CONF-771217-5

MASTER

REVIEW OF

FFTF AND CRBRP

CONTROL ROD SYSTEMS DESIGNS

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October 4, 1977

1.0 INTRODUCTION

Much of the design experience for the Clinch River Breeder Reactor (CRBR design was developed in the design of the Fast Flux Test Facility (FFTF). CRBR designers were able to review the concepts developed for FFTF, integrate the current test data, and modify the designs and concepts as necessary to meet CRBR requirements. The primary control rod system design for CRBR progressed by the same evolutionary process, starting from the FFTF design concepts and integrating the considerable test data available and the specific requirements of CRBR.

This paper describes the evolution of the primary control rod system design for FFTF and CRBR, beginning with the initial choice of the basic concepts. The significant component and systems tests are reviewed together with the test results which referenced the development of the CRBR primary control rod system design. Modifications to the concepts and detail designs of the FFTF control rod system were required principally to satisfy the requirements of CRBR, and at the same time incoporating design refinements shown desirable by the tests.

The present status of the CRBR control rod system design is the inception of the systems and component test program to verify performance of the CRBR primary control rod system. The planned tests reflect the emphasis on reliability, and address the potential failure modes which the design experience has shown to be significant. It is expected that the experience from the current design experience and tests will contribute to future control rod systems designs as the FFTF experience contributed to CRBR.

2.0 FFTF Control Rod System Design

The choice of a collapsible rotor-roller nut control rod drive mechanism for FFTF and the CRBR Primary Control Rod System has essentially the same basis. The fundamental requirement is that the system provide incremental rod motions small enough, when compared to the reactor controller dead band, to preclude controller limit cycling. Rod motion steps on the order of 0.025 inch are desired to maintain adequate margin against limit cycling. A second concept limit factor was the desire to provide positive drive-in capability for the control rod which leads to a requirement to provide a 1000 lb minimum drive-in force to free a stuck rod. Other factors which did not necessarily fix the choice of systems but certainly influenced the choice were:

- Interface constraints of limited space and desired geometry
- Desired maintenance and refueling mode
- "Fail-safe" characteristics. The system must put the reactor in a safe condition if external power fails.
- Prior operational experience

An independent study was performed to integrate the basic requirements with the known available concepts (Ref. 1). This study identified three candidate systems as having the potential for satisfying the requirements. These were the Collapsible Rotor-Roller Nut Mechanism (CRRNM), the Magnetic Jack, and the Ball Screw. The former two had wide usage on thermal reactors, while the latter was successfully used on the Fermi Reactor a liquid metal reactor, as well as other reactors. The only one of these systems which had all the required attributes was the CRRNM. The magnetic jack could not provide either the required rod motion steps (the .025 inch step required motion is approximately the lower limit of magnetic jack capability) or positive drive-in capacity. Despite its use on several existing reactors, the technology for the ball screw mechanism, with its required separate scram latch was not as well developed in the U.S.A. as the roller nut type. In addition, the maintenance functions are not as straightforward with the existing ball screw type drive. The modifications required to improve the maintenance functions as well as to meet the FFTF space constraints would have resulted in an essentially new and untested design. Therefore, the roller nut drive mechanism was the logical choice, based on its operational capabilities and well developed technology.

Since the operating experience in sodium vapor was minimal, it was recommended that the drive mechanism be sealed from the sodium vapor by metallic bellows. The only test data available at the time of this recommendation showed no degradation of drive mechanism performance due to the sodium vapor. However the test was not sufficient basis to justify operation in sodium vapor, and the bellows seal system was incorporated into the design.

Detailed design features of the control rod drive mechanism are fixed by specific operating requirements, interfaces and environments. The requirements typically include stroke length, velocity, system weights, scram and safety requirements. Environmental considerations include steady state and transient thermal duty cycle, atmosphere and seismic loading. The integration of the specific set of requirements for the FFTF mechanism, and the resulting design configuration are detailed by Toepel and Moodey (Ref. 2).

For FFTF, the connecting link between the drive mechanism and the control rod - the driveline - was based principally on the FFTF refueling requirements. Both top and bottom driveline disconnects were required to permit lateral motion of the instrument tree and obtain access to the core assemblies by the fuel handling machine. Coupling operations are performed using a special disconnect actuating tool entered through the top of the CRDM. Material selections were made for the coupling and its sleeve to produce thermally induced joint lockup for buckling rigidity of the shafting, and prevent motion which might lead to fretting and wear.

