ORNL/Sub-81/92336/1
WARD-GCFR-81-01
Distribution Category UC-77

GAS-COOLED FAST REACTOR
CONTROL-ROD-DRIVE-MECHANISM
DECELERATION UNIT
TEST REPORT

ORNL/Sub--81/92336/1

DE82 014725

Author:
T. H. Wagner

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Work performed by
Westinghouse Advanced Reactors Division
under Subcontract No. 40X-92336V
for Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

Operated by Union Carbide Corporation
for the Department of Energy
Contract No. W7405-eng-26

Westinghouse Electric Corporation
Advanced Reactors Division
P.O. Box 158
Madison, Pennsylvania 15663

October 1981

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TABLE OF CONTENTS

	<u>Page</u>
LIST OF FIGURES	ii
LIST OF TABLES	iv
SUMMARY	1
1.0 INTRODUCTION	2
1.1 Test Purpose	3
2.0 SUMMARY DESCRIPTION OF GCFR CRDM/CRD DESIGN	4
2.1 Design Description	4
2.2 Scram Deceleration Requirements	10
3.0 TEST ARTICLE	11
3.1 Description of Deceleration Unit	11
3.2 Fabrication Experience	13
3.3 Planned Differences between Test Unit and Reference Design	14
3.4 Analysis of Decelerator Design	16
4.0 TEST FACILITY	20
4.1 Description	20
4.2 Instrumentation	24
4.3 Test Operations	28
5.0 TEST RESULTS	30
5.1 Initial Test Result	30
5.2 Examination of Failed Cam Follower	39
5.3 Retest Results	41
5.4 Post-Test Examination of Decelerator Components	41
6.0 EVALUATION OF TEST RESULTS	47
6.1 Initial Test Data Evaluation	48
6.2 Retest Data Evaluation	70
7.0 TEST CONCLUSIONS	91

LIST OF FIGURES

	<u>Page</u>
Figure 2.1 CRDM Schematic	5
Figure 2.2 Rotor Action	6
 Figure 3.1.1 GCFR Deceleration Test Article	 12
Figure 3.2.1 Flywheel Assembly	15
Figure 3.2.2 View of Flywheel Grooves	15
Figure 3.2.3 Cam Follower Assembly	15
Figure 3.3.1 Test Unit Housing	15
 Figure 4.1.1 Test Console Instrument Panel	 21
Figure 4.1.2 View of Upper Portion of Test Assembly	21
Figure 4.1.3 View of Lower Portion of Test Assembly	21
Figure 4.1.4 Planned Test Vessel	22
Figure 4.1.5 Planned System Schematic	23
Figure 4.1.6 Typical Visicorder Trace of Scram Action	25
 Figure 5.1.1 12" Withdrawal Scram Visicorder Trace	 31
Figure 5.1.2 18" Withdrawal Scram Visicorder Trace	32
Figure 5.1.3 24" Withdrawal Scram Visicorder Trace	33
Figure 5.1.4 30" Withdrawal Scram Visicorder Trace	34
Figure 5.1.5 36" Withdrawal Scram Visicorder Trace	35
Figure 5.1.6 42" Withdrawal Scram Visicorder Trace	36
Figure 5.1.7 48" Withdrawal Scram Visicorder Trace	37
Figure 5.1.8 53" Withdrawal Scram Visicorder Trace	38
Figure 5.2.1 Failed Cam Follower and Second Cam Follower Removed after First Test Phase	40
Figure 5.3.1 Selected Visicorder Trace Representing Retest Phase Tests	42
Figure 5.4.1 Outer Race of Overrunning Clutch W/ Cam Followers	44
Figure 5.4.2 Closeup of Loose Cam Follower Showing Rubbing Results	44
Figure 5.4.3 Over-Running Clutch Showing Destroyed Garter Springs	44
Figure 5.4.4 View of Inside of Flywheel Showing Rub Marks from Cam Follower	44
Figure 5.4.5 Broken Flywheel Insert Bolts	45
Figure 5.4.6 Rub Area on Outside of Flywheel from Broken Bolts	45
Figure 5.4.7 Flywheel Track	45
Figure 5.4.8 Flywheel Track	45

LIST OF FIGURES
(contd)

	<u>Page</u>
Figure 6.1.1.1 30" Withdrawal Scram .05 Δt Network Analysis	51
Figure 6.1.1.2 30" Withdrawal Scram Velocity Curve	52
Figure 6.1.1.3 30" Withdrawal Scram Acceleration Curve	53
Figure 6.1.2.1 36" Withdrawal Scram .05 Δt Network Analysis	55
Figure 6.1.2.2 36" Withdrawal Scram Velocity Curve	56
Figure 6.1.2.3 36" Withdrawal Scram Acceleration Curve	57
Figure 6.1.3.1 42" Withdrawal Scram .05 Δt Network Analysis	59
Figure 6.1.3.2 42" Withdrawal Scram Velocity Curve	60
Figure 6.1.3.3 42" Withdrawal Scram Acceleration Curve	61
Figure 6.1.4.1 48" Withdrawal Scram .05 Δt Network Analysis	63
Figure 6.1.4.2 48" Withdrawal Scram Velocity Curve	64
Figure 6.1.4.3 48" Withdrawal Scram Acceleration Curve	65
Figure 6.1.5.1 53" Withdrawal Scram .05 Δt Network Analysis	67
Figure 6.1.5.2 53" Withdrawal Scram Velocity Curve	68
Figure 6.1.5.3 53" Withdrawal Scram Acceleration Curve	69
Figure 6.2.1.1 30" Withdrawal Scram .05 Δt Network Analysis	72
Figure 6.2.1.2 30" Withdrawal Scram Velocity Curve	73
Figure 6.2.1.3 30" Withdrawal Scram Acceleration Curve	74
Figure 6.2.2.1 36" Withdrawal Scram .05 Δt Network Analysis	76
Figure 6.2.2.2 36" Withdrawal Scram Velocity Curve	77
Figure 6.2.2.3 36" Withdrawal Scram Acceleration Curve	78
Figure 6.2.3.1 42" Withdrawal Scram .05 Δt Network Analysis	80
Figure 6.2.3.2 42" Withdrawal Scram Velocity Curve	81
Figure 6.2.3.3 42" Withdrawal Scram Acceleration Curve	82
Figure 6.2.4.1 48" Withdrawal Scram .05 Δt Network Analysis	84
Figure 6.2.4.2 48" Withdrawal Scram Velocity Curve	85
Figure 6.2.4.3 48" Withdrawal Scram Acceleration Curve	86
Figure 6.2.5.1 53" Withdrawal Scram .05 Δt Network Analysis	88
Figure 6.2.5.2 53" Withdrawal Scram Velocity Curve	89
Figure 6.2.5.3 53" Withdrawal Scram Acceleration Curve	90

LIST OF TABLES

		<u>Page</u>
Table 3.3.1	Material Tested	18
Table 3.3.2	Major Component Forces and Design Margins	19
Table 4.2.1	Deceleration Test Instrumentation	26
Table 6.1.1	Tabular Calculation of Control Rod Velocity and Acceleration 30" Scram	50
Table 6.1.2	Tabular Calculation of Control Rod Velocity and Acceleration 36" Scram	54
Table 6.1.3	Tabular Calculation of Control Rod Velocity and Acceleration 42" Scram	58
Table 6.1.4	Tabular Calculation of Control Rod Velocity and Acceleration 48" Scram	62
Table 6.1.5	Tabular Calculation of Control Rod Velocity and Acceleration 53" Scram	66
Table 6.2.1	Tabular Calculation of Control Rod Velocity and Acceleration 30" Scram	71
Table 6.2.2	Tabular Calculation of Control Rod Velocity and Acceleration 36" Scram	75
Table 6.2.3	Tabular Calculation of Control Rod Velocity and Acceleration 42" Scram	79
Table 6.2.4	Tabular Calculation of Control Rod Velocity and Acceleration 48" Scram	83
Table 6.2.5	Tabular Calculation of Control Rod Velocity and Acceleration 53" Scram	87

SUMMARY

This report presents the results of the airtesting portion of the proof-of-principle testing of a Control Rod Scram Deceleration Device developed for use in the Gas Cooled Fast Reactor (GCFR). The device utilizes a grooved flywheel to decelerate the translating assembly (T/A). Two cam followers on the translating assembly travel in the flywheel grooves and transfer the energy of the T/A to the flywheel. The grooves in the flywheel are straight for most of the flywheel length. Near the bottom of the T/A stroke the grooves are spiraled in a decreasing slope helix so that the cam followers accelerate the flywheel as they transfer the energy of the falling T/A.

