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COMPOSITE FLYWHEEL DEVELOPMENT

(April 1 - June 30, 1977)

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MASTER

October 1977

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HIGHLIGHTS

Additional experimental prestressed rim evaluations indicate that this technique should permit near full utilization of Kevlar-49 hoop strength in a prestressed flywheel rim with resultant energy densities up to 44 Wh/lb.

A finite-element model of the Deltawrap flywheel was generated, and several analyses were made.

Design of the containment assembly hardware is 90% complete.

COMPOSITE FLYWHEEL DEVELOPMENT

INTRODUCTION

This report summarizes Union Carbide Corporation-Nuclear Division's (UCC-ND's) Composite Flywheel Program status and results for the third quarter of FY 1977 (April 1 - June 30, 1977). This work was conducted for and funded by the Advanced Physical Methods Branch, Division of Energy Storage Systems, Office of Conservation, ERDA, Washington.

As a part of its energy conservation program, ERDA is developing a heat-engine/flywheel hybrid vehicle. This goal will be accomplished by incorporating a high-speed flywheel energy storage system into a heat-engine vehicle. The flywheel system will be designed for peak energy storage and retrieval to promote more efficient engine operation and, also, to provide a system for regenerative braking. The composite flywheel and its containment-suspension mount system are the key elements being developed in UCC-ND's program.

PRIOR WORK

This program was initiated in May 1976. The first program phase, which was conducted during, FY 1976/76T, was devoted to utilizing state-of-the-art UCC-ND technology to design fabricate, and successfully spin test a nominal 0.5-kWh Bandwrap flywheel, seen in Figure 1. An average energy density of 10.1 watt hours per pound (Wh/lb) was attained for the combined flywheel and hub.[1]

During the first two quarters of FY 1977, design concepts were generated for improving the FY 1976/76T flywheel performance. These concepts have been analytically evaluated, using finite-element methods and have been shown to provide a means for increased performance in the flywheel. These concepts have included modification of the outer Bandwrap flywheel contour to a rotational catenary, use of prestressed rims, use of dead-weight loadings, use of a hybrid rim, and a change to the Deltawrap flywheel design.[2,3]

A design concept for a vehicular-sized containment housing to be utilized in evaluation of containment materials and flywheel failure modes was also generated.[2,3]

FY 1977 PROGRAM OBJECTIVES

The overall objectives of UCC-ND's program is to develop state-of-the-art, high-speed, composite flywheel and containment systems. The FY 1977 program encompasses the following technical objectives:

1. Design and fabricate an adequate, but not necessarily optimum, vehicular-sized containment housing and a special load-cell-instrumented mounting. The assembly will be designed for installation into a suitable spin test stand.