The control rod design is dictated by interfaces such as nuclear, refueling and geometrical requirements. Its hexagonal inner and outer duct cross section conforms to the chosen core pitch and maximizes the absorber volume fraction. A 61 pin, sealed pin absorber utilizing Natural B_4C was chosen for FFTF based on estimated lifetime behavior. Clearances between the movable control rod and its duct were established to minimize the number of contact points, and hard wear pads were provided at the contact points on the top and bottom of the movable rod. The control rod shaft was sized to introduce rotational flexibility, and sleeved to retain buckling strength to transient drive-in loads applied against a stuck rod. In the fully inserted position, the movable control rod rests on a scram arrest flange in the handling socket at the top of the assembly.

3.0 FFTF Testing

The major tests conducted on FFTF components and prototypes were bellows seal tests, a CRDM life test in air, a control assembly hydraulics test, a scram dynamics test, and prototype system life tests in prototypic sodium environments. The bellows test provided initial data for large metallic bellows subject to scram motion in a sodium environment. The control assembly hydraulic test and the scram dynamics test provided hydraulic data emphasizing the flow split between the pin bundle and bypass flow, pressure drops and flow induced vibrations and the scram characteristics of the control rod driveline. The data from these tests was used primarily to calibrate analytical models. The life tests provided performance and wear related data over lifetimes exceeding expected FFTF operational requirements. More detailed discussions of the bellows and life tests are given below.

Other basic technology testing, of general interest for all core assemblies, benefited the control rod system design. Among these tests are the piston ring tests (Ref. 3) performed to evaluate various material combinations of piston rings to limit core assembly flow from the high pressure inlet to the low pressure plenum. The data from these tests provided the basis for the selection of chrome plated inconel rings for use on the core assemblies for both FFTF and CRBRP.

3.1 Bellows Test

FFTF bellows were tested at LMEC prior to fabrication of prototype drive mechanisms by Royal Industries and as a part of the CRDM life test in air. Additional performance data available from the control rod system life test are discussed later.

The design of the FFTF main bellows is described in Table 1. Accelerated tests were performed at LMEC on three prototype bellows to simulate the 10 year design duty cycle in one month (Ref. 4). The environment for these tests was argon controlled at 450 ± 25°F over liquid sodium at 1050°F with the bellows located above the sodium pool. To simulate the actual bellows operating conditions, the test installation was designed to provide the design compression velocity (9 ipm) as well as prototypic scram acceleration and deceleration. In addition, the material couples of the test installation were made the same as the FFTF drive mechanism design at critical points to simulate the wear potential. Each bellows was Helium leak tested prior to cycling, and all three bellows exhibited leak rates below the 1×10^{-4} scc/sec allowed. Bellows internal pressure was maintained at the design pressure (21 psig) in the compressed state. An additional test of the bellows was performed as a part of the control rod drive suppliers equipment life test (see below), in an Argon/air environment at a temperature of 325 ± 25°F.

The results of these bellows tests are summarized in Table 2. Failure of all bellows failures were attributed to fatigue of the bellows plates. A single failure in the center of the nineteenth convolute was attributed to a pre-existing hot spot on the plate. The source of this hot spot could not be identified and was not considered to be serious. It was noted that increased quality control on the source material would most likely prevent additional occurrences of similar hot spots. Since all bellows had surpassed the expected control drive mechanism life, no further testing was performed.

3.2 FFTF Life Tests - CRDM and System

Two accelerated life tests were performed on FFTF control rod drive prototypes. The first of these tests was performed in an argon atmosphere using a dummy mass to simulate the driveline and control rod weight (Ref. 5). Table 3 provides a summary of the significant test conditions, and observations made during inspections at various times during the test. The required control rod drive life was exceeded by 80%, and functional tests (release and scram) were made before the start of testing and at 10% of life increments. Various components exhibited wear (e.g. scram spring guide tube, scram spring seat, torque taker) during the test and were replaced by components modified in either design, material or lubrication. However, all reference design components, those with which the test was begun, were tested to at least 100% of design life. The only significant failure was the bellows (S/N 001 discussed above). In addition, the original absolute position detector assembly failed to meet accuracy requirements and was replaced with a switch type position indicator which was adopted as the reference design.