To expedite proof-of-principle testing, some of the materials used in the fabrication of certain test article components were not prototypic. With these exceptions the concept appears to be acceptable. The initial test of 300 scrams was completed with only one failure and the failure was that of a non-prototypic cam follower outer sleeve material.

The cam followers were replaced on the T/A and lubrication was added to the flywheel bearings and the unit was subjected to additional scram testing. The retest completed 250 scrams before the test was terminated as a result of a loose cam follower. The cam follower was not properly pinned to the translating assembly and unthreaded sufficiently to prevent translating assembly withdrawal and to indicate erratic flywheel RPM readings.

If the GCFR program is reinstated this test should be repeated using prototypic materials to assure ability of all components to withstand the 750 scram lifetime.

1.0 INTRODUCTION

This report outlines the ARD activities directed toward testing a control rod scram deceleration device to be used in the Gas Cooled Fast Reactor Demonstration Plant. The deceleration device absorbs the forces of the scram within the drive mechanism to minimize deceleration forces on the control absorber assembly in the active core region.

The Gas Cooled Fast Reactor program has been suspended, but this testing activity of the deceleration device was continued to assure the prior design and fabrication work would be supported by a proof-of-principle test. The test results indicate the design is feasible and should be developed further if the GCFR program is reactivated.

The deceleration device operates on an energy exchange principle. The falling translating assembly is coupled to a rotatable mass and after the scram is initiated the translating assembly falls, inserting the control absorber into the active core region. The energy of the falling translating assembly is transferred to a flywheel making the flywheel rotate. The deceleration unit is designed so that the translating assembly impacts a bottom stop in the CRDM with a maximum "g" force impact of 10 g's.

The deceleration device testing was performed with a nearly prototypic deceleration mechanism configuration consisting of a translating assembly and a flywheel mounted on bearings in a mocked up CRDM housing. The test consists of withdrawal and scrambling the translating assembly and recording the time and distance measurements of the scram and bottoming events. The tests were performed in air to verify proof-of-principle of the design and acceptability of the scram performance.

1.1 Test Purpose

The purpose of the Deceleration Test is to provide assurance that the selected deceleration device design will reduce the deceleration forces at the bottom of the reactor shutdown stroke of the Control Rod Translating Assembly without overstressing the system with excessive "g" loadings. The test also provides assurance that the scram times are acceptable. The test is a proof-of-principle test that was conducted in air. Original plans for the test were to conduct the scram life test in a prototypic reactor helium environment, but because of the program suspension only air testing was performed.

Actual scrams were measured with distance versus time and flywheel revolution data recorded to permit determination of deceleration rates and scram forces on the critical components.

2.0 DESCRIPTION OF GCFR CRDM/CRD DESIGN

2.1 Design Description

The proposed Control Rod Drive Mechanism is shown schematically in Figure 2.1 which is included to aid in following the nomenclature presented in the following paragraphs.

The Control Rod Drive Mechanism assemblies are totally within the pressure boundary. Electrical and cooling connections penetrate the individual reactor nozzles utilizing sealed fittings.

The CRDMs control the reactivity of the GCFR by positioning selected control rods in or out of the active core in response to signals from the electrical control system.

When current is applied to the stator by the electrical control system, a magnetic field is created around the segment arms at the upper end of the rotor assembly. The field draws the upper end of the segment arms outward, rotating them on the segment pivot pins. As the upper end is drawn outward, the lower end moves inward, causing the teeth on the four roller assemblies at the bottom end of the rotor assembly to engage with the threads on the leadscrew. When the current is applied to the motor phases in a programmed sequence, the rotor assembly rotates and the leadscrew is translated in either the in or out direction depending upon the sequence of applied pulses. When stator power is interrupted, the segment arm springs force the lower end of the segment arms to pivot radially outward, releasing the leadscrew and allowing it to travel to the full in position. Scram is initiated by opening of the scram breaker in the controller which removes the electrical power from the stator. See Figure 2.2 for pictorial presentation of rotor action.

The following paragraphs describe the major assemblies of the CRDM.

UPPER CONTROL ROD DRIVE MECHANISM

The Position Indicator mounts in a holddown housing bolted to the top of the motor tube. The position indicator extends downward through this housing and into the hollow leadscrew. This detector determines the

FIGURE 2.1 - CRDM SCHEMATIC

COLLAPSIBLE ROTOR ROLLER NUT DRIVE

FIGURE 2.2 - ROTOR ACTION

absolute distance of the leadscrew above the full IN position by sensing the position of a permanent ring magnet located on the top of the leadscrew.

The Stator-Jacket Assembly consists of an electrical stator surrounded by stator cooling coils. The stator assembly and the rotor assembly form a 4 pole 6 phase, reluctance type stepping motor, in which the rotor poles tend to maintain alignment with a stepwise rotating stator field. Because the motor is a 4 pole, two complete electrical cycles are required for one rotor revolution and 0.3 inches of leadscrew travel. A combination of 0.3 inch leadscrew pitch and 12 pulses per rotor revolution lead to a incremental step of 0.025 inch per stator pulse. To minimize leads penetrating the pressure boundary, the GCFR design will utilize pulse counts to the stator for relative rod position indication (RRPI independent of the ARPI) and monitor stator resistance for indication of stator temperature. These monitors are incorporated in the electrical control system. The RRPI provides a highly accurate (<0.1 inch) position indication relative to the full IN position. The signal is not absolute in that position indication is lost upon loss of power or a rod scram.

The motor tube is the structural support for the rotor tube and stator. The motor tube is made up of a lower section, a middle section and an upper section which are welded together to form one piece. The rotor assembly mounts inside the motor tube.

The main parts of the Rotor Assembly are a rotor tube, two segment arms and four rollers. The leadscrew passes through the center of the rotor assembly. The rotor tube is the structural support for the rotor assembly. It rotates on an upper radial bearing and a lower thrust bearing. These bearings are mounted on the rotor tube outer diameter and seat in the inner diameter of the motor tube. Two segment arms, made from magnetic 403 stainless steel, are pinned to the rotor tube by means of pivot pins. A synchronizer bearing located at the top of the segment arms ensures that both segment arms pivot through the same angle simultaneously. Four roller assemblies are mounted in the lower end of the segment arms, two on each arm. The rollers are mounted on ball thrust bearings with the axis of rotation perpendicular to the helix of the leadscrew. When the

four rollers are engaged with the leadscrew, they form a roller nut which efficiently converts rotation of the rotor into translation of the leadscrew and control rod. When the stator is not energized, the rollers are held disengaged by means of eight springs mounted between the lower ends of the segment arms below the pivot pins. When sufficient current is applied to the stator, a magnetic field is created which overcomes the spring forces and pulls the upper end of the segment arms radially outward. The arms rotate on the pivot pins causing the rollers to swing radially inward and contact the leadscrew potentially at the land-to-land position. When the CRDM stator coils are energized sequentially, the rotor rotates, allowing the roller teeth to fully engage the leadscrew thread within one-half revolution of the rotor. Engagement must be accomplished while driving in the IN direction to assure complete roller engagement prior to lifting the control rod. After the rollers are engaged, the CRDM "slips poles" until the power supply phase sequence is reversed to drive the rotor in the OUT direction. The direction in which the rotor is turned determines the direction of the vertical movement of the leadscrew. Because the leadscrew is right-hand threaded, clockwise rotation of the rotor assembly (looking down on the CRDM) moves the leadscrew in the OUT direction to lift the control rod and counter-clockwise rotation lowers it. The rollers remain engaged with the leadscrew during all changes in direction of rotation. The rollers disengage the leadscrew only when the current to the stator drops to a level where the magnetic field is not strong enough to overcome the force of the segment arm springs and hold the segment arms engaged. A rotational stop limits the upward stroke of the leadscrew and the control rod. A spring loaded pawl to limit rod withdrawal is pinned to the bottom of one segment arm. In normal operation it slides on the major diameter of the leadscrew thread. At maximum withdrawal the pawl engages a detent in the leadscrew (rotational stop) and prevents further OUT rotation of the rotor. During unlatch the segment arms pivot and the stop swings clear of the leadscrew. Two anti-ejection pawls can be fastened to the segment arms. These pawls are designed such that when the leadscrew scrams the pawl fingers ratchet out against a spring return system as the

leadscrew threads pass by. This action allows the scram to continue. The finger configuration is such that they will not allow the leadscrew to move upward unless the rotor assembly is rotated. These pawls are designed to stop any ejection action of the translating portion of the drive mechanism during any abnormal event.