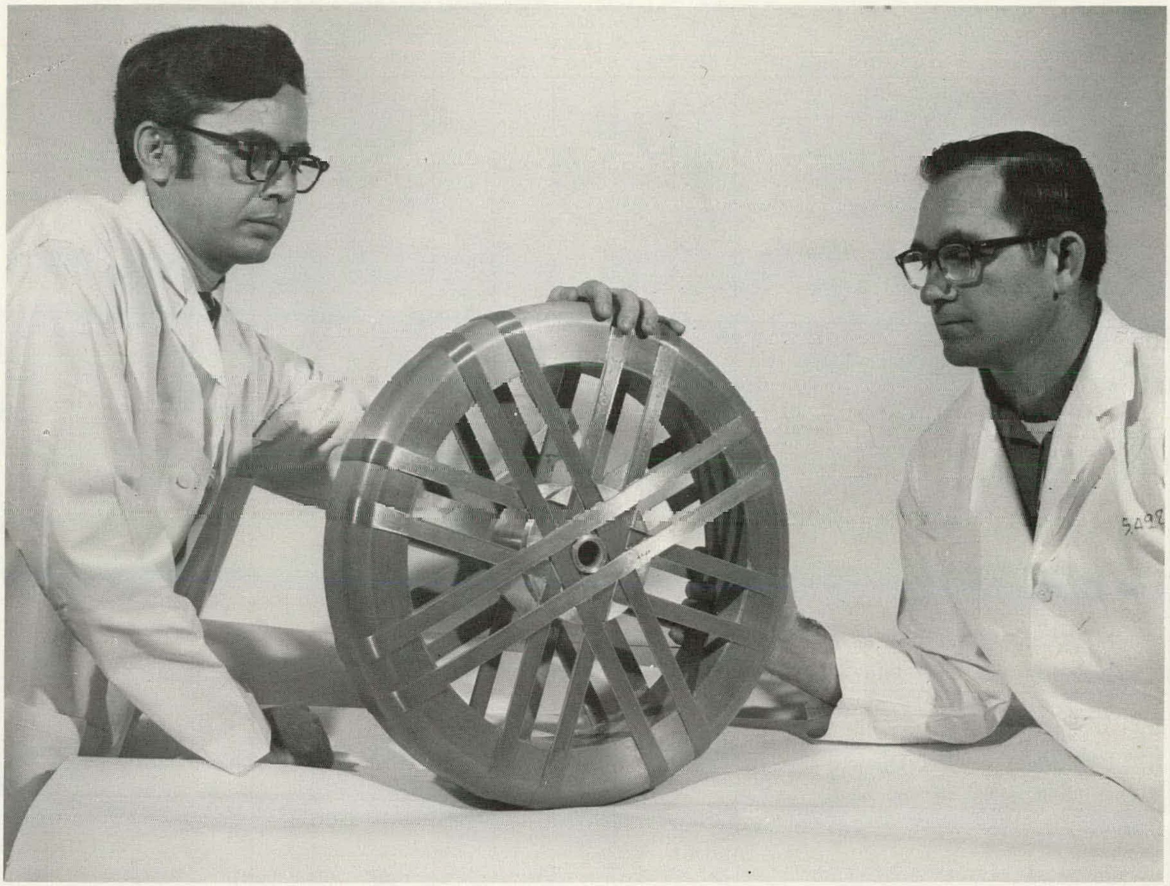

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Figure 1. BANDWRAP KEVLAR-49/EPOXY FLYWHEEL. (Fabricated in FY 1976T)

2. Design and fabricate an improved, prototype composite flywheel which will be available for evaluation and burst testing in the instrumented containment package. Efforts will be keyed on developments which increase the energy density of the 0.5-kWh flywheel and hub assembly to a level above the 10.1 Wh/lb achieved in FY 1976T.

The containment package and composite flywheel will be available for test and evaluation by the end of this fiscal year. Subsequent burst testing of the composite flywheel and additional similar flywheels in the instrumented containment-mount assembly can provide a minimum amount of necessary data on transient loading and containment damage for design and development of a safe vehicular flywheel-containment system. Test and evaluation of the flywheel-containment-mount package will be conducted as a part of UCC-ND's FY 1978 program.

DEVELOPMENT PLANS

An updated schedule of tasks directed toward design and fabrication of the FY 1977 flywheel and containment-mount assembly is summarized in Figure 2; a simplified schematic of the assembly mounted in a spin test chamber is depicted in Figure 3.