No degradation in the function of the drive mechanism was observed. Normal wear was observed on drive components at 100% of design life, and measurable wear was observed after 130% of design life. Increased wear during the extended life was attributed to increasing wear particle contamination. The overall conclusions of the test were that the mechanism operated satisfactorily for greater than its design life.

A Control Rod System Life Test was performed at W-ARD in sodium on the FFTF drive mechanism, driveline, and control rod prototypes. This test had multiple objectives and was divided into four separate phases as follows:

1. Phase I objectives were to test the performance of the control rod driveline and the control rod under prototypic FFTF environments, and the performance of the drive mechanisms in conjunction with the balance of the control rod system. The success criterion of this test was the system scram performance, over a duty cycle equivalent to two years operation of the control rod and five years driveline operation and including a 30 day soak. In addition, this test simulated anticipated misalignment conditions, which resulted in a total offset of 0.45 inches between the drive mechanism centerline at the head and the control assembly top plane centerline.

   The scram performance of the control rod system exceeded specifications and analytical predictions for the control rod withdrawal positions and flow rates tested. No significant variation of scram performance was observed as a result of either the cycling tests (repeated ± 1.5 inch excursions around various axial positions) or the accumulated travel tests. Table 4 summarizes the essential parameters of the Phase I duty cycle.

   Two occurrences were observed in the drive mechanism which did not affect performance, but which influenced subsequent design efforts. A conoseal in the joint between the leadscrew extension and the lower extension shaft was discovered to be leaking. The conoseal was replaced and the joint was retorqued. No further leakage was observed. The extension shaft bellows failed during a room temperature disconnect operation. Fracture was caused by a heavy material deposition between the bellows sleeve. The deposits were thought to be the result of the cleaning process employed in a prior cleanup and a different process was subsequently employed. No further bellows failures were observed. These bellows are not the same bellows tested and discussed above. Post-test component examination indicated some pitting of the control drive extension shaft and wear of the leadscrew and scram spring guide tube. The driveline did not exhibit significant wear. The control assembly outer duct exhibited wear streaks up to 0.010 inch deep approximately 0.35 inch to 0.55 inch from the corners. This wear pattern was attributed to rotation of the control rod through

The control rod duct corner scoring was again observed as in prior tests. In addition, the absorber shaft exhibited a wear ring from contacting its sleeve, caused by the driveline and control rod shaft deformation required to conform to the misaligned conditions. The female driveline coupling on the control rod shaft was heavily scored on its outside diameter, matching similar score marks on the ID of the handling socket on the outer duct. This coring results from the misalignment and the shaft centering action of the coupling in approximately the last 9 inches of travel.

4. Phase IV objectives were to determine the control rod system performance with intentionally failed bellows with the system aligned, including the effects of a three (3) months soak. Test articles and environments were the same as in the prior tests. The main bellows were faulted by machining a 1/8 inch hole in the center convolution of each of the three sections comprising the bellows. The system was then subjected to the duty cycle given in Table 4, and scram times were recorded as in the prior tests.

   The scram performance of the system was found to be reduced compared to prior testing, by an average of approximately 5% (8.3% max.). At the same time, the scram performance still exceeded requirements by approximately 20%, based on time to travel 27 inches. The three (3) months soak with the failed bellows had no significant affect on scram performance. The reduction of scram performance with failed bellows is the result of the absence of a pressure differential across the bellows. With unfailed bellows, the normal 2 psig pressure differential across the bellows in the fully inserted position rises to approximately 8 psig in the fully withdrawn position. This normally provides a small additional scram assist. However with failed bellows, no pressure differential normally exists across the bellows. During scram, the bellows plenum volume expands rapidly, resulting in a small negative pressure differential. The cumulative effect of (1) no addition scram assist,and (2) the slight retardation due to negative bellows pressure differential is the apparent source of the observed reduction in performance.