LOWER CRDM ASSEMBLY

The Lower CRDM seats on a ledge in its resident cavity and extends up through the top of the PCRV closure plug. It consists of a torque spline, leadscrew, scram spring, driveline and scram deceleration unit. The torque spline which is a ball bushing and grooved shaft assembly, reacts the torque delivered to the driveline by the motor and the flywheel/ translating assembly energy exchange. This design feature isolates the CRDM torque from the driveline and control rod and transfers it into the housing. The leadscrew is the translating member of the CRDM. It is connected to the control rod through the driveline. The upper end is hollow to permit insertion of the position indicator and to provide access to the disconnect actuating shaft which extends upward into the leadscrew extension. When the power to the CRDM is interrupted to initiate a scram, the leadscrew is released by the rotor assembly and the scram spring drives the leadscrew and control rod to the full IN position at a speed greater than normal driving in speed or that caused by gravity. Three concentric shafts couple the leadscrew extension to the lower driveline assembly. The inner shaft rests on top of the position indicator rod in the lower driveline and provides an extension to it. The actuating shaft is used to disconnect the control rod coupling. The outer shaft is the load carrying member of the lower mechanism assembly. The deceleration unit is described in Section 3.1.

CONTROL ROD DRIVELINE

The Control Rod Driveline consists of the maintenance coupling, three concentric shafts and the control rod disconnect coupling. The maintenance coupling is a hands-on feature utilized to separate the lower driveline from the lower control rod drive mechanism when necessary to disconnect the more highly irradiated lower driveline from the upper driveline. The inner shaft is the position indicator shaft which is used during a disconnection sequence to maintain the control rod in the IN position. The actuating shaft is used to operate the extension

shaft of the disconnect coupling.

2.2 Scram Deceleration Requirements

The overall Primary Control Rod System scram requirements include

a) unlatch time, b) scram insertion, and c) scram deceleration.

a. Unlatch Time

The CRDM unlatch time is defined as the time from start of stator current decay to the initial insertion motion of the leadscrew and is designed for a maximum of 120 milliseconds at normal CRDM and stator operating temperatures.

b. Scram Insertion

The system has the capability of allowing the control assembly to be inserted into the reactor to a shutdown control level in a time period of less than three seconds. A requirement for fast initial rod insertion to limit transient peak temperatures would be developed during GCFR project design efforts. A scram spring is utilized to assist scram insertion to assure insertion during a seismic event,

c. Scram Deceleration

The deceleration device reduces the velocity of the translating assembly when scrambled from any position to less than 14 inches per second at the time of impact on the hard stop at the end of scram insertion. This measurable impact velocity assures that deceleration loads including the impact at the hard stop are limited to 10 "g's" or less on the translating driveline and outbounding will not exceed 1/2".

GCFR reactor system requirements have specified that the scram arrest or impact be located in the CRDM rather than the control assembly to minimize evaluation efforts for highly irradiated core components due to scram force loads transmitted thru the control absorber assembly.

This test activity only addresses b) Scram Insertion and c) Scram Deceleration.

3.0 TEST ARTICLE

3.1 Description of Deceleration Unit

The deceleration test unit shown in Figure 3.1.1 consists of a cylindrical flywheel, with a helix groove cut on the inside, mounted on spherical roller bearings. Two cam followers attached to an overrunning clutch mechanism are mounted on opposite sides of the translating assembly. A simulated weight is attached to the translating assembly to mock up the total weight of the plant unit translating assembly. The cam followers couple the flywheel to the translating assembly. As the translating assembly is withdrawn, the cam followers enter the grooves in the flywheel. After the initial entry of the cams at the beginning of the stroke, the cams remain in the grooves at all times thru the scram event except at the extreme bottom of the translating assembly stroke. After the scram trip, as the translating assembly falls, the cams react to the curved portion of the grooves in the lower section of the flywheel. The overrunning clutch engages and transfers the energy developed by the falling translating assembly to the flywheel which causes the flywheel to rotate. The grooves in the flywheel have straight portions for the initial 35 inches of the total 53 inch scram insertion stroke and then form a helix curve as they approach the bottom of the flywheel. In the lower section of the flywheel, the grooves decrease in slope until at a strategically calculated height they flatten out to allow the falling translating assembly to reach negligible velocity. At that moment of negligible velocity the translating assembly seats on the bottom stop. The flat section of the curve and the bottom stop are close enough physically so that the thermal gradients of the operating reactor will not vary the height difference significantly and a small variation in the bottoming "g" force is all that ever exists. The exit of the cam follower unit from the flywheel at the bottom of the scram stroke is aided by a spring action. This action decouples the cams from the rotating flywheel and reduces the chance of the failure mode of a non-functioning overrunning clutch and subsequent windup of the driveline during the flywheel coast and slowdown period.

FIGURE 3.1.1

GCFR
DECELERATION TEST ARTICLE

3.2 Fabrication Experience

The fabrication activity of the deceleration unit components can be divided into three categories, the flywheel, the bearings and the remainder of the components.

The flywheel fabrication was the most unique of all the other components. Its basic configuration is a cylindrical mass with two helix grooves cut on the inside surface of the cylinder. The flywheel body consisted of an assembly of three separate pieces; an upper portion, that consisted of a one piece forging with two straight internal grooves machined 180° apart; a lower inner portion that formed a decreasing slope helix portion of the grooves; and a lower outer portion that served as a sleeve for the inner portion.

The upper portion was machined to the final configuration with the two inner straight grooves formed by conventional machining. The lower outer sleeve was machined to a close fit with the lower inner body. The lower grooves in the inner portion of the flywheel were formed using a special numerically controlled machine. The helix groove slope coordinates were plotted on a drawing board at double scale and the coordinate points were measured and tabulated. These coordinate points were fed into a computer and the curve was optimized and a machine control tape was generated and tested to assure the proper curve. The helix shape of the groove was machined as the forging, mounted in a fixture, was rotated at the related indexing rate to form the decreasing slope of the groove. The grooves were cut on the outside of the slug and an inner membrane held the part as an integral piece. After completion of the grooves the inner portion was fitted to the outer sleeve, bolted and pinned with a number of strategically placed fasteners and pins. The inner membrane of the inner piece was machined and ground away leaving the grooves exposed to the inside of the tube.

The upper part was fitted to the lower assembled part and pinned at the proper orientation to align the straight grooves to the curved grooves. This formed a continuous path on the inside of the flywheel for the cam followers of the translating assembly.

The flywheel material was made from a forging of a special 4340 material designated 300M. Special heat treating procedures were used to obtain the hardness specified to assure the groove track surface would withstand the high hertzian stresses introduced by the falling translating assembly. The flywheel was subjected to a double tempering heat treatment following machining. The heat treatment consisted of austenitizing at 1575°F to 1625°F, oil quenching to below 160°F and double tempering 2+2 hours at 575°F. The hardness after heat treating was in the Rc range of 52 to 54. Precautions were taken to avoid surface carburization of the cam follower groove tracks. Figures 3.2.1 and 3.2.2 show photos of the flywheel body as assembled and a photo of the grooves on the I.D.

The majority of the bearings and the torque spline bushing were designed with materials and heat treatments to withstand the forces generated during the scram, enhance the life of the units, and operate in the high purity helium GCFR environment. When the inquiries were sent out to the various bearing and spline manufacturers, no one responded to the inquiries because of the small number of components required, the strict program requirements specified, and the schedule limitations. All of the bearings and the torque spline assembly had to be purchased to standard catalogue numbers and were not prototypic of the materials planned for the plant units. A decision was made to test the units with the non-prototypic materials to expedite the proof-of-principle tests since the GCFR design project was in the process of being terminated. Figure 3.2.3 is a photo of the cam follower assembly which housed the overrunning clutch. The clutch allowed the housing to rotate in one direction only.

The remaining parts were purchased from various suppliers using normal processes and materials and no special considerations or major problems were encountered.

3.3 Planned Difference between Test Unit and Reference Design

The basic variances between the deceleration unit tested and the reference design are limited to the bearing and rolling elements of the decelerator.

Figure 3.2.1. Flywheel Assembly

Figure 3.2.2. View of Flywheel Grooves

Figure 3.2.3. Cam Follower Assembly

Figure 3.3.1. Test Unit Housing

Specifically the non-prototypic components include the following:

- o Flywheel Bearings
- o Cam Followers
- o Overrunning Clutch
- o Translating Assembly/Cam Follower Unit Ball Bearings
- o Torque Spline Bushing and Shaft

These units were all purchased as standard catalogue items instead of the reference specified materials requirements. Dimensional characteristics were as designed.