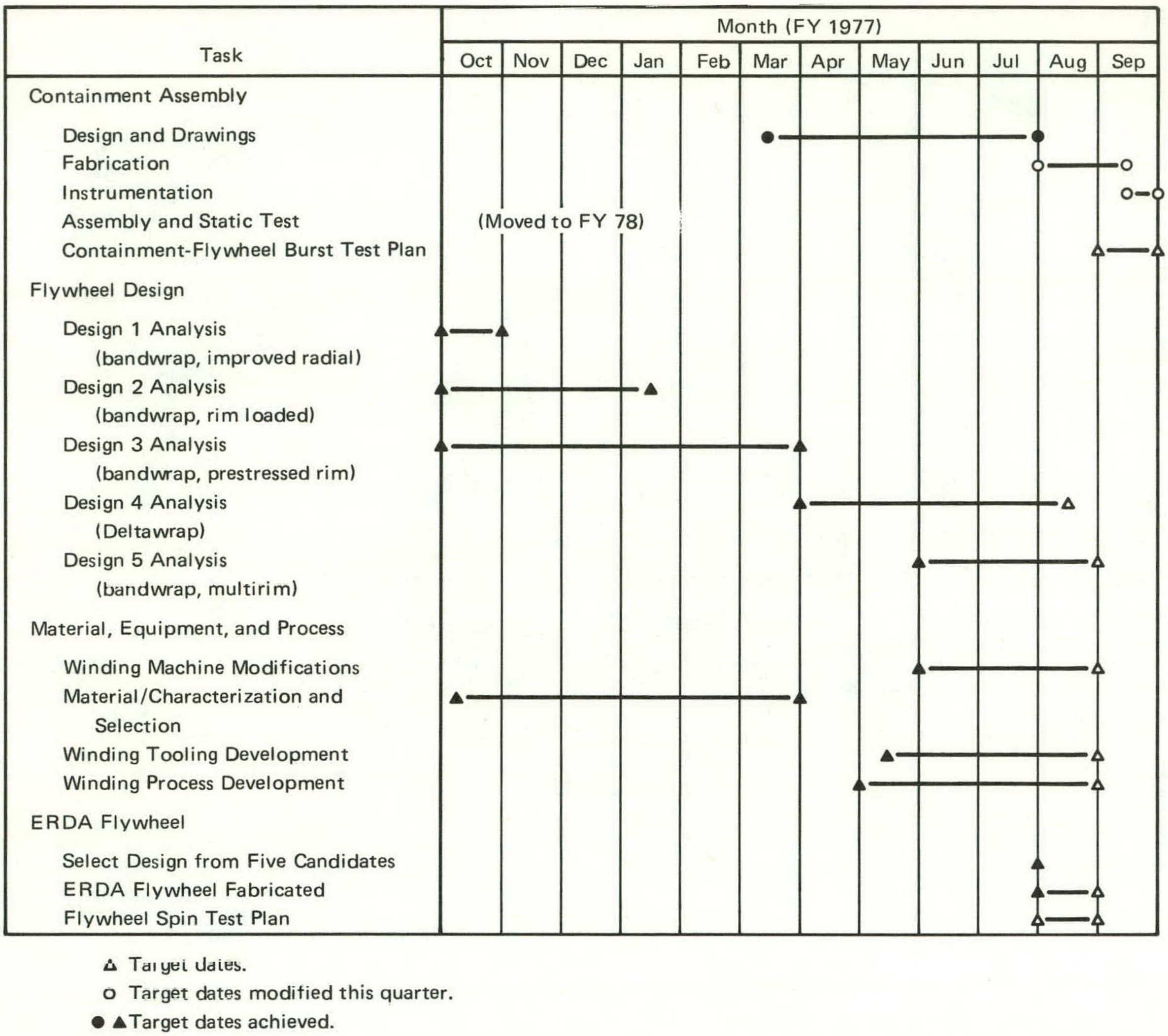

Figure 2. CURRENT DEVELOPMENT PLANS. (Will Lead to the Fabrication of an Improved Composite Flywheel and Instrumented Containment-Mount Assembly by September 30, 1977; as of July 1, 1977)

Flywheel design and development activities are on schedule; however, it was necessary to adjust the containment package development schedule again this quarter in order to mesh this work with other on-going activities. Rescheduling of these tasks will not affect the committed September 30, 1977 completion date for the flywheel-containment package.

CONTAINMENT ASSEMBLY

Design of the instrumented containment-mount assembly, as illustrated in Figure 4, is approximately 90% complete, with detailed fabrication drawings currently in preparation. Fabrication and instrumentation of the assembly are scheduled for August and September 1977. Design and instrumentation details will be reported in the FY 1977 year-end progress report.

FLYWHEEL DEVELOPMENT ACTIVITIES

Rotor development continued on the prestressed rim for the Bandwrap flywheel. A test ring was fabricated and its prestress state was evaluated. The prestress level was adequate to allow near-full utilization of the Kevlar-49/Epoxy composite hoop stress.

Several cases of the finite-element analysis on the Deltawrap flywheel design were run and are being evaluated. The model was analyzed by the WILPLAS code (in use in Y-12 for several years) as well as by the newly acquired ADINA finite-element code. Different interface conditions between the overwrap and rim and hub were studied. The WILPLAS code was also modified to calculate stresses along and transverse to the fiber directions in the overwrap.

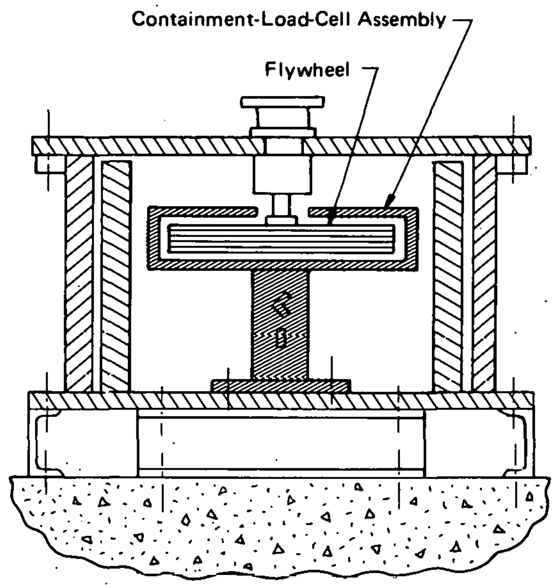

Figure 3. FLYWHEEL-CONTAINMENT ASSEMBLY, DEPICTED IN A SPIN TEST STAND.