   Detailed post-test inspections of the test components were made after completion of all four test phases. These phases had cumulative service life exceeding the design requirements so that wear effects beyond the design basis were expected. The drive mechanism main bellows showed separation of convolutions at the inside weld bead (Fig. 2). There were indications that the bellows ID had worn against the leadscrew extension shaft. The cause of this wear was attributed to wear of the lower guide bushing which resulted in sufficient additional misalignment to permit bellows to shaft contact. The leadscrew extension shaft exhibited wear marks matching the guide bushing wear. Circumferential wear of the motor tube (drive mechanism outer boundary) inside surface was also evident at the elevation corresponding to the top of the segment arms. Similar wear was found on the segment arms in a pattern which suggested skewed contact between the segment arms and motor tube. The wear apparently resulted from contact only during latching cycles, and was probably the result of the misalignment condition imposed in the Phase III tests. Minor wear of the rotor tube and segment arms was observed, apparently from contact of these components in the "unlatched" condition. Table 5 summarizes the significant observations regarding test components for all phases of the test.

The summary conclusion of all the testing was that the FFTF control rod system performed within requirements over the specified range of environments, misalignments and duty cycle. Wear effects resulted principally from off normal conditions such as extreme misalignments, failed bellows and excess travel and cycling. However, the system scram performance was within specification for all test phases, despite the off-normal conditions and wear.

4.0 CRBR Primary Control Rod System Design

The design of the CRBR Primary Control Rod System (Fig. 3) relies heavily on the experience gained on FFTF. The concepts from the fundamental components - mechanism driveline and control rod - are similar for both CRBR and FFTF, however the design manifestations of these concepts differ in certain areas (Table 6), principally to satisfy CRBR requirements. The CRBR through the head refueling scheme, using rotating plugs in the vessel head, and the addition of axial blankets to the core, required both a longer control rod and driveline.

The increased load due to the longer driveline and control rod resulted in CRDM motor redesign by a complex cause and effect chain. The immediate effect was to increase the motor torque required to lift the load. The secondary effect of the higher load was to reduce the static unlatch margin of the mechanism. This margin is the theoretical im-balance of forces applied by the segment arm radial springs tending to separate the segment arms in a scram and opposed by the friction forces (induced between the rollers and the leadscrew by the axial load) tending to prevent segment arm separation. In order to provide an adequate static scram margin, it was necessary to increase the radial spring force. This in turn increased the radial moment the stator had to apply to the upper segment arms in order to latch the mechanism. Because the FFTF drive mechanism had been optimized for the extremely narrow space constraints of FFTF, there were insufficient design margins in the stator and segment arms to accommodate both the increased torque and moment required for the greater CRBR load. Since the space constraints for CRBR were less limiting, the drive mechanism design was modified to meet the CRBR requirements.

For CRBR, the Primary Control Rod System serves both reactor reactivity control and primary shutdown functions. The normal operation rod bank positions vary from approximately 11 inches to fully withdrawn at the beginning of a reactor cycle. In order to assure some scram assist above gravity in the intermediate withdrawn positions, the scram spring was increased to 27 inches from the 14 inch spring used on FFTF, which permitted eliminating at the time, the spring seat and spring guide tube. The CRBR scram spring is withdrawn with the driveline for 9 inches, the length of the dashpot action, at which point the upper end of the spring is constrained from further motion. Any additional withdrawal results in spring compression. The maximum compressed spring force for CRBR is approximately 10% greater than for FFTF. The additional available scram assist, particularly in the partial withdrawal positions of the rod provides increased reliability of scram, and is especially important for CRBR misalignment and seismic requirements discussed below.

In addition to the modifications for the new scram spring, the leadscrew to upper driveline interface was improved. The decision to ship and handle the lower mechanism and upper driveline as a single unit permitted supplier assembly of the leadscrew and upper driveline, instead of field assembly. As a result, the main bellows seat conoseal, which had been found sensitive to assembly procedures, was replaced by a welded joint. This permanently eliminates the potential for cover gas leakage through this interface. To minimize the potential for segment arm to motor tube contact as found in FFTF testing, clearances between these components were increased and the contact area of the segment position stop was increased. To accommodate structural margin and seismic requirements for CRBR, the stator has been clamped to the CRDM support nozzle in order to reduce loads on the motor tube and pressure boundary seals. Structural margin requirements reflect the CRBR design philosophy which includes provisions for design margins for events outside the design basis, which are not expected to occur during the lifetime of the plant.