Since the deceleration test unit housing design is not prototypic of the CRDM body, the components making up the housing were fabricated from common cold rolled steel tubing adapted to fit the internal components. Figure 3.3.1 is a photo of the housing ready to receive the flywheel assembly.

Table 3.3.1 outlines materials similarities and differences of the major decelerator components. The 17-4 Ph/440C planned materials for bearings is based on improved friction and wear behavior in a high purity helium environment. Friction and wear tests (Ref. WARD-GC-94000-1) in support of this program showed substantially better wear performance for this couple than for 52100 steels.

3.4 Analyses of Decelerator Design

Extensive analyses were performed on the various attributes of the mechanical deceleration unit. Computer analyses and hand calculations indicate that the flywheel device meets the design requirements and is a feasible decelerating concept. The following analysis listing indicates the types of analyses performed and is only a representative sample:

- o Calculation of equivalent flywheel weight and mass moment of inertia
- o Assessment of sensitivity of the decelerator to certain design factors

- o Computer runs using the latest design parameters to obtain performance curves, comparison of runs, and design summary charts
- o Alternate concept studies
- o Flywheel Thermal Bowing
- o Twisting of driveline to stop translating assembly in stuck flywheel
- o Natural frequency of driveline components in bending, torsion and axial modes
- o Flywheel whirling and bursting forces
- o Hertz stresses for cam follower/flywheel groove interface
- o Forces on cam followers, cam groove shoulder and rod bottom stop
- o Comparisons of roller and ball bearings for application in the decelerator device
- o Scram spring forces and design factors

Representative samples of some of the above analyses were selected and an independent cross-check analysis was performed to verify the analysis activity. The original analysis and the selected cross-checks agreed very closely.

Table 3.3.2 summarizes predicted forces, analysis and design margins for the major components.

TABLE 3.3.1
MATERIAL TESTED

ITEM	PLANNED MATERIAL	MATERIAL TESTED	COMMENTS
Leadscrew	SA-564, Type 630*	Same	Age hardened
Guide Bushings	Stellite 6B	Same	--
Scram Spring	SA-564, Type 630	AMS 5673B	Material is the same
Scram Spring Guide	ASTM A-269, Type 304	Same	Inside dia. Vitrolubed
Flywheel Body	AMS 6419, 300M	Same	Double tempered
Flywheel End Caps	ASTM A-36	Same	Thread areas chrome plated
Bottom Stop	4340 Steel	Same	Heat treated
Splined Extension Shaft	ASTM A-564-17-4 Ph	Same	Age hardened and vitrolubed
Cam Follower Body	SA-564, Type 630	Same	Age hardened
Overrunning Clutch Flywheel Bearings Cam Followers Spline Bushing and Shaft	440C Rolling elements 17-4 Ph Race elements	Standard 52100 Bearing Steels	Purchased as catalogue items

*SA 564 - Type 630 is 17-4 Ph age hardenable stainless steel.

TABLE 3.3.2
MAJOR COMPONENT FORCES AND DESIGN MARGINS

Component	Predicted Force	Design Margin
Flywheel Bearings	2528 lb (thrust) 3152 lb (radial)	1.1 to 2.3
Cam Followers One	4240 lbs	2.55
Two	2120 lbs	5.10
Hertz Stresses on Track:		
One Cam Follower	350,818 psi	--
Two Cam Followers	279,369 psi	--
Maximum g's on T/A	7 to 8 g's	1.25 to 1.43
Torque on Linear Bushing	13000 to 14000 in lbs	1.14 to 1.23
Maximum Force on Sprag Coupling	8667/9333 lb (twist) 0 lb (axial)	2.31 to 2.49

4.0 TEST FACILITY

4.1 Description

The test article was installed in a test facility located in the ARD Hydraulic Test area adjacent to an existing test structure. Figure 4.1.1 shows the working center of the instrument panel with the withdrawal indicator and the RPM indicator along with the magnetic release switches. Figures 4.1.2 and 4.1.3 shows the test unit assembled in the test stand ready for testing. The location was chosen because it provided existing work platform and overhead crane access. The test facility provided the capability for handling the test equipment with minimum site modification. The originally planned test equipment included a test vessel, a helium purification and recirculating system, a deceleration unit heating system, an instrumentation and control system, and a data acquisition system. Figure 4.1.4 is an outline of the test vessel planned for the original test. In the actual test only the bottom section was used. Figure 4.1.5 is a schematic of the complete planned system. The original test system had been designed to performance test the deceleration test article in a helium environment at an elevated temperature, but because of the suspension of the program only a preliminary test in room temperature air was performed.

The basic abbreviated test rig consisted of:

- o A test stand made from the lower section of the test vessel shown in Figure 4.1.4.
- o An electromagnetic assembly attached to the crane to raise the translating assembly and provide a controlled disconnect with the translating assembly
- o An LVDT transducer to measure the position of the translating assembly
- o A load cell to measure the scram spring force and weight of the T/A

Figure 4.1.1. Test Console Instrument Panel

Figure 4.1.2. View of Upper Portion of Test Assy.

Figure 4.1.3. View of Lower Portion of Test Assy.

FIGURE 4.1.4
PLANNED TEST VESSEL

Special instrumentation provided monitoring and control of the test article. A high speed oscillograph (Visicorder) recorded the scram transient. Test variables obtained on the visicorder for each transient are translating assembly position versus time, flywheel rpm, impact location identified by an accelerometer, and magnet release and decay. Translating assembly weight and scram spring forces were indicated on the instrument panel and used for monitoring during each scram. A copy of a representative visicorder trace is shown in Figure 4.1.6.

The upper portions of the LVDT distance versus time curves indicate wavy patterns. This wavy pattern is a result of the method of attaching the LVDT displacement indication wire. The wire was attached to a block mounted on the top of the translating assembly. As the translating assembly fell, it was guided by a relatively close fitting guide bushing and the top of the translating assembly developed a whipping action as it approached the bottom of the stroke. This whipping action was accentuated by the block attached to the top of the translating assembly.

The LVDT indicator attaching cable length is also accentuated with this whip since it is a thin wire extended 53". The whip appears as a wavy line on the oscilloscope trace. Any detailed fine analysis in this area must be corrected for this condition and the curve must be smoothed to a steady average path. The peaks and valleys would give velocity and acceleration differentials that are not indicative of true conditions.

4.2 Instrumentation

The test facility is instrumented to measure and record various scram parameters. The parameters measured include stroke of the translating assembly, scram spring force, magnet release time, flywheel rpm and impact locations. Table 4.2.1 summarizes instrumentation used to measure and record the test parameters.

FIGURE 4.1.6
TYPICAL VISICORDER TRACE
OF SCRAM ACTION

TABLE 4.2.1
DECELERATION TEST INSTRUMENTATION

Measurement	Sensor	Range	Readout
Stroke - Distance vs Time	Reel Potentiometer - Visicorder	0 to 75 inch	Visicorder
Force to Lift Translating Assembly and Compress Scram Spring	Load Cell	0 to 1000 lbs	Instrument Panel
Translating Assembly Impacts	Piezoresistive Accelerometer	-25 to 25 Gs	Visicorder
Flywheel Speed	Special ultrasonic transducer device	0 to 60 RPM	Visicorder

The stroke of the translating assembly is measured by mounting a LVDT transducer on the test frame and connecting the reel to the translating assembly. The instrument unit is connected to a visicorder and to an indicator on the instrument panel. The indicator displays the elevation of the translating assembly to allow correct positioning for scram initiation, and the visicorder plots time versus distance of the scram event. This plot is used in a network analysis to obtain velocity and acceleration at various scram elevations.

A load cell is mounted between the lift and the translating assembly to display the translating assembly weight and also the scram spring force at the higher withdrawn positions. The load cell is connected to the instrument panel.

A magnet is mounted between the load cell and the translating assembly with a release switch on the instrument panel. The magnet provides a controlled release to initiate the scram. The magnet voltage is displayed by the visicorder trace.

The flywheel rpm is measured using a special ultrasonic transducer that counts the rpm of the flywheel by sensing a small groove cut in the flywheel O.D. The rpm counter is connected to the visicorder and records pulses on the visicorder trace that can be used to count the flywheel revolutions and can also be used to calculate the rpm's and flywheel coast and slow down time.