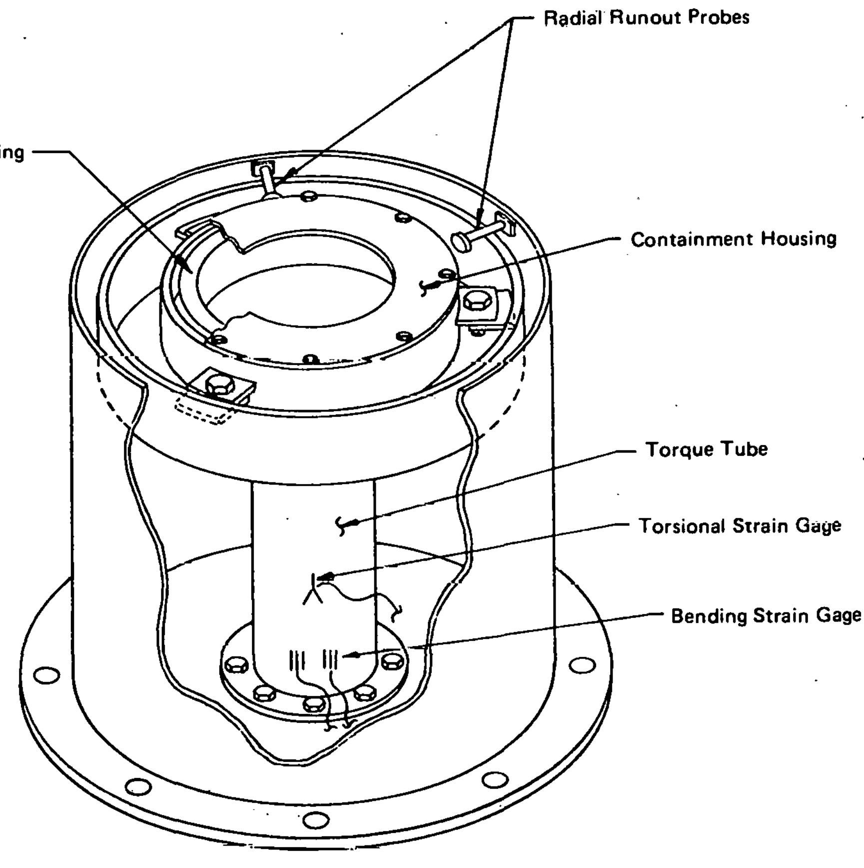

Figure 4. INSTRUMENTED CONTAINMENT HOUSING CONCEPT.

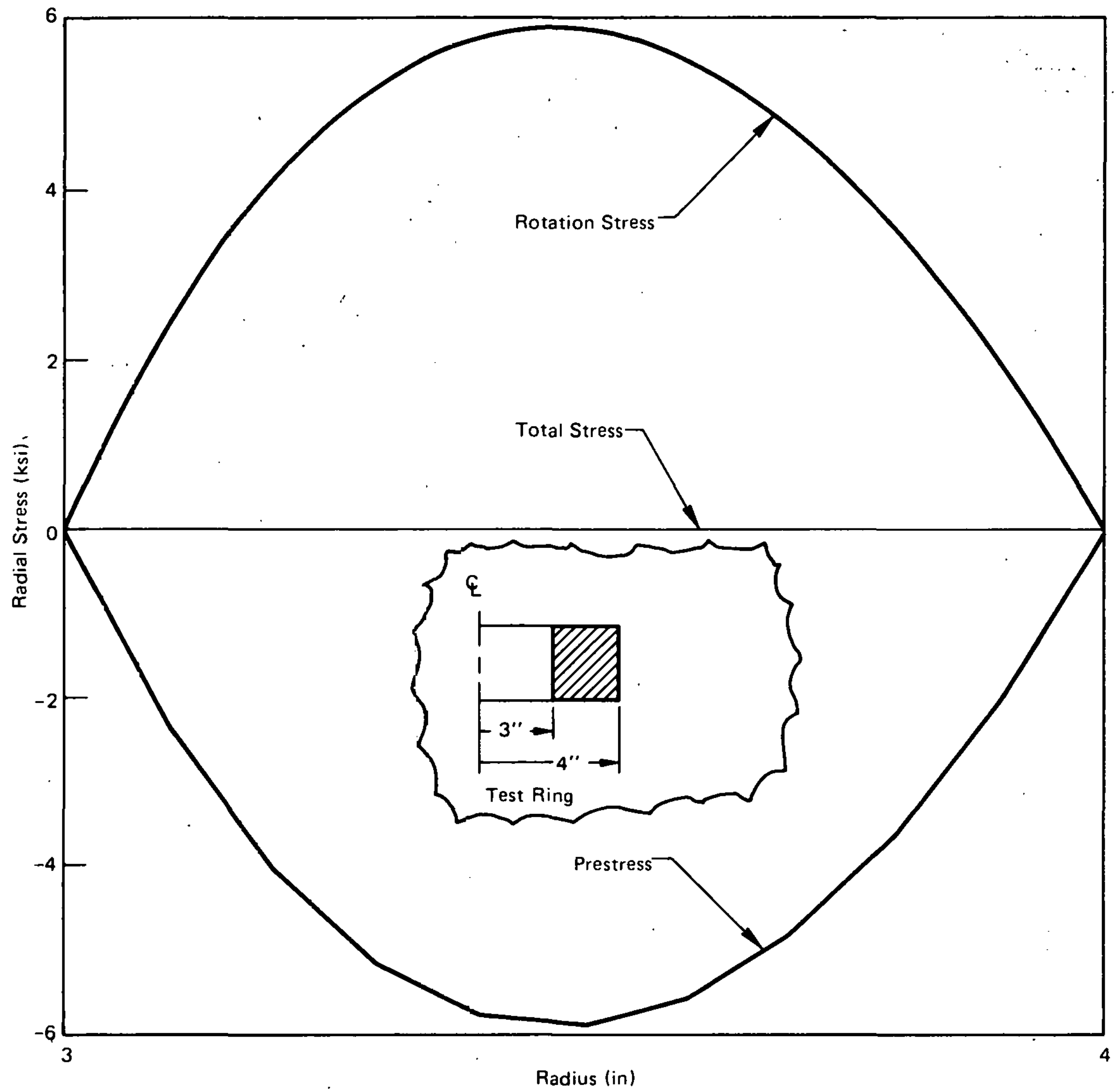

Figure 5. RADIAL-STRESS AND IDEAL PRESTRESS DISTRIBUTIONS IN A KEVLAR-49/EPOXY COMPOSITE RIM AT A 0.75 INSIDE/OUTSIDE RADIUS RATIO.