To complete the lower drive mechanism modifications, several convolutions were added to the main bellows to reduce bellows fatigue and improve lifetime potential. The CRDM lower bushing diameter was slightly decreased and the bushing material was changed from Ni-Resist to Stellite 6B to improve wear characteristics and to reduce the potential for leadscrew to bellows contact.

The CRBR through-the-head refueling scheme positions new core assemblies over their respective core lattice positions by rotation of three eccentric plugs in the head. The clearances required by the rotating plugs supports (risers and bearings) significantly increase the maximum potential misalignments of the drive mechanism relative to the core (approximately 1.0 inch from plug penetration to core position in CRBR compared to about 0.45 inch in FFTF). In addition, the larger core of CRBR also increases potential misalignments of the top of the core relative to the core support. The clearances between the translating assembly (leadscrew, driveline and control rod) and its fixed interfaces were adusted to accommodate additional misalignment. The handling socket bore at the scram arrest ledge was increased. The shroud tube inside diameter was increased to prevent contact with the driveline coupling flange. To complement clearance modifications, several significant feature modifications were made which reduce potential misalignments and drag load. The leadscrew was redesigned as a single shaft, eliminating the leadscrew extension and the resulting assembly misalignment potential. The control rod sleeved shaft was replaced by a solid shaft with an anti-torsion joint above the control rod. This feature relieves outer duct wear and torsionally induced drag loads and provides a degree of lateral freedom to prevent introduction of lateral loads due to the increased CRBR system misalignment.

The CRBR refueling scheme permitted elimination of the upper driveline disconnect. In CRBR, the driveline is decoupled from the control rod and withdrawn to a position such that it does not interfere with free rotation of the head during refueling. The upper disconnect was replaced by a simple maintenance coupling which permits replacement of only the lower driveline if required by lifetime (wear and radiation effects) considerations. This feature is advantageous from both alignment - and, therefore, performance - and economic viewpoints.

An evaluation of the inherent uncertainities in the absolute position indication for the primary control rods indicated that the reed switch type absolute rod position indicator (ARPI) developed for the FFTF drive mechanism was not adequate for the more stringent CRBR position accuracy requirements when operational uncertainties are considered. The uncertainties in this system are greater for CRBR than for FFTF because (1) CRBR is longer; therefore differential thermal growth uncertainties are accentuated, and (2) fuel swelling uncertainties are greater due to the desired longer core life. To account for the greater uncertainties, an ultrasonic position indicating system was evaluated. This system measures the modification by the leadscrew magnet to an ultrasonic pulse transmitted in a wire wave guide in the position indicator housing. The time phasing of the transmitted and returned pulses provides the indication of rod position based on the known properties of the wave guide. The accuracy of this system in preliminary tests was approximately twice that of the reed switch system which more than offsets the increased CRBR uncertainties. Therefore, in order to more fully evaluate the ultrasonic position indicator, the prototype CRBR drive mechanisms will be equipped with this system. The final decision on reed switch vs ultrasonic position indicators for the plant units will follow complete system evaluation in the prototype tests.

The primary control assembly design was modified as a normal step in the design evaluation. The principal goals of the modifications were to perform the design for a two year life and to reduce the cost of the assembly. A significant part of the assembly cost is related to subcomponent fabrication, such as absorber pellets and cladding tubes, with a compounding cost factor in final assembly. Because of this, the number of absorber pins was reduced to 37 in a CRBR Primary Control Assembly from 61 for FFTF. This represented a 39% reduction in quantity of cladding tubes, absorber pellets, end caps and wire wrap and a corresponding reduction in assembly fabrication effort. Other modifications made for cost reduction purposes were elimination of inner duct perforations and simplification of the orifice shield assembly. The inner duct perforations were shown to be unnecessary since the maximum predicted pressure gradient across the duct was very small for CRBR

The control assembly mechanical design was modified for two reactor cycle operation. The clearance between the inner and outer ducts was increased to accommodate two cycle bowing effects with a margin against three point rod to duct contact (the rod cam - locked in the duct). In addition, the structural evaluation of the assembly components is performed assuming two cycle fluence.