An accelerometer was mounted on the translating assembly, but the only information gained from it was the indication of the sequence of impacts not the magnitude. The accelerometer trace on the visicorder paper shows when the cam follower assembly entered the curve and when the bottom stop impacted and also when the cam follower assembly ejected from the flywheel. No definitive data was gained from the accelerometer since geometry of the test article dictated the mounting of the accelerometer at the top of the translating assembly and not at the point of impact.

4.3 Test operations

The translating assembly was withdrawn to 6", 12" and 18" heights and a scram was initiated from each of these positions to check capability of the system to survive these scram transients. A number of scrams were performed at 12" height to calibrate the instrumentation and visicorder output. Additional scrams were performed from 18" and at each 6" additional withdrawal until scrams from full withdrawal of 53" were attained. Visicorder traces were run on each of the scrams for detailed comparison of individual test results. Two hundred and sixty additional scrams were run at full stroke (53") and visicorder traces were printed at every fifteenth scram for comparison as the scrams progressed. No variations were noted until after the 300th scram after which the translating assembly could not be withdrawn,

The decelerator unit was removed from the test vessel and disassembled to determine the reasons for the inability to withdraw the T/A. One cam follower on the translating assembly had failed. A reminder is injected here that the cam follower material was not prototypic. The outer race had fractured and a piece approximately 3/8" in length separated from it. This failure is discussed further in Paragraph 5.2. The second cam follower was still functional, but was removed also. Two new cam followers were installed on the translating assembly. No other component or area showed any sign of wear or effect from the scrams. Along with the new cam followers changes, two additional changes were effected. In the original design at the upper and lower ends of the flywheel a grease seal was installed to prevent chips and debris from entering the flywheel bearings. These grease seals were of the design that incorporated garter springs behind the rubber seal. To check the friction these seals caused on the flywheel they were removed on the retests. Also the flywheel bearings were lubricated with a small amount of molybdenum disulphide grease. The changes were incorporated to make a friction loss comparison and is discussed further in Section 6.0. The decelerator was reassembled and testing was continued. The reassembled decelerator was subjected to 250 scrams before erratic rpm readings were observed and the translating assembly could not be withdrawn.

The decelerator unit was again removed from the test vessel and disassembled to determine the cause of failure. This time a cam follower had loosened in the Translating Assembly and worked its way out until it was rubbing on the ID of the flywheel thereby affecting the flywheel operation and translating assembly withdrawal. This failure is discussed in detail in Paragraph 5.4.

5.0 TEST RESULTS

5.1 Initial Test Results

The visicorder traces of the scrams as shown typically in Figures 5.1.1 to 5.1.8 were reviewed. All of the distance time curves have a similar bumpy pattern at rod bottoming. This phenomenon was discussed in Paragraph 4.1. The extreme consistency of the curves within each withdrawal group indicates only one curve in each group need be analyzed. The test results show little variation in the distance-time measurements. This was also indicated by the small variation in the final flywheel maximum rpm's for the 53" scram test data.

There were three consistent accelerometer patterns for rod withdrawals $\geq 24"$. These were at points interpretable as maximum deceleration, rod bottoming, and clutch dropout or rod bounce. For withdrawals $\leq 18"$, only the maximum deceleration and rod bottoming patterns are clearly indicated on the accelerometer traces. The maximum deceleration pattern, which could be a cam follower/cam groove impact, occurs at apparently random heights above full insertion between about two and eight inches and therefore does not correlate to any specific feature of the flywheel helix groove. At 53" withdrawal additional accelerometer patterns are significant at start of rod motion and at approximately seven inch insertion. The latter peak varies between scrams and has no physical interpretation other than a potential lateral impact between the cam roller and the side of the flywheel groove, or the translating assembly impacting the guide bushing.

Interpretation of the accelerometer peak pattern occurring at full insertion as the rod bottoming impact appears consistent for all recorded scrams. Only the 53" scram case of Figure 5.1.8 appears potentially inconsistent with this interpretation. The bumpy distance versus time curve near full insertion could be interpreted to indicate full insertion before the accelerometer peak. It is not known whether the bumpy distance curve indicates physical scram behavior or if it is a characteristic of the reel potentiometer used for the insertion distance measurement. The condition could be interpreted as a whipping action of the cord

FIGURE 5.1.1
12" WITHDRAWAL SCRAM VISICORDER
TRACE

FIGURE 5.1.2
18" WITHDRAWAL SCRAM VISICORDER
TRACE

FIGURE 5.1.3
24" WITHDRAWAL SCRAM VISICORDER
TRACE

FIGURE 5.1.4
30" WITHDRAWAL SCRAM VISICORDER
TRACE

FIGURE 5.1.5
36" WITHDRAWAL SCRAM VISICORDER
TRACE

FIGURE 5.1.6
42" WITHDRAWAL SCRAM VISICORDER
TRACE

FIGURE 5.1.7
48" WITHDRAWAL SCRAM VISICORDER
TRACE

FIGURE 5.1.8
53" WITHDRAWAL SCRAM VISICORDER
TRACE

attached between the translating assembly and the reel pot body as discussed in Paragraph 4.1. Since the slopes of the distance versus time curves are very small near full insertion, it is difficult to obtain accurate scram times or final impact velocities from the distance curves. Use of the accelerometer peak as the full insertion indication appears to provide the most reliable full insertion scram time estimate. Accelerometer magnitude was ignored since the mounting of the accelerometer magnified the readings and is no indication of the "g" level at impact.

5.2 Examination of Failed Cam Follower

At scram 300 one of the cam followers failed. The outer race fractured and a piece about 3/8" separated from the outer race. A reminder is repeated here: the outer race material was not prototypic of the material type specified for the plant unit cam followers. Figure 5.2.1 is a photograph of the failed cam follower and the other cam follower removed from the decelerator unit after 300 scrams. Both cam followers show a circumferential polishing which indicates the expected rolling contact with the flywheel groove. The broken cam follower has a slightly higher degree of polishing which could indicate that this follower carried higher loads than the other.

The fractured section exhibited a slight wear flat on the OD surface that appears to indicate the outer race was subjected to a sharp blow in the scram transient which caused the fracture. Smaller chips were recovered, one of which is shown in the photograph which also seems to indicate failure by impact. The mating groove in the flywheel has no damage. It is conceivable the cam follower was struck by the nose of the groove web at the bottom exit area of the groove as the flywheel rotated after the cam follower mechanism exited the flywheel at the bottom of the groove.

Since no other component in the decelerator unit exhibited any damage, an actual cause cannot be attributed to the cam follower failure. A possible cause could be a defective outer race in the as-manufactured state since no special handling of the components was specified.

Figure 5.2.1. Failed Cam Follower and Second Cam Follower Removed After First Test Phase

5.3 Retest Results

A visicorder trace of a selected scram representing the second series of scram tests is shown in Figure 5.3.1. The difference in the visual appearance of the traces when compared to the initial test traces is a result of slowing down the paper speed from 10 inches a second to 4 inches a second. Flywheel coast down time increased significantly therefore the paper speed reduction was initiated to conserve on visicorder paper.

The distance versus time curve has a similar bumpy pattern at rod bottoming. The consistency of the curves within the retest phase compare with the consistency of the initial phase tests. There is a slight variation in velocity and acceleration between the initial phase and the retest phase curves because of the elimination of some friction forces, therefore, a network analysis was performed on representative curves and are included in Section 6.2. There was also a variation in the rpm maximum value and flywheel coast down time. These variations were caused by removal of the debris seal which incorporated a garter spring design to hold the rubber seal portion of the seal against the rotating hubs of the flywheel.

The retest phase traces appeared to parallel the actions of the initial test and it is concluded the garter springs from the debris seals had only minimum effect on the deceleration.

At around scram No. 250 the rpm indications were erratic and difficulties were encountered during translating assembly withdrawal, at this time testing was terminated. The unit was removed from the test facility and disassembled for post-test examination. The results of the examination are described in the next paragraph.

5.4 Post-Test Examination of Decelerator Components

The deceleration unit was completely disassembled and the components were inspected for damage and wear. Upon examination it was determined that the failure was caused by faulty pinning of a cam follower stud to the body of the clutch housing. The cam follower unthreaded after the pin separated from the stud. The clearances between the flywheel groove and the cam follower only allowed the cam follower to ratchet out until it started rubbing the inside of the flywheel.