Prestressed Rim Evaluation

The prestress theory and results for the first two test rings were presented in previous reports.[2,3] A third six-inch inside-diameter by eight-inch outside-diameter test ring was fabricated and evaluated. The winding-tension schedule was scaled down to prevent hoop compressive failure of the inner layers which occurred in the first two test rings.

The third test ring was successfully fabricated, with none of the inner-layer compressive failure experienced on prior rings. The winding-tension schedule was scaled to produce a maximum inner-layer hoop compressive stress of 2.9 ksi. However, the retained tensions, based on the strain-gage results, again exceeded the expected values. The results calculated from the strain-gage measurements during fabrication indicate an inner-layer hoop compressive stress of 50 ksi and a maximum radial compressive stress of 4 ksi. Residual-stress analysis of this ring by incremental material removal is to be done to verify these strain-gage calculations.

Results on this ring and its relation to the applied rotation stresses are given in Figures 5 through 8. Figure 5 shows the radial stress distribution due to rotation of a Kevlar-49/Epoxy composite rim of an inside/outside radius ratio of 0.75. The ideal prestress for this case is also shown. This prestress combines with the rotation stress to result in a net radial stress of zero throughout the rim.

Figure 6 shows the corresponding hoop-stress distributions. The theoretical and experimental prestress results from Test Ring 3 are reported in Figures 7 and 8. The negative of the radial rotation stresses for two different rim speeds is also included in Figure 7. The lower speed is the point where the theoretical prestress results in a net zero radial stress. The higher speed is the point where the experimental prestress results in a net zero radial stress. The total hoop stresses (rotation plus prestress) are also shown in Figure 8 for the same two speeds.

The total theoretical energy stored per unit weight, based on the rim weight alone, is 31 Whr/lb at 74,500 rpm and 44 Whr/lb at 87,800 rpm for a 6-inch inside-diameter by 8-inch outside-diameter rim (29,800 and 35,100 rpm, respectively, for a 15 x 20-inch rim). Even though the failure mode in this case would still be by delamination, it offers a very significant improvement to the Bandwrap design performance.

Deltawrap Flywheel Design

The Deltawrap flywheel design concept was presented previously;[4] and a method for computing thickness, fiber orientations, and elastic properties in the overwrap was presented last quarter.[3] A finite-element model has been generated this quarter, and several analysis cases have been run.

A mesh-generation program was utilized to prepare the finite-element mesh shown in Figure 9. The top illustration shows the boundaries of the hub, overwrap, and rim portions of the

