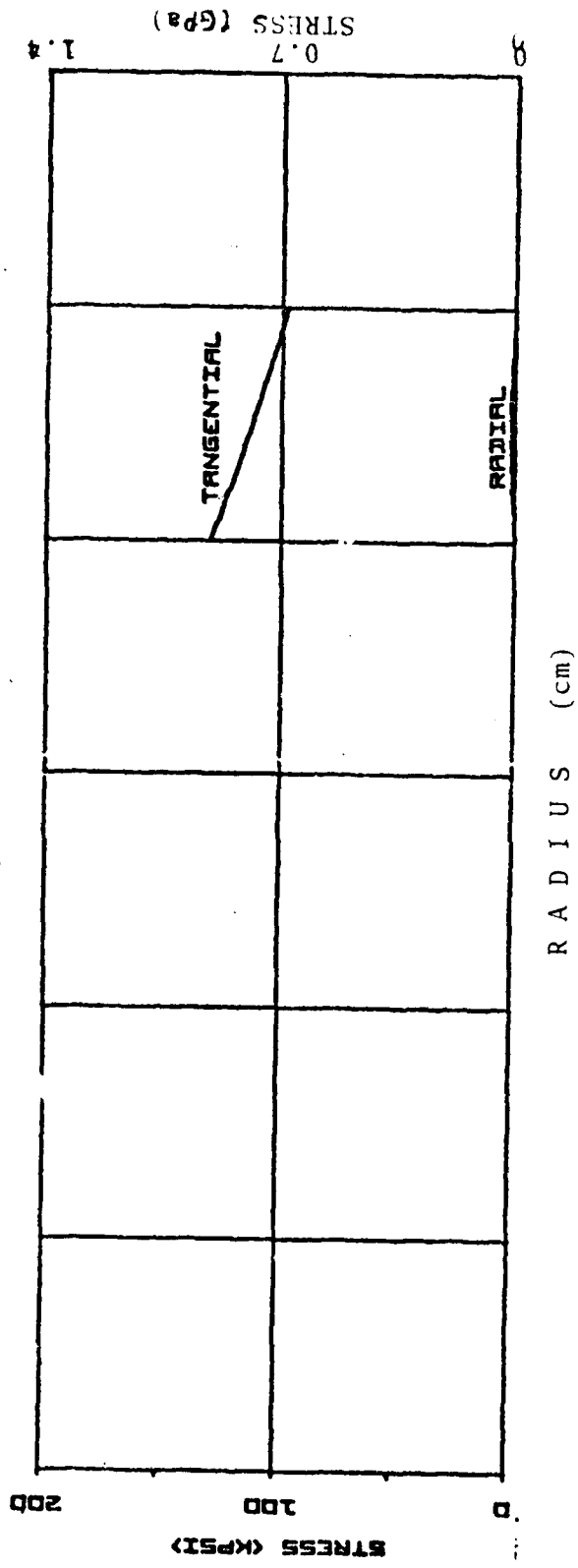


Figure 4. Stress Plots for a Rim Flywheel 5

5 Ibid

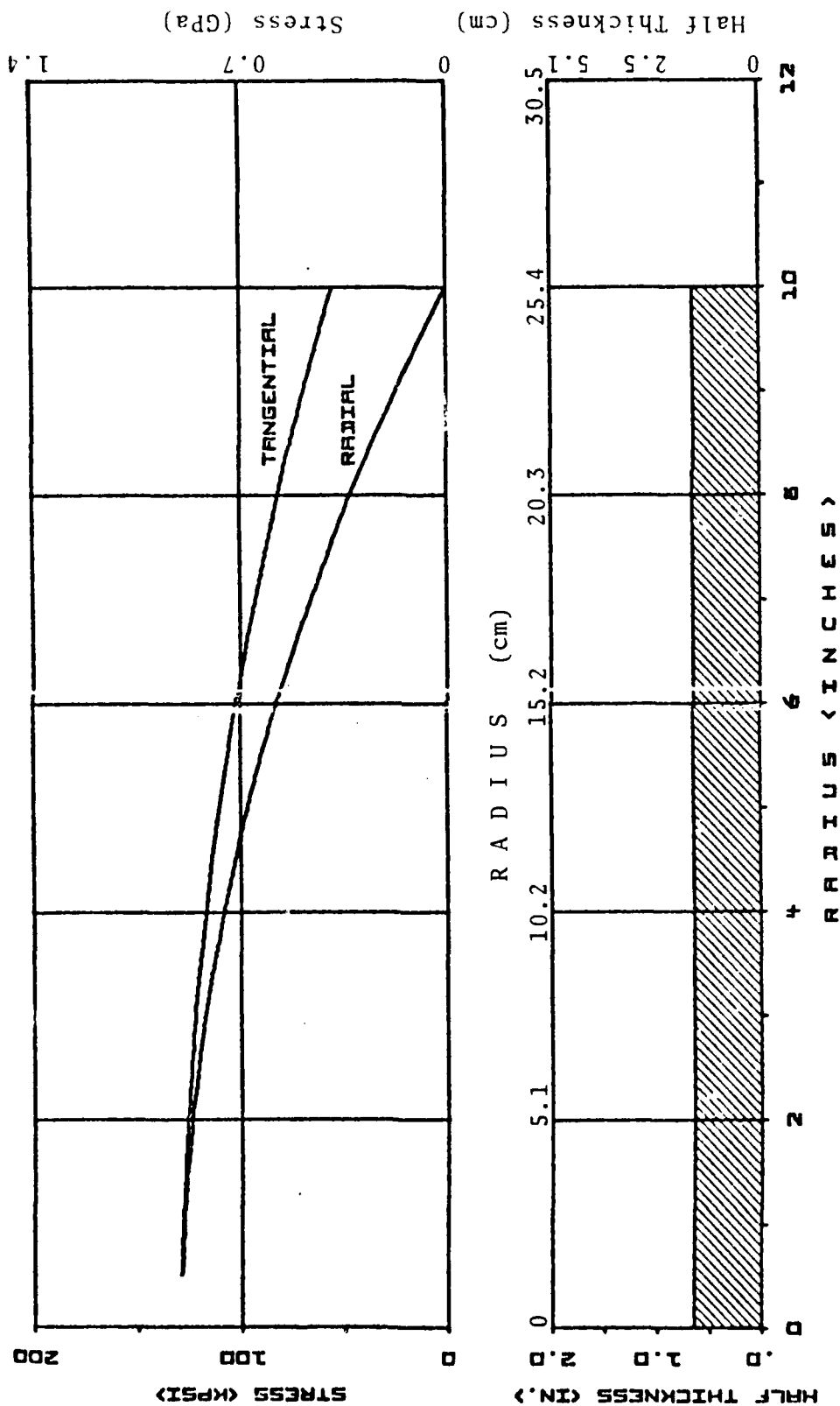


Figure 5. Stress Plots for a Flat Disc Flywheel ⁵

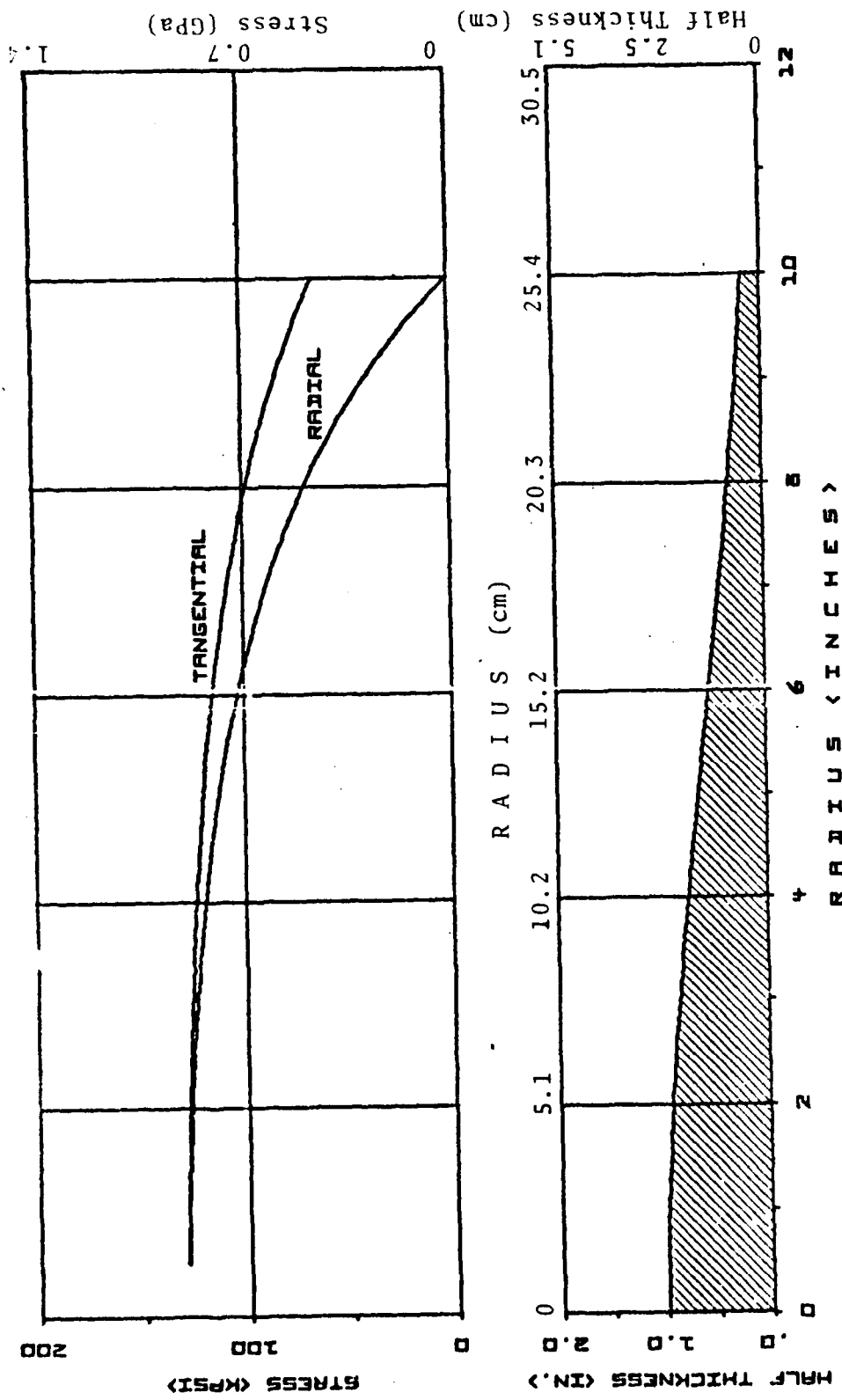


Figure 6. Stress Plots for an Exponential Disc Flywheel⁵

⁵ Ibid

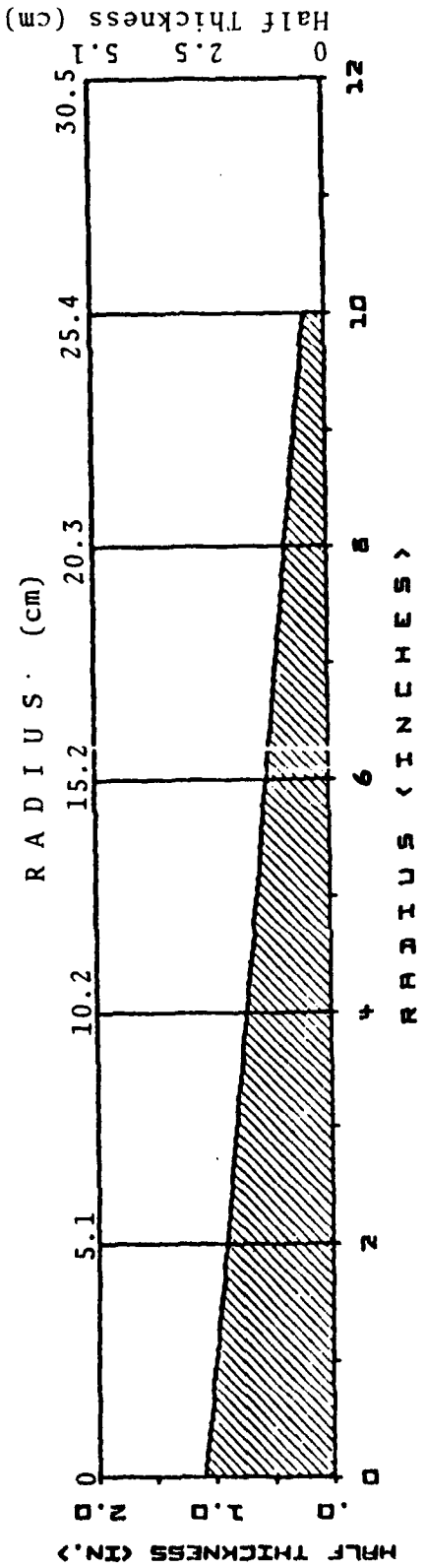
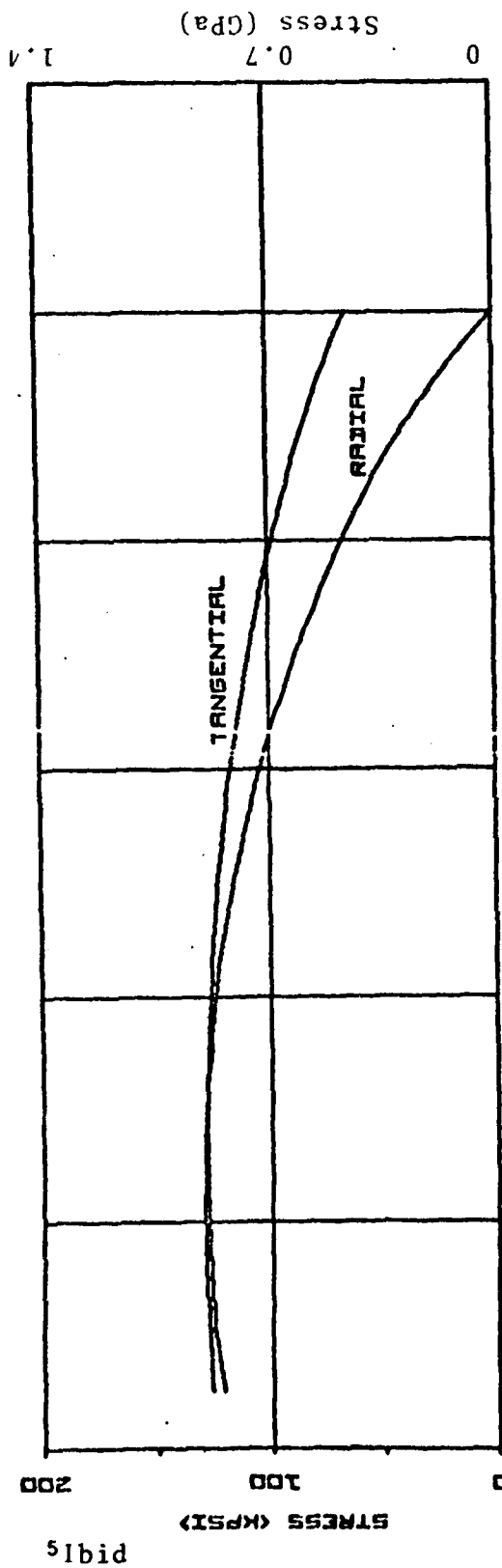


Figure 7. Stress Plots for a Cental Disc Flywheel⁵

FLYWHEEL MODEL DESIGN AND FABRICATION TECHNIQUE

A model design was selected in this project based upon the following considerations:

1. The model would be fabricated from unidirectional fiber/epoxy tape.
2. The configuration would have a relatively large shape factor.
3. The trajectory of the fibers would lie in directions of greatest stresses.
4. The fabrication technique for the model would be relatively easy and not require expensive equipment.

After investigating many different configurations and possible fabrication techniques, a rounded tapered disk configuration was selected, as shown in Figures 8 and 9. This tapered disk configuration is similar to the exponential disk shown at the bottom of Figure 1 but is more rounded and has a hole for the shaft. Its shape factor is about 0.46. It can be constructed by wrapping unidirectional fiber tape around a thin steel plate which has a steel shaft through it. This plate serves two purposes: First, it provides a foundation on which the tape can be wound; second, it provides a hub which is solidly attached to the shaft. Calculations based upon a Kevlar/epoxy composite model of this design show that it would weigh about 11 kg (25 pounds) including the steel disk and it would store up to 3.6 MJ (1 kWh) if rotated at the maximum allowable speed of 30,000 rpm.