FIGURE 5.3.1
 SELECTED VISICORDER TRACE REPRESENTING RETEST
 PHASE TESTS
 (53" Scram Withdrawal)

Figure 5.4.1 shows the clutch housing and the cam followers. Figure 5.4.2 shows the extent of damage on the cam follower caused by the rubbing action against the flywheel. Figure 5.4.4 shows the rub marks on the inside of the flywheel. (Note: This picture of the flywheel was taken after the groove tracks were removed). The flywheel tracks were not affected by this anomaly. The cam followers show smooth, even rub marks on the outer races which would indicate good contact and rolling action.

Figure 5.4.3 shows the disassembled overrunning clutch. This clutch was purchased from catalog specifications and worked satisfactory. Upon disassembly, it was discovered the garter springs that hold the over-running elements in place in their cage were destroyed. This failure did not affect the clutch operation and the spring pieces were captured. Some different design such as elimination of the spring or a material change should be considered if further use or testing is performed.

Figure 5.4.5 shows broken fragments of bolts that were used to hold the internal groove segments to the outer sleeve and Figure 5.4.6 shows rub marks caused by the head action of the bolts as they worked their way out of the holes and lodged between the flywheel OD and housing. This is not a significant failure since it does not represent prototypic manufacture of the flywheel. It was contemplated to machine the flywheel from one piece using a special groove cutting device but time and money prevented use of this method. Instead the flywheel was made from three pieces as explained in Paragraph 3.2. This method of fabrication resulted in a weak area of track force reaction. Figures 5.4.7 and 5.4.8 show the sections of track removed from the sleeve. As can be seen the lower end of the track becomes very thin and could only be bolted and pinned in very selective areas. This method of holding the track was satisfactory until the one cam follower loosened and allowed the full scram load to be carried by one cam follower toward the end of the test cycle. This action also caused the load to be reacted by a single track which proved to be too great for the bolts holding the lower section of the track to the sleeve.

The contemplated fabrication process for the plant unit eliminates the need for these bolts, therefore this failure is ignored for this evaluation.

Figure 5.4.1. Outer Race of Over Running Clutch w/Cam Followers

Figure 5.4.2. Closeup of Loose Cam Follower Showing Rubbing Results

Figure 5.4.3. Over Running Clutch Showing Destroyed Garter Springs

Figure 5.4.4. View of Inside of Flywheel Showing Rub Marks from Cam Follower

Figure 5.4.5. Broken Flywheel Insert Bolts

Figure 5.4.6. Rub Area on Outside of Flywheel from Broken Bolts

Figure 5.4.7. Flywheel Track

Figure 5.4.8. Flywheel Track

Figures 5.4.7 and 5.4.8 also show the wear surfaces upon which the cam followers interfaced. No significant deleterious wear areas were noticed.

All the remaining parts were inspected and showed no signs of damage or wear.

Results of the test show that closer control of the assembly activities with respect to the cam follower assembly should be exercised. The cam followers should seat solidly against the housing with some preload. The threads on the cam followers should be left hand threads so that the scram action tends to tighten the cam followers instead of loosen them.

There was no damage or wear discernable on the tracks, or on the ball bushing which reacts the torque developed by the scram forces. All the bearing elements functioned satisfactorily even though the materials were not representative of design specifications.

In general even though only 550 scrams were achieved it is considered that the failures were not design related and the goal of 700 scrams could easily be achieved with the contemplated deceleration unit.

6.0 EVALUATION OF TEST RESULTS

Detailed evaluation was performed on initial and retest phase of the 30", 36", 42", 48" and 53" withdrawals.

The test numbers are summarized below for 53 inch scrams:

Parameter	Design Base*	Analysis Value*	Test Value*	Retest Value
Insertion velocity in/sec	186/196	186.7/196	195	200
Max. Deceleration G's	10	6.5/6.0	5.6	5.7
Rod bottoming velocity in/sec	14	10/9.6	<13**	
Scram time sec	<3	.5	.5	.5
Number of scrams	700		300	250
Max. flywheel RPM	500	500	444	462
Flywheel run time	<5 min.	<5 min.	~4 sec.	20 sec

*The two values listed bound the values used in analytical efforts and the values encountered during the test.

**Difficult to obtain accurately due to fluctuations in reel pot position indicator traces. Value of 13 in/sec is maximum obtained from various smoothed curve estimates over last 0.05 sec prior to full insertion accelerometer indication.

A summation of maximum velocities and accelerations are presented below:

Scram Height	In/Sec Max. Velocity	In/Sec ² Max. Accel.	In/Sec ² Max. Decel.	Max. G's
<u>Initial Testing</u>				
30"	113	552	-860	2.23
36"	127	652	-1400	3.63
42"	154	1020	-1260	3.26
48"	178	932	-1736	4.49
53"	194	820	-2172	5.63
<u>Retest</u>				
30"	122	800	-920	2.38
36"	143	1020	-1304	3.38
42"	160	920	-2064	5.35
48"	197	1160	-1624	4.21
53"	200	920	-2200	5.7

The variation in readings that do not match the trends of velocity, acceleration and g's are due to the course method of analysis of the visicorder traces. A slight variation of measurement on the traces can cause a significant difference in the attained parameters. No attempt was made to adjust original readings and measurements to improve the parameter continuity or to smooth the curves.

6.1 Initial Test Data Evaluation

Figures 6.1.1.1 thru 6.1.5.3 are visicorder traces and curves that plot the insertion distance versus time curve, velocity curve and deceleration curve. The velocity and accelerometer curves were plotted using a Δt versus distance network analysis and the results are tabulated in Tables 6.1.1 thru 6.1.5.

The distance versus time curves of four cases of the 53" scram were analyzed for flywheel rpm results. The curves were almost the same and appear as if they are tracings of each other. The rpm ranges from 435 to 444 rpm are within 500 rpm of the analysis rpm values. The 53" scram data is quite consistent without much spread.

The RPMs are calculated from the visicorder traces as follows:

$$\begin{aligned} \text{RPMs (calculated)} &= \frac{1/2 \text{ Rev.}}{\text{distance between } 1/2 \text{ Rev. markers on visicorder paper}} \times \frac{1'' \text{ visicorder paper}}{.10 \text{ sec}} \times \frac{60 \text{ sec}}{\text{min.}} = \\ &\quad \frac{300}{\text{distance between } 1/2 \text{ Rev. markers on visicorder paper}} \text{ RPMs} \end{aligned}$$

Based on the data collected from the initial test of 300 scrams, the amount of energy lost to friction in the test relative to the conservative analysis prediction assuming no friction is found from an energy balance on the flywheel at the final maximum flywheel speed.

Calculations of energy lost to friction for a typical test rpm at 444.2 are:

Fraction of
energy initially
lost to friction

$$= \frac{\frac{1}{2} I_{\text{flywheel}} W_{\text{no friction}}^2 - \frac{1}{2} I_{\text{flywheel}} W_{\text{friction case}}^2}{\frac{1}{2} I_{\text{flywheel}} W_{\text{no friction}}^2}$$

$$= \frac{\text{RPM}_{\text{no friction}}^2 - \text{RPM}_{\text{friction}}^2}{\text{RPM}_{\text{no friction}}^2}$$

$$= \frac{495^2 - 444.2^2}{495^2} \quad (\text{minimum analysis value} = 495 \text{ rpm})$$

$$= \frac{513^2 - 444.2^2}{513^2} \quad (\text{maximum analysis value} = 513 \text{ rpm})$$

$$= .195 \text{ to } .250$$

Thus about 20% to 25% of the rod energy is initially lost to bearing, seal, sliding friction and air drag at the instant the flywheel reaches its maximum rpm prior to the start of flywheel coast and slow down period.

TABLE 6.1.1
 TABULAR CALCULATION OF CONTROL ROD VELOCITY AND ACCELERATION - 30" SCRAM
 30" Withdrawn
 Medium Network Analysis: $\Delta t = .05$ sec.

Time	Insertion Distance	Δy	$V = \frac{\Delta y}{\Delta t}$	ΔV	$A = \frac{\Delta V}{\Delta t}$	$g's = \frac{A}{386}$
Seconds	Inches	Inches	in/sec	in/sec	in/sec ²	g's
$\Delta t = .05$ [0	0	.10	2.00	23.00	460.	1.19
[.05	.10	1.25	25.00	21.60	432.	1.12
.10	1.35	2.33	46.60	27.60	552.	1.43
.15	3.68	3.71	74.20	24.00	480.	1.24
.20	7.39	4.91	98.20	15.20	304.	.79
.25	12.30	5.67	113.40	-19.40	-388.	-1.00
.30	17.97	4.70	94.00	- 7.60	-152.	- .39
.35	22.57	4.32	86.40	-43.00	-860.	-2.23
.40	26.99	2.17	43.40	-30.20	-604.	-1.56
.45	29.16	.66	13.20	-10.00	-200.	- .52
.50	29.82	.16	3.20	- 2.80	- 56.	- .14
.55	29.98	.02	.40			
.60	30.00					

FIGURE 6.1.1.1
30" WITHDRAWAL SCRAM .05 Δt NETWORK
ANALYSIS

FIGURE 6.1.1.2

30" WITHDRAWAL SCRAM
VELOCITY CURVE

FIGURE 6.1.1.3
30" WITHDRAWAL SCRAM
ACCELERATION CURVE

TABLE 6.1.2
 TABULAR CALCULATION OF CONTROL ROD VELOCITY AND ACCELERATION - 36" SCRAM
 36" Withdrawn
 Medium Network Analysis: $\Delta t = .05$ sec.