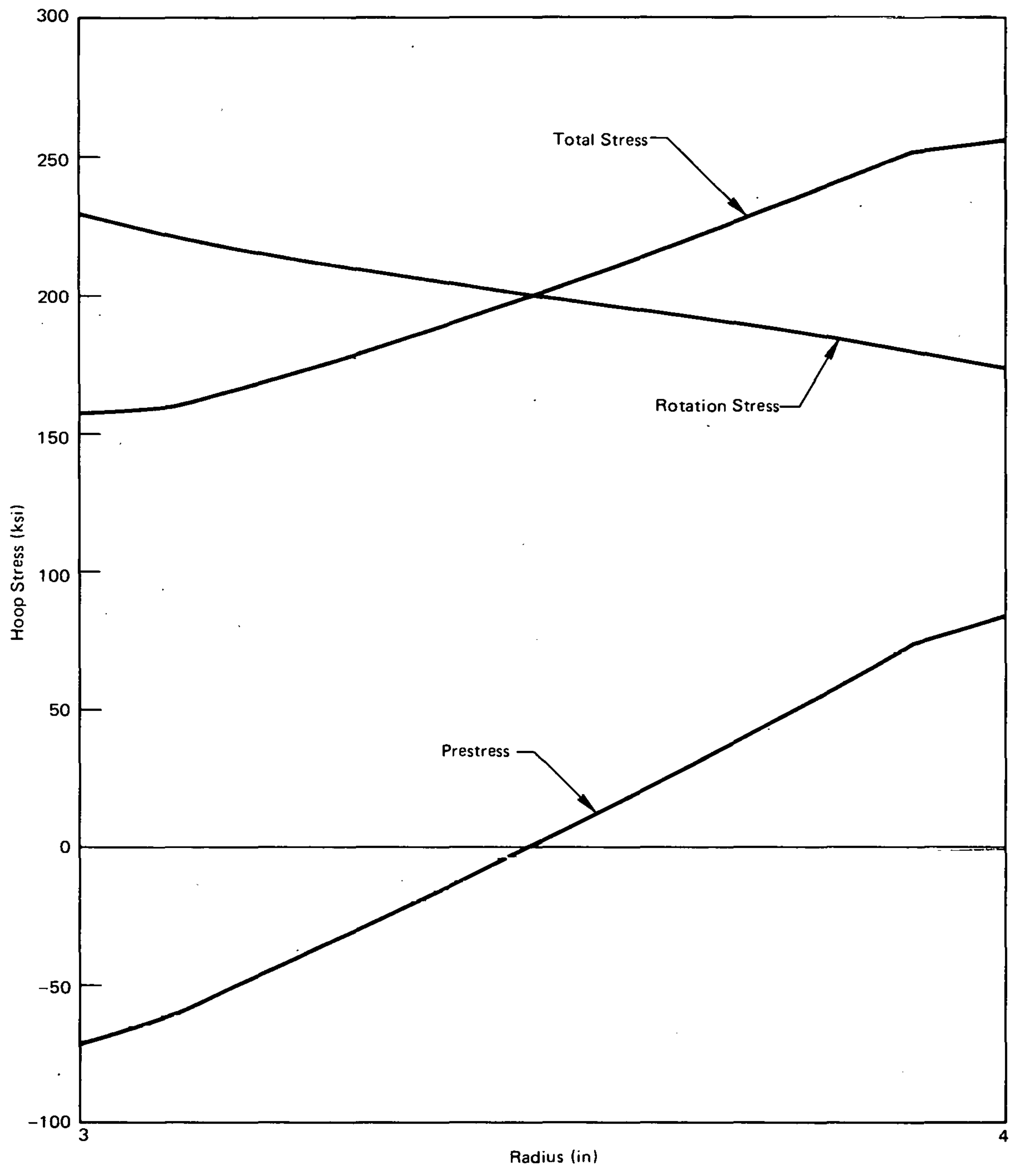

Figure 6. HOOP-STRESS DISTRIBUTION IN THE IDEALLY PRESTRESSED KEVLAR-49/EPOXY COMPOSITE RIM AT A 0.75 INSIDE/OUTSIDE RADIUS RATIO.

Deltawrap design. Thin interface layers are between the hub and overwrap and the overwrap and rim to represent the bond lines. The lower illustration of Figure 9 shows the quadrilateral mesh used in the analysis. The Z axis is the center of rotation for the axisymmetric model, and the model is symmetric about the R axis.

The hub is made of an isotropic metal, such as aluminum. The overwrap is made of incrementally positioned parallel fiber bands resulting in full coverage of the rim circumference. The rim is made of a circumferentially wound unidirectional composite. The interfaces may be modeled with epoxy or rubber bonds. The same mesh was used in both the WILPLAS and ADINA analyses.

The older WILPLAS code used the constant-strain triangle as the basic element, with the quadrilateral in the mesh represented by four triangular elements. As reported previously, the overwrap portion of the Deltawrap design is modeled as an angle-ply composite, and the fiber angle varies with position.

In order to estimate the failure load, the stress components in the local fiber coordinate system need to be determined. The stresses are normally computed in the WILPLAS code in the R-Z global coordinate system. Modifications were made to the code to compute the fiber coordinate components in addition to those normally computed. Basically, this change involves computing the strain components in fiber coordinates first and using the unidirectional fiber composite stiffness matrix to compute the stresses.

The ADINA code is a later, more refined code and should provide greater accuracy with fewer elements. The element used in this analysis is a quadrilateral, isoparametric element. The capability to compute fiber coordinate stress components is not available in this code