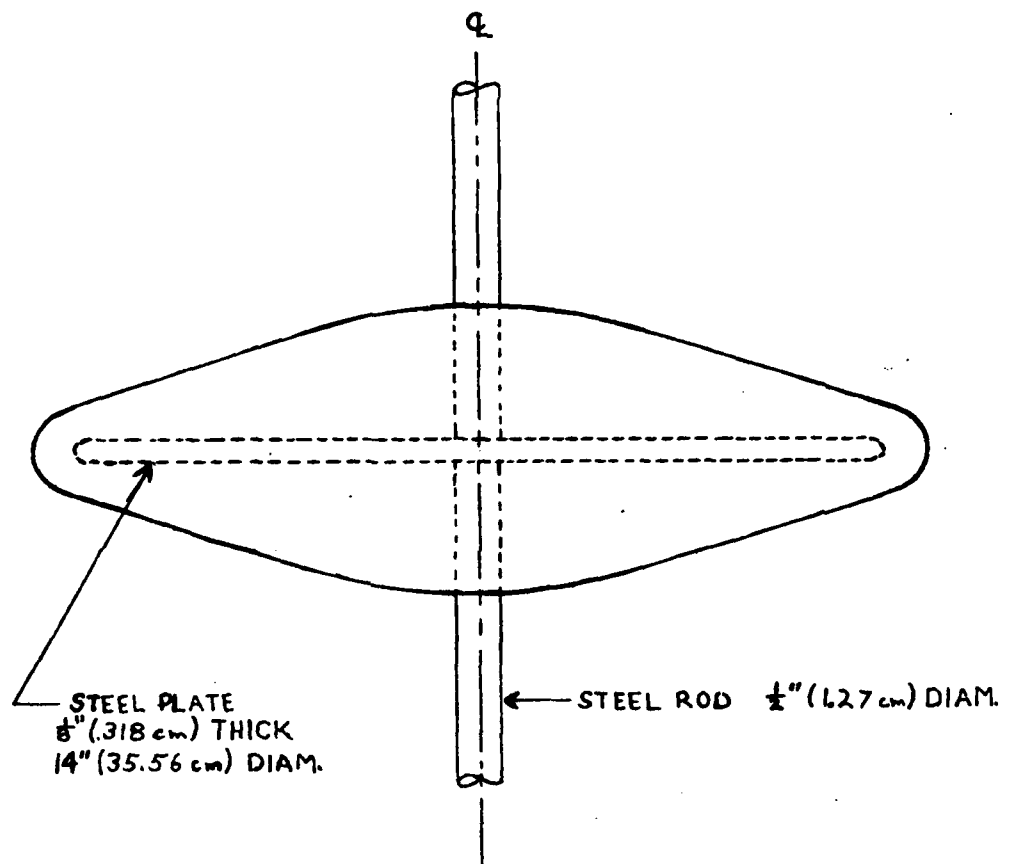


Figure 8. Flywheel Model, edge view

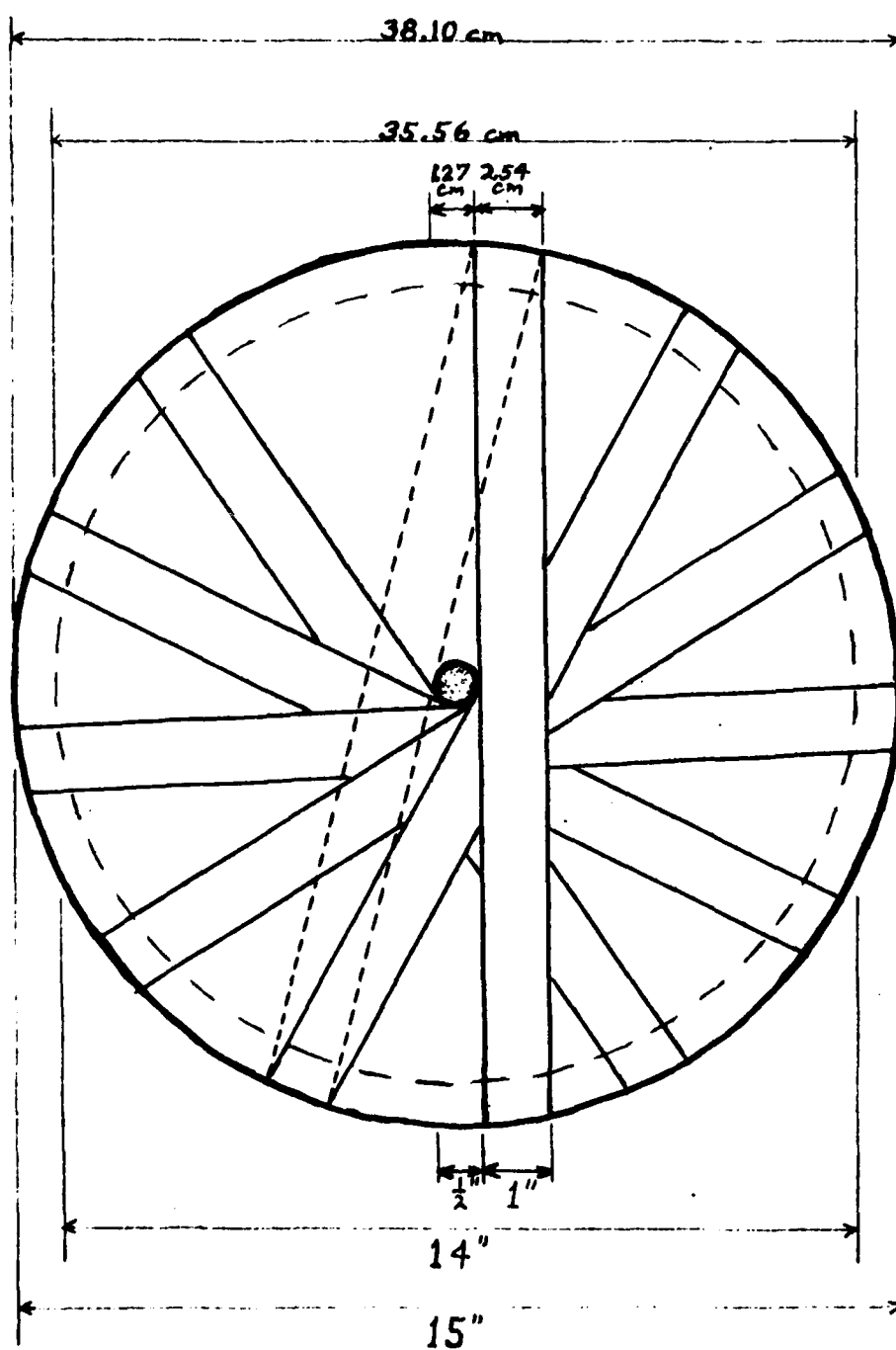


Figure 9. Flywheel Model, axial view

This configuration could be fabricated using a continuous 2.54 cm (1-inch) wide unidirectional fiber tape pre-impregnated with the epoxy resin which cures under heat and pressure subsequent to lay up. A possible wrapping apparatus is shown in Figures 10 and 11. The motion is like wrapping tape under tension around a plate by rotating the tape roll around the plate. The center hole for the shaft does not cut the fibers of the tape since the tape is applied with one edge tangent to the shaft. The heat guns blow hot air onto the tape as it is being wound causing the resin to soften. This procedure yields a more compact composite with good bonding between the layers of tape. After the winding procedure is complete, the flywheel would have to be baked at an elevated temperature for a given time period to complete the curing of the resin.

The orientation of the fibers in the design are the key to its success. As seen in Figure 9, the fibers immediately adjacent to the shaft will all be tangential. This is the same direction of the disk stresses present in this region as shown in Figure 3. At a distance out from the shaft the tapes overlap at various angles, so the fibers add both radial and tangential strength to this region. Both tangential and radial stresses of about equal intensities are found in the regions between the shaft and the outer tips of the disk, as shown in Figure 6. At the outer tip of the disk, the tapes are at an angle of about 10 degrees off from the radial direction, thus giving about 17% of their strength in the tangential direction. As seen in Figure 6