Emphasis on shutdown reliability has had a significant effect on the CRBR Control Rod System design effort. The reliability program emphasizes enhanced component reliability and elimination of potential "common-cause" failures of the reactor shutdown and control systems. The design and reliability effects are focused by using Failure Mode and Effects Analyses (FMEA) to highlight potential design problems for resolution. The effect of the FMEA on CRBR Control Rod System design has been both design modifications, such as the inclusion of the Rotational Joint, and establishment of test programs to prove component and system performance relative to specific failure modes identified in the FMEAs.

In support of the principal objective of CRBRP of demonstrating safe and reliable operation of an LMFBR in a utility environment, licensing activities assume a major role in CRBR system design. The increased emphasis on safety and reliability has resulted in the development and utilization of advanced design technology. Of particular interest is the application of this methodology for the control rod system response to the increased seismic environment applicable to CRBR.

Verification of the control rod scram function during an earthquake is a complex problem, requiring that the control rod system gross response to the seismic excitation be calculated, and then determining the interaction of the translating components with their fixed boundary. The gross response is determined from a reactor system structural model, in which the control rod system is represented as several key lumped masses, linked to the reactor through the appropriate chain of springs and gap elements. The control system response at the key interfaces -

head, core restraint, core support - is used as input to a detailed control rod system model which determines the lateral interactive forces between the translating and stationary components. Pennell (Ref. 7) presents the methodology in some detail.

Uncertainties in these analyses which require conservative assumptions for design analyses include: the coefficient of friction between impacting components, the effect of the coolant as a lubricant and damping medium, and the local dynamics of an impact, i.e. the spring coefficient and natural structural damping. These uncertainties primarily affect seismic scram performance with minor impact on structural considerations. Several tests are in place which are expected to aid resolution of the uncertainties and provide verification of the analysis methodology. These CRBR control rod system tests are discussed below.

5.0 CRBR Control Rod System and Component Test Program

The Control Rod System test program is directed at the three major areas addressed in the design discussion: Design Performance Verification, Significant Uncertainties, and Reliability: The design performance verification tests include life testing, and verification of new or previously untested features. Tests to resolve uncertainties include misalignment, seismic scram response and irradiation effects. Scram reliability tests include the effects of failed bellows and duct bowing.

The principal system level design test is the Primary Control Rod System (PCRS) Prototype Test. This test will utilize full scale prototypes of the drive mechanism, driveline, and control assembly. The objective of this test is to verify PCRS lifetime performance in the design basis sodium and argon environments, over a range of misaligned conditions. In addition, an accelerated life test of the drive mechanism unlatching function, equivalent to twice the design lifetime, will be included to verify margins against wear and cyclic related failures. This test will be performed in air. Other information obtained from this test will be the performance of the Disconnect Actuating Tool and maintenance tools, scram times and the implied drag forces, and operational data on the new ultrasonic absolute position indicator. Figure 4 shows the range of the design basis misalignments covered in this test, and Table 7 is the expected test duty cycle. Test rigs and sodium loops for all systems tests are in place, and test component deliveries are scheduled between November, 1977 and March, 1978.

Additional PCRS tests extend the data from the accelerated life test to include the effects of hold times, determination of the flow induced vibration potential of the PCRS, system performance with failed bellows and evaluation of design uncertainties relating to bellows pressure, system misalignments, system coolant flow rates and CRDM stator current and coolant. The test environment will be liquid sodium and argon at prototypic temperatures. Test components will be full scale prototypes. The duty cycle for the systems tests will be equivalent to one design life (750 scram, 17,000 ft. travel) and will include hold times from 10 to 90 days. The holds are an important simulation of the CRBR Row 4 control rods which are fully withdrawn and held at the start of a cycle, and are required to scram as necessary during a reactor transient. The potential for flow induced vibrations will be determined by instrumenting the driveline and the control assembly. Flow rates and rod positions will be varied to provide complete data covering the expected rod positions and flow rates. For the failed bellows, tests are planned for an equivalent of 2/3 of the design lieftime scrams and travel from various positions to establish a system performance baseline; then the main bellows will be failed and an additional 1/3 design life will be accumulated, including hold times, over one year real time. Comparison of pre- and post-bellows failure performance will indicate the effect of long-term operation with a failed bellows. The design uncertainties test, as described above extends the prototype test and completes systems testing. This test will utilize evaluations of previous tests to assure testing against identified design uncertainties.