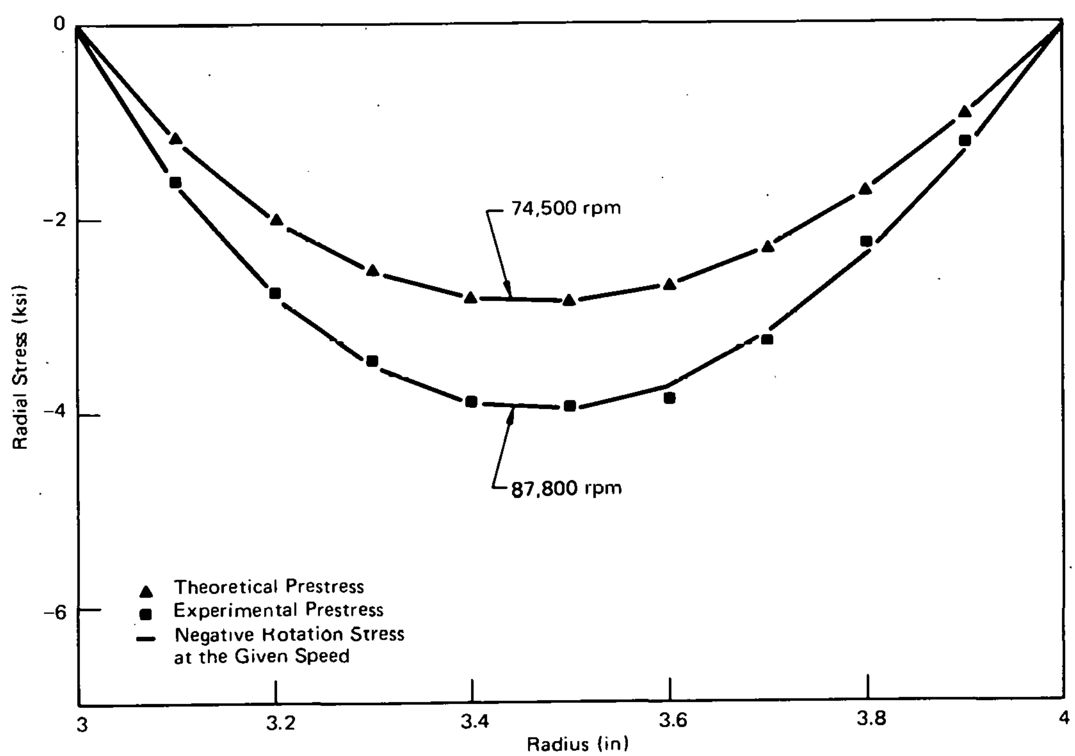

Figure 7. THEORETICAL AND EXPERIMENTAL RADIAL PRESTRESSES AND THE NEGATIVE OF THE ROTATIONAL RADIAL STRESSES. (These Stresses would Respectively Balance in a 3-Inch Inside-Radius by 4-Inch Outside Radius Kevlar-49/Epoxy Composite Ring)