Time	Insertion Distance	Δy	$V = \frac{\Delta y}{\Delta t}$	ΔV	$A = \frac{\Delta V}{\Delta t}$	$g's = \frac{A}{386}$
Seconds	Inches	Inches	in/sec	in/sec	in/sec ²	g's
$\Delta t = .05$ [0	0	.10	2.00	29.00	580.	1.50
[.05	.10	1.55	31.00	22.80	456.	1.18
.10	1.65	2.69	53.80	32.60	652.	1.69
.15	4.34	4.32	86.40	20.40	408.	1.06
.20	8.66	5.34	106.80	20.20	404.	1.05
.25	14.00	6.35	127.00	6.20	124.	.32
.30	20.35	6.66	133.20	-33.40	-668.	-1.73
.35	27.01	4.99	99.80	-23.80	-476.	-1.23
.40	32.00	3.80	76.00	-70.00	-1400.	-3.63
.45	35.80	.30	6.00	- 7.00	-140.	- .36
.50	36.10	-.05	-1.00	0		
.55	36.05	-.05	-1.00			
.60	36.00					

FIGURE 6.1.2.1
36" WITHDRAWAL SCRAM .05 Δt NETWORK
ANALYSIS

FIGURE 6.1.2.2
3C WITHDRAWAL SCRAM
VELOCITY CURVE

FIGURE 6.1.2.3

36" WITHDRAWAL SCRAM
ACCELERATION CURVE

TABLE 6.1.3

TABULAR CALCULATION OF CONTROL ROD VELOCITY AND ACCELERATION - 42" SCRAM

42" Withdrawn
 Medium Network Analysis: $\Delta t = .05$ sec.

Time	Insertion Distance	Δy	$V = \frac{\Delta y}{\Delta t}$	ΔV	$A = \frac{\Delta V}{\Delta t}$	$g's = \frac{A}{386}$
Seconds	Inches	Inches	in/sec	in/sec	in/sec ²	g's
$\Delta t = .05$ [0	0	.55	11.00	24.00	480.	1.24
[.05	.55	1.75	35.00	51.00	1020.	2.64
.10	2.30	4.30	86.00	16.00	320.	.83
.15	6.00	5.10	102.00	25.60	512.	1.33
.20	11.10	6.38	127.60	23.80	476.	1.23
.25	17.48	7.57	151.40	2.80	56.	.14
.30	25.05	7.71	154.20	-38.80	-776.	-2.01
.35	32.76	5.77	115.40	-63.00	-1260.	-3.26
.40	38.53	2.62	52.40	-38.40	-768.	-1.99
.45	41.15	.70	14.00	-12.00	-240.	-.62
.50	41.85	.10	2.00	-2.00	-40.	-.10
.55	41.95	0	0			
.60	41.95					

FIGURE 6.1.3.2

42" WITHDRAWAL SCRAM
VELOCITY CURVE

FIGURE 6.1.3.3
42" WITHDRAWAL SCRAM
ACCELERATION CURVE

TABLE 6.1.4

TABULAR CALCULATION OF CONTROL ROD VELOCITY AND ACCELERATION - 48' SCRAM

48" Withdrawn

Medium Network Analysis: $\Delta t = .05$ sec.

Time	Insertion Distance	Δy	$V = \frac{\Delta y}{\Delta t}$	ΔV	$A = \frac{\Delta V}{\Delta t}$	$g's = \frac{A}{386}$
Seconds	Inches	Inches	in/sec	in/sec	in/sec ²	g's

$\Delta t = .05$	[0	0	.41	8.20	46.60	932.	2.41
	[.05	.41	2.74	54.80	34.60	692.	1.79
	.10	3.15	4.47	89.40	29.80	596.	1.54
	.15	7.62	5.96	119.20	22.40	448.	1.16
	.20	13.58	7.08	141.60	30.20	604.	1.56
	.25	20.66	8.59	171.80	6.40	128.	.33
	.30	29.25	8.91	178.20	-35.40	-708.	-1.83
	.35	38.16	7.14	142.80	-86.80	-1736.	-4.49
	.40	45.30	2.80	56.00	-57.00	-1140.	-2.95
	.45	48.10	- .05	- 1.00	6.00	120.	.31
	.50	48.05	.25	5.00	- 6.60	-132.	-.34
	.55	48.30	- .08	- 1.60			
	.60	48.22					

FIGURE 6.1.4.1

48" WITHDRAWAL SCRAM .05 Δt NETWORK

FIGURE 6.1.4.2
48" WITHDRAWAL SCRAM
VELOCITY CURVE

FIGURE 6.1.4.3

48" WITHDRAWAL SCRAM
ACCELERATION CURVE

TABLE 6.1.5
TABULAR CALCULATION OF CONTROL ROD VELOCITY AND ACCELERATION - 53" SCRAM
53" WITHDRAWN

Medium Network Analysis: $\Delta t = .05$ sec.

Time	Insertion Distance	Δy	$V = \frac{\Delta y}{\Delta t}$	ΔV	$A = \frac{\Delta V}{\Delta t}$	$g's = \frac{A}{386}$
Seconds	Inches	Inches	in/sec	in/sec	in/sec ²	g's
$\Delta t =$ [0	0	.92	18.4	41.0	820.	2.12
.05 [.05	.92	2.97	59.4	43.2	864.	2.24
.10	3.89	5.13	102.6	14.2	284.	.74
.15	9.02	5.84	116.8	24.6	492.	1.27
.20	14.86	7.07	141.4	34.8	696.	1.80
.25	21.93	8.81	176.2	18.4	368.	.95
.30	30.74	9.73	194.6	-22.4	-448.	-1.16
.35	40.47	8.61	172.2	-65.6	-1312.	-3.40
.40	49.08	5.33	106.6	-108.6	-2172.	-5.63
.45	53.41	-.10	-2.0	-.20	-4	-.01
.50	53.31	-.11	-2.2	.20	4	.01
.55	53.20	-.10	-2.0			
.60	53.10					

FIGURE 6.1.5.1
53" WITHDRAWAL SCRAM .05 Δt NETWORK
ANALYSIS

FIGURE 6.1.5.2
53" WITHDRAWAL SCRAM
VELOCITY CURVE

6.2 Retest Data Evaluation

Figures 6.2.1.1 thru 6.2.5.3 are the visicorder traces and curves that plot the insertion distance versus time curves, velocity curve, and decelerating curve. The velocity and deceleration curves were plotted using a Δt versus distance network analysis and the results are tabulated in Tables 6.2.1 thru 6.2.5.

The flywheel rpm increased because of the elimination of the drag caused by the debris seals. The rpm readings increased from 495 to 513 revolutions per minute and the coast down time increased to approximately 20 seconds.

With the debris shields removed and the flywheel bearings greased in the retest phase the same energy balance calculations as performed in the initial test evaluation are:

$$\begin{aligned} &\text{Fraction of} \\ &\text{Energy initially} \\ &\text{lost to friction} \\ &= \frac{\text{RPM}_{\text{no friction}}^2 - \text{RPM}_{\text{friction}}^2}{\text{RPM}_{\text{no friction}}^2} \\ &= \frac{495^2 - 462^2}{495^2} = .128 \quad \text{minimum value} \\ &= \frac{513^2 - 462^2}{513^2} = .189 \quad \text{maximum value} \\ &= .128 \text{ to } .189 \end{aligned}$$

About 13% to 19% of the rod energy is lost to bearing and sliding friction and air drag in the retest phase. Comparing this loss to the initial phase testing it would appear that the 6% to 7% rod energy difference is attributable to the removal of the debris shields and to bearing lubrication.

TABLE 6,2,1

TABULAR CALCULATION OF CONTROL ROD VELOCITY AND ACCELERATION - 30" SCRAM

30" Withdrawn
 Medium Network Analysis: $\Delta t = .05$ sec.