In order to verify the scram performance of the PCRS, a dynamic test simulating seismic excitation is planned to verify the CRDM unlatch function. The lateral dynamic response of both the CRDM segment arms and the leadscrew during seismic excitation leads to uncertainties in the unlatch time, an integral component of scram performance. The objectives of the planned test are to determine CRDM unlatching time under conditions of simulated seismic excitation and verify leadscrew motion through the collapsed roller nuts. The prototype CRDM, previously tested in the unlatch tests, supporting a simulated driveline and control rod, will be excited at frequencies and accelerations typical of the predicted CRDM seismic response, in vertical and horizontal axes. The time for interruption of stator current to first leadscrew motion will be measured.

A separate test will verify the PCRS scram insertion function under dynamic excitation. Seismic scram performance depends upon the dynamic response and structural interaction of the translating and fixed components. The magnitude of friction forces generated by the leadscrew, driveline and control rod impacting the CRDM, shroud tube, and outer ducts affects the time from first rod motion to full insertion. The uncertainties associated with seismic scram related to the magnitude of the coefficient of friction, the effects of the coolant, both as a lubricant and as a damping medium, and local structural effects such as impact coefficients and structural damping.

The tests will provide data to determine an integral coefficient of friction (includes mechanical and hydraulic effects) for a simple rod traveling through three bushings in air, water and sodium under dynamic input at the frequencies and accelerations determined to yield the highest rod response. These data will be used to refine the analytical tools currently used, and to pre-predict the scram performance of a full scale prototype dynamic input test. The data from this test are expected to significantly reduce the seismic scram uncertainties and improve analytical capabilities. This test is currently in progress.

The CRBR Primary Control Assembly design has been performed for the two year goal lifetime. A test of the CRBR control assembly in FFTF is planned, in which a CRBR control rod will replace an FFTF control rod, to verify the two year (550 FPD) performance of the rod. The necessary modification will be made to meet FFTF interface constraints, however the essential features will be the CRBR design, including the 37-pin bundle, clearances, pellet size, and orifice design. This test will establish CRBR control assembly replacement schedules and provide integral operating data for an enriched rod to reduce the uncertainties of the design methodology. Testing is currently scheduled to begin in March, 1980. Other tests are in place to verify control rod performance for various effects. A complete summary of all PCRS component and systems tests is given in Table 8.

Conclusions

From this review of the design evolution of the FFTF and CRBR Primary Control Rod System it is concluded that the systems' concepts are appropriate for FFTF and CRBR requirements. The testing of the FFTF control rod system has verified the performance of the drive mechanism driveline and control assembly with comfortable margins beyond the required service. The data from the tests and particularly the extension of the test program beyond the design basis service conditions provided valuable insight to potential areas for improvement of lifetime and performance.

The modifications made for the CRBR PCRS design were primarily predicated on the different requirements for CRBR, including a major emphasis on shutdown reliability, and utilization of the FFTF Test experience. All evaluations and preliminary test data to date have indicated that the CRBR PCRS will perform safely and reliably beyond the required design lifetime of the system.

References

1 - MPR-184, "Control Rod Drive Mechanism Concept for the FFTF Reactor" MPR Associates; Washington, D. C., August, 1969

2 - Toepel, F. P. and Moodey, J. C., "Development of a Roller Nut Control Rod Drive Mechanism for the Fast Flux Test Facility", ASME 75-WA/NE-2, 1975

3 - HEDL-TC-738, "Final Test Report and Hydraulic Balance Piston Ring Life Test Phase III of WDTRS 2.49", April, 1977

4 - LMEC-73-1, "LMEC, Annual Technical Progress Report", January - December, 1976

5 - Royal Industries Report 128X929, Rev. N/C, "FFTF, CRDM Life Test Report Lead Unit #2", March, 1973

6 - WARD SCT-9, "FFTF Control Rod Systems Enviromental Life Test Report", Westinghouse Electric Corp.- Dec., 1976