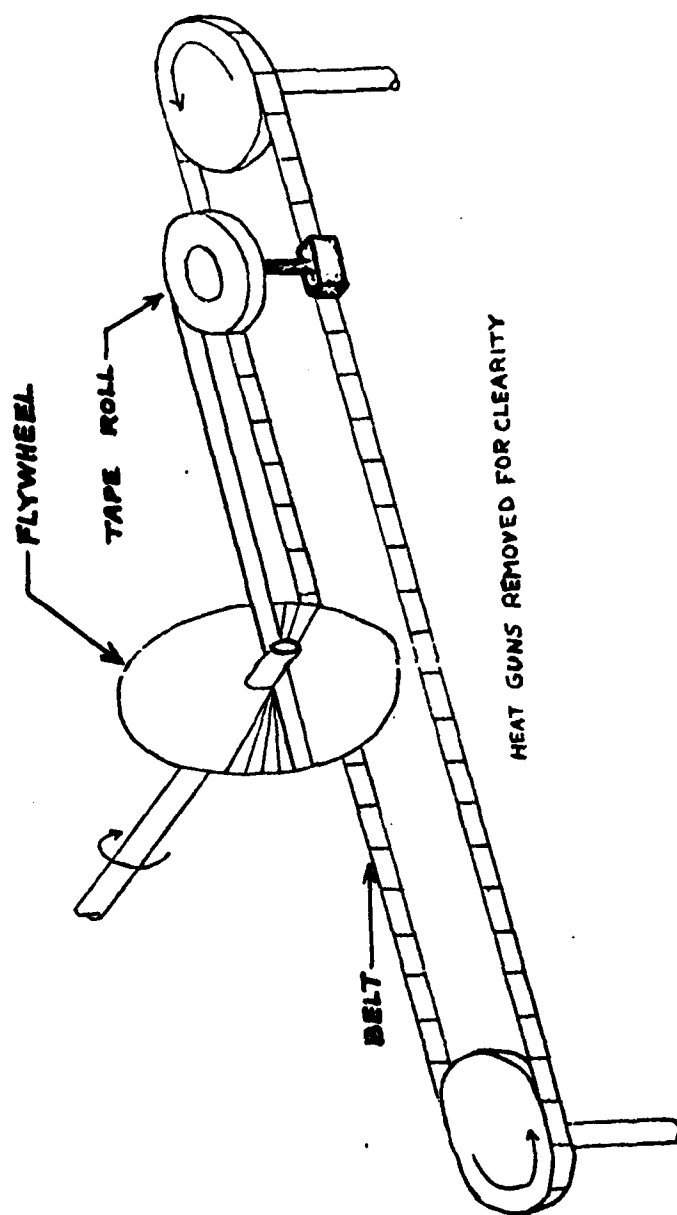


Figure 10. Wrapping Apparatus

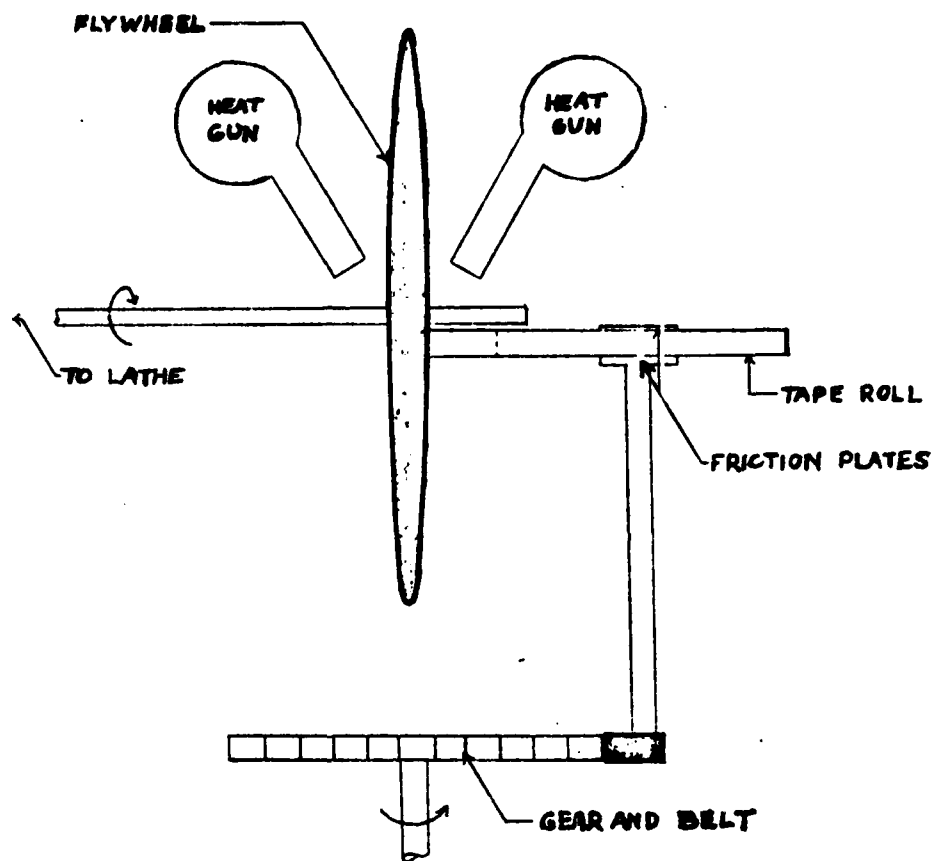


Figure 11. Wrapping Apparatus, edge view

both radial and tangential stresses die off significantly near the outer tip of the disk. Thus in all regions of this design, the fibers are aligned properly so as to withstand the stresses created when the flywheel is spinning. Several small cylindrical rotors of the unidirectional E-glass/epoxy prepeg tape were fabricated to evaluate various lay-up techniques.