Time	Insertion Distance	Δy	$V = \frac{\Delta y}{\Delta t}$	ΔV	$A = \frac{\Delta V}{\Delta t}$	$g's = \frac{A}{386}$
Seconds	Inches	Inches	in/sec	in/sec	in/sec ²	g's
0	0	.05	1.00	40.00	800.	2.07
.05	.05	2.05	41.00	22.00	440.	1.14
.10	2.10	3.15	63.00	24.00	480.	1.24
.15	5.25	4.35	87.00	35.00	700.	1.81
.20	9.60	6.10	122.00	- 4.00	- 80.	- .21
.25	15.70	5.90	118.00	-22.00	-440.	-1.14
.30	21.60	4.80	96.00	-38.00	-760.	-1.97
.35	26.40	2.90	58.00	-46.00	-920.	-2.38
.40	29.30	.60	12.00	- 4.00	- 80.	- .21
.45	29.90	.40	8.00	-12.00	-240.	- .62
.50	30.30	- .20	- 4.00	2.00	40.	.10
.55	30.10	- .10	- 2.00			
.60	30.00					

FIGURE 6.2.1.1
30" WITHDRAWAL SCRAM .05 Δt NETWORK
ANALYSIS

FIGURE 6.2.1.2

30" WITHDRAWAL SCRAM
VELOCITY CURVE

FIGURE 6.2.1.3
30" WITHDRAWAL SCRAM
ACCELERATION CURVE

TABLE 6.2.2

TABULAR CALCULATION OF CONTROL ROD VELOCITY AND ACCELERATION - 36" SCRAM

36" Withdrawn
 Medium Network Analysis: $\Delta t = .05 \text{ sec.}$

Time	Insertion Distance	Δy	$V = \frac{\Delta y}{\Delta t}$	ΔV	$A = \frac{\Delta V}{\Delta t}$	$g's = \frac{A}{386}$
Seconds	Inches	Inches	in/sec	in/sec	in/sec ²	g's
0	0	.50	10.00	15.00	300.	.78
.05	.50	1.25	25.00	51.00	1020.	2.64
.10	1.75	3.80	76.00	23.00	460.	1.19
.15	5.55	4.95	99.00	41.00	820.	2.12
.20	10.50	7.00	140.00	3.00	60.	.15
.25	17.50	7.15	143.00	-31.00	-620.	-1.61
.30	24.65	5.60	112.00	-22.00	-440.	-1.14
.35	30.25	4.50	90.00	-65.20	-1304.	-3.38
.40	34.75	1.24	24.80	-14.80	-296.	-.77
.45	35.99	.50	10.00	-18.80	-376.	-.97
.50	36.49	-.44	-8.80	7.80	156.	.40
.55	36.05	-.05	-1.00			
.60	36.00					

FIGURE 6.2.2.1
36" WITHDRAWAL SCRAM .05 Δt NETWORK
ANALYSIS

FIGURE 6.2.2.2
36" WITHDRAWAL SCRAM
VELOCITY CURVE

FIGURE 6.2.2.3

36" WITHDRAWAL SCRAM
ACCELERATION CURVE

TABLE 6.2.3

TABULAR CALCULATION OF CONTROL ROD VELOCITY AND ACCELERATION - SCRAM NUMBER

42" Withdrawn
Medium Network Analysis: $\Delta t = .05$ sec.

Time	Insertion Distance	Δy	$V = \frac{\Delta y}{\Delta t}$	ΔV	$A = \frac{\Delta V}{\Delta t}$	$g's = \frac{A}{386}$
Seconds	Inches	Inches	in/sec	in/sec	in/sec ²	g's
0	0	1.25	25.00	45.00	900.	2.33
.05	1.25	3.50	70.00	46.00	920.	2.38
.10	4.75	5.80	116.00	11.00	220.	.57
.15	10.55	6.35	127.00	33.00	660.	1.71
.20	16.90	8.00	160.00	- 1.00	- 20.	- .05
.25	24.90	7.95	159.00	-16.00	-320.	- .83
.30	32.85	7.15	143.00	-103.20	-2064.	-5.35
.35	40.00	1.99	39.80	-36.60	-732.	-1.89
.40	41.99	.16	3.20	- 4.20	- 84.	- .22
.45	42.15	- .05	- 1.00	0	0	0
.50	42.10	- .05	- 1.00	0	0	0
.55	42.05	- .05	- 1.00			
.60	42.00					

FIGURE 6.2.3.1
42" WITHDRAWAL SCRAM .05 Δt NETWORK
ANALYSIS

FIGURE 6.2.3.2

42" WITHDRAWAL SCRAM
VELOCITY CURVE

FIGURE 6.2.3.3
42" WITHDRAWAL SCRAM
ACCELERATION CURVE

TABLE 6.2.4

TABULAR CALCULATION OF CONTROL ROD VELOCITY AND ACCELERATION - 48" SCRAM

48" Withdrawn
 Medium Network Analysis: $\Delta t = .05$ sec.

Time	Insertion Distance	Δy	$V = \frac{\Delta y}{\Delta t}$	ΔV	$A = \frac{\Delta V}{\Delta t}$	$g's = \frac{A}{386}$
Seconds	Inches	Inches	in/sec	in/sec	in/sec ²	g's
0	0	1.10	22.00	58.00	1160.	3.00
.05	1.10	4.00	80.00	40.00	800.	2.07
.10	5.10	6.00	120.00	27.00	540.	1.40
.15	11.10	7.35	147.00	23.40	468.	1.21
.20	18.45	8.52	170.40	27.20	544.	1.41
.25	26.97	9.88	197.60	-44.80	-896.	-2.32
.30	36.85	7.64	152.80	-81.20	-1624.	-4.21
.35	44.49	3.58	71.60	-63.60	-1272.	-3.29
.40	48.07	.40	8.00	-14.40	-288.	-.75
.45	48.47	-.32	-6.40	5.40	108.	.28
.50	48.15	-.05	-1.00	-1.00	-20.	-.05
.55	48.10	-.10	-2.00			
.60	48.00					

FIGURE 6.2.4.1
48" WITHDRAWAL SCRAM .05 Δt NETWORK
ANALYSIS

FIGURE 6.2.4.2

48" WITHDRAWAL SCRAM
VELOCITY CURVE

FIGURE 6.2.4.3

48" WITHDRAWAL SCRAM
ACCELERATION CURVE

TABLE 6.2.5

TABULAR CALCULATION OF CONTROL ROD VELOCITY AND ACCELERATION - 53" SCRAM

53" Withdrawn

Medium Network Analysis: $\Delta t = .05$ sec.

Time	Insertion Distance	Δy	$V = \frac{\Delta y}{\Delta t}$	ΔV	$A = \frac{\Delta V}{\Delta t}$	$g's = \frac{A}{386}$
Seconds	Inches	Inches	in/sec	in/sec	in/sec ²	g's
0	0	.90	18.00	46.00	920.	2.38
.05	.90	3.20	64.00	38.00	760.	1.97
.10	4.10	5.10	102.00	18.00	360.	.93
.15	9.20	6.00	120.00	22.00	440.	1.14
.20	15.20	7.10	142.00	16.00	320.	.83
.25	22.30	7.90	158.00	42.00	840.	2.18
.30	30.20	10.00	200.00	-62.00	-1240.	-3.21
.35	40.20	6.90	138.00	-24.00	-480.	-1.24
.40	47.10	5.70	114.00	-110.00	-2200.	-5.70
.45	52.80	.20	4.00	-4.00	-80.	-.21
.50	53.00	0	0	0	0	0
.55	53.00	0	0			
.60	53.00					

FIGURE 6.2.5.1
53" WITHDRAWAL SCRAM .05 Δt NETWORK ANALYSIS

FIGURE 6.2.5.2
53" WITHDRAWAL SCRAM
VELOCITY CURVE

FIGURE 6.2.5.3
53" WITHDRAWAL SCRAM
ACCELERATION CURVE

7.0 TEST CONCLUSIONS

Based on the evaluated results the test article has achieved its design function and met its proof-of-principle goals and analysis values within normal allowance for experimental error. Mechanically, the test article runs relatively smoothly, the rod is stopped with a minimal bottom bump, and all operational requirements appear to be satisfied.

The test has verified the decelerator design meets GCFR requirements with the exception that helium environmental effects were not tested.

If the GCFR program is reactivated, additional testing is required with prototypic components in helium atmosphere at reactor temperatures to make a final conclusion with respect to final design goals.