7 - Pennell, W.E., "LMFBR Reactor Structures Design", Westinghouse Electric Corporation, Advanced Reactors Division, May, 1975

TABLE 1

FFTF CRDM MAIN BELLOWS DESIGN DATA

Number of Sections	3
Convolutions per section	62/62/61
Plates per section	124/124/122
Plate thickness (in) [1]	.010, 008, .006 [1]
OD/ID (in)	3.450/1.800
Material	Inconel 718
Installed Length (in)	44.41
Stroke (in)	36.5
Design travel (excluding scrams) (ft)	20,000 [2]
Design scrams	1,500 [2]

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[1] - End convolution, transition convolution main bellows body

[2] - Equal to twice the CRDM design life

TABLE 2

FFTF CRDM MAIN BELLOWS TEST PERFORMANCE DATA

Bellows Number	Test Environment	Number of Scrams	Travel (ft)	Percent of Bellows Design Life	
				Scram	Travel
1	Argon/Air 325°F	1200	19,000	80	95
2	Argon/Na Vapor 450°F	2500	23,000	167	115
3	Argon/Na Vapor 450°	2250	20,700	150	104
4	Argon/Na Vapor 450°F	1530	13,700	102	70

TABLE 3
FFTF LIFE TEST SUMMARY

Environment	Argon/Air @325°F
Total travel @9 ipm	15,000 feet
Scrams	1,500
Disconnect/Latch Cycles	100
Oscillation Cycles (0.75 in)	2,500
Start Stop Cycles	30,000

Observations

10% Design Life	Slight, normal wear on torque taker, upper and lower guide bushings, scram spring, spring seat, and spring guide
50% Design Life	Same as above. Slight, normal wear on leadscrew in latch area, rotational stop, synchronizer pins and position indicator housing.
70% Design Life	Heavy wear on torque taker keys. New Stellite keys installed. No significant additional wear on other components.
100% Design Life	Main bellows failure. Normal wear on all other components.
130% Design Life	Leadscrew worn on loaded flank.
180% Design Life	Torque taker key wear

TABLE 4

FFTF ENVIRONMENTAL LIFE TEST DUTY CYCLE

Test Phase	Temp.	SCRAMS Full	SCRAMS Partial	Start-Stop Cycles	Residence Time (Hrs)	Total Travel
I	400	31	8	----	95	3874
	600	35	8	1008	78	
	800	39	8	1450	71	
	1100	50	9	1008	831 (30 day)	
II	400	18	12	----	936	1144
	600	20	12	----	696	
	800	32	12	1500	264	
	1100	37	14	----	3144 (90 day)	
III Pre-Soak	400	45	2	2600	371	14,400
	600	46	12	2600	198	
	800	51	12	2600	109	
	1100	51	12	2600	286	
				SOAK 30 DAYS		
Post Soak	400	33	--	2600	52	
	600	34	12	2600	39	
	800	39	12	2600	31	
	1100	39	13	2600	76	
				SOAK 90 DAYS		
III Pre-Soak	400	2	--		21	3085
	600	5	--	250	8	
	800	5	--	250	99	
	1100	5	--	250	8	
III Post Soak	400	2	--	---	124	
	600	11	--	250	96	
	800	11	--	250	36	
	1100	11	3	250	108	

TABLE 5
SUMMARY OF OBSERVATIONS
FFTF CRDM ENVIRONMENTAL LIFE TEST

1. Lower bellows support conoseal leaked. Resolved by reassembly of the joint at higher bolt preload (Phase I).

2. Extension Shaft Bellows Failed: attributed to conoseal leakage, ingress and deposition of sodium on the bellows. Subsequent disassembly operations fractured the bellows (Phase I).

3. Rotary Position Indicator Failure: Electronics failure unrelated to the mechanical tests (Phase II).

4. Control Assembly Duct Corner Wear: Due to rotation of the control rod in the duct until the wear pad corners contact the duct. No degradation of performance noted (Phases I and IV).

5. Motor Tube ID and Rotor OD Wear: Contact during latching under severe misalignments. No degradation of performance observed.

6. Leadscrew Wear: Only slight wear observed and attributed to unlatch operations.

7. Control Rod Shaft/Sleeve Wear: Attributed to severe misalignment tests. No degradation of performance noted.

8. CRDM