FLYWHEEL TEST CHAMBER

The vacuum chamber shown in Figure 12 to experimentally test the flywheel models was designed and partially built. The tests would be conducted in a vacuum of 1.3 Pa (10^{-2} torr) to reduce air resistance. The maximum rotational speed of the apparatus would be limited to 30,000 rpm. The objectives of the experimental tests would be to verify the following:

1. Structural integrity of the models
2. Shape factors
3. Energy storage capacities

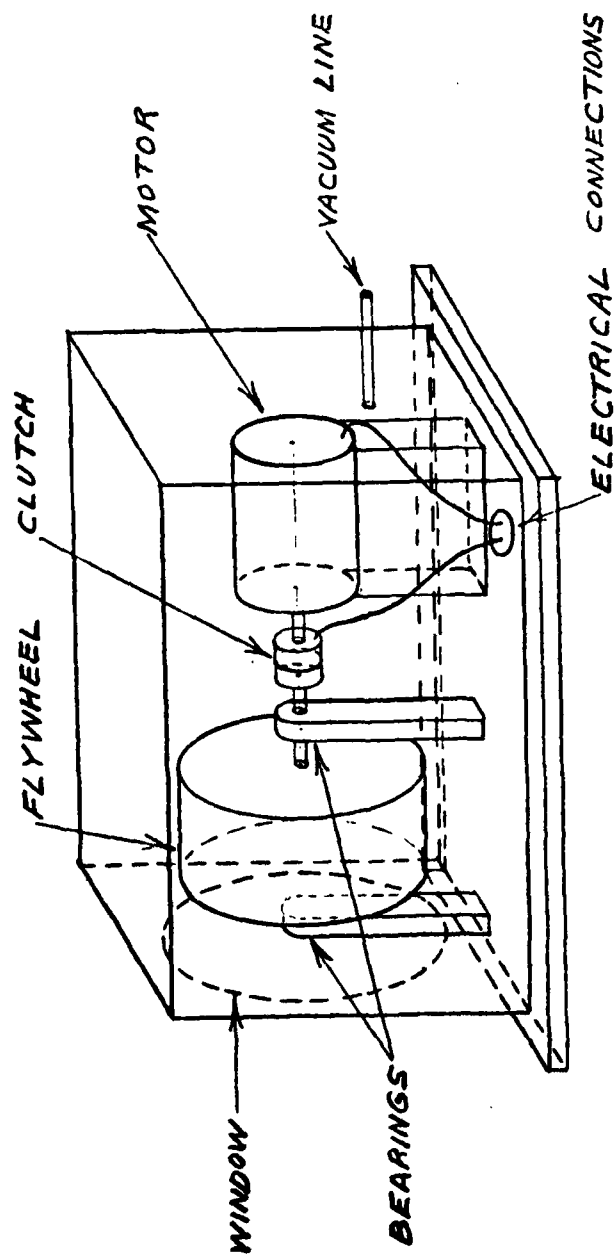


Figure 12. Flywheel Test Chamber

SUMMARY

In this flywheel project the interrelationships between the specific energy, shape factor, strength-to-weight ratio, configuration, stress distribution and fiber directions were analyzed and an optimal flywheel configuration and fabrication technique was proposed. This optimal configuration, a rounded tapered disk should have a shape factor of about 0.46. An 11 kg (25 pound) Kevlar/epoxy model should be able to store up to 3.6 MJ (1 kWh) if rotated at the maximum allowable speed of 30,000 rpm. The proposed fabrication technique employs a simple wrapping apparatus by which the unidirectional prepreg fiber tape is wound so that the fiber directions coincide with the major stresses within the flywheel when spinning. A follow-up project to fabricate, test, and evaluate this flywheel model is highly recommended.