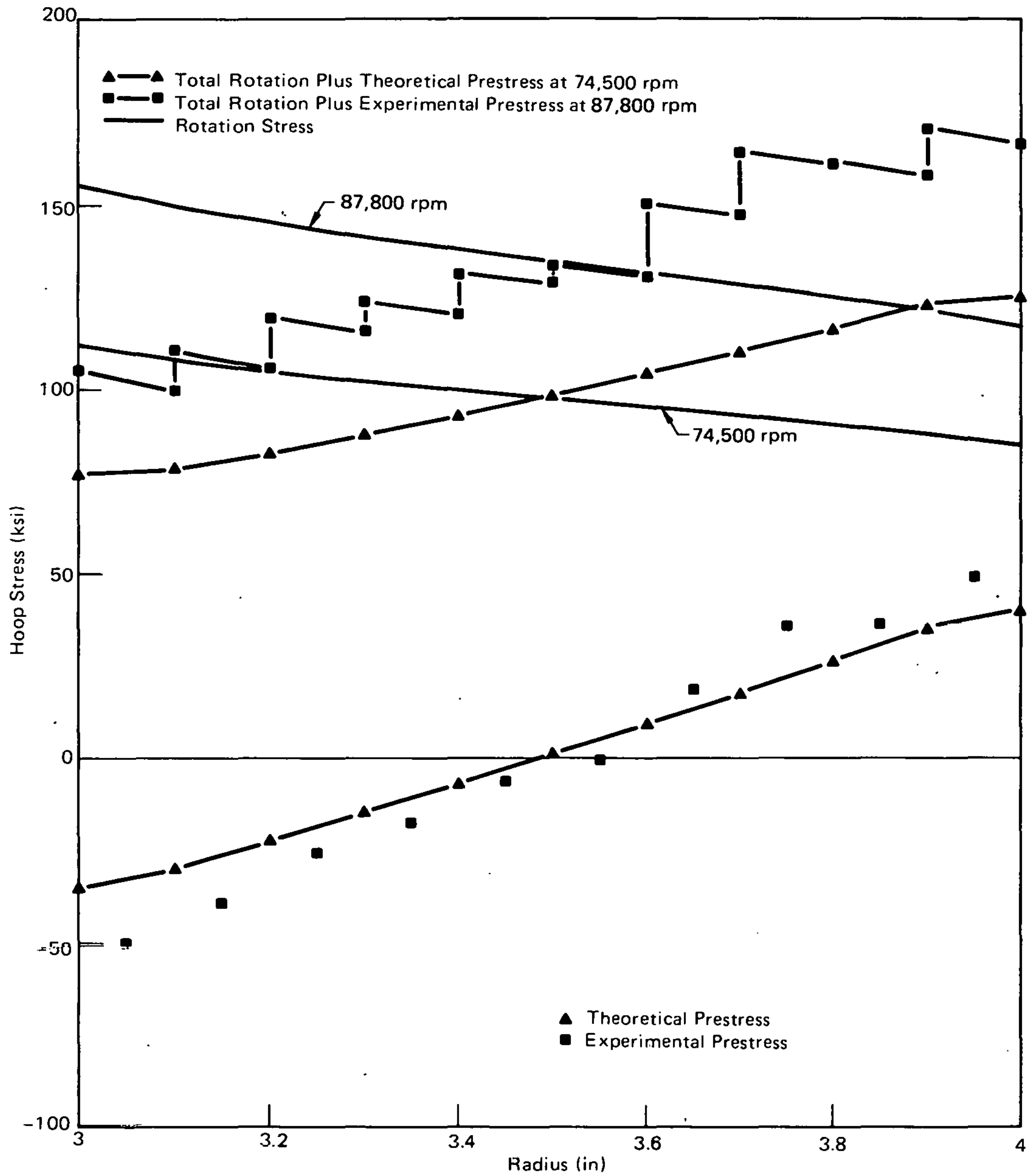

Figure 8. THEORETICAL AND EXPERIMENTAL HOOP PRESTRESS DISTRIBUTION AND THE TOTAL HOOP-STRESS DISTRIBUTION OF THE SPEEDS WHERE THE RADIAL PRESTRESSES PRODUCE A NET ZERO RADIAL STRESS.

either, and a separate program is being prepared to operate on the output for the overwrap portion to compute these values.

Several cases have been run in both the ADINA and WILPLAS codes, and the results agree very well. The voluminous output is in the process of being studied and condensed for proper presentation. Estimates of the potential performance will be made at the completion of the data reduction.

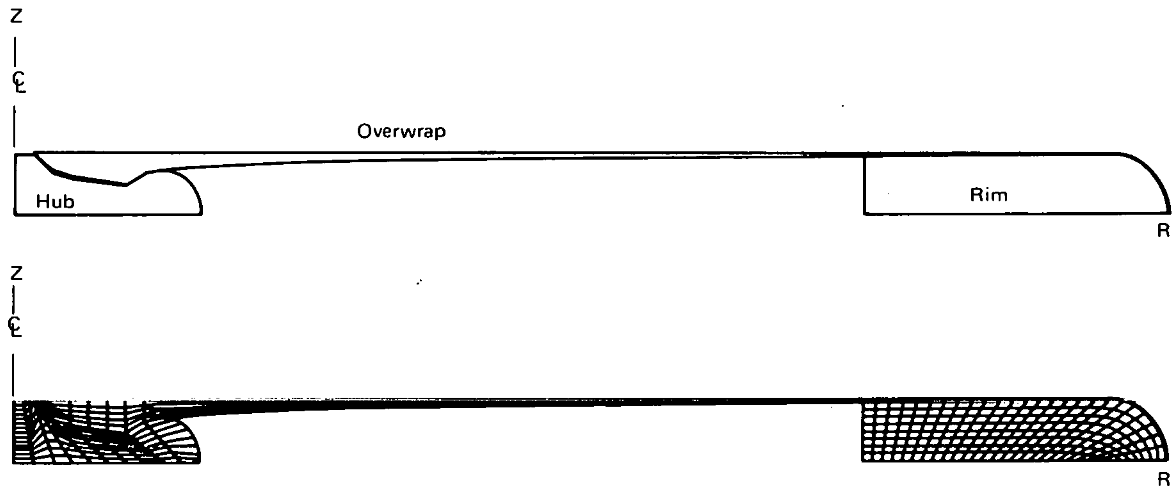

Figure 9. FINITE-ELEMENT MODEL FOR THE DELTAWRAP FLYWHEEL DESIGN.

FUTURE WORK

Data reduction of the Deltawrap analysis results should be completed next quarter. The best of the designs analyzed and studied this year will be selected, and the flywheel for the FY 1977 package will be fabricated next quarter.

Design drawings for the containment-mount assembly, as well as fabrication and instrumentation of the assembly, will also be completed during the next quarter. Calibration of the assembly, initially scheduled for FY 1977, will be done in FY 1978 since test-stand rigidity affects the calibration and response of the containment assembly to flywheel failure transient loadings. Because a suitable test stand will not be available until FY 1978, the calibration will be made on the test stand next year.

REFERENCES

1. Huddleston, R. L., Kelly, J. J., and Knight, C. E.; *Composite Flywheel Development* (May 1-September 30, 1976), Y-2080; Union Carbide Corporation-Nuclear Division, Oak Ridge Y-12 Plant, Oak Ridge, Tennessee; May 11, 1977.

2. Huddleston, R. L., Kelly, J. J., and Knight, C. E.; *Composite Flywheel Development* (October 1-December 31, 1976), Y-2081; Union Carbide Corporation-Nuclear Division, Oak Ridge Y-12 Plant, Oak Ridge, Tennessee; May 11, 1977.

3. Huddleston, R. L., Kelly, J. J., and Knight, C. E.; *Composite Flywheel Development* (January 1-March 31, 1977), Y-2087; Union Carbide Corporation-Nuclear Division, Oak Ridge Y-12 Plant, Oak Ridge, Tennessee; September 19, 1977.

4. Huddleston, R. L., Kelly, J. J., and Knight, C. E.; *Composite Flywheel Development* (May 1-June 30, 1976), Y-2072; Union Carbide Corporation-Nuclear Division, Oak Ridge Y-12 Plant, Oak Ridge, Tennessee; January 24, 1977.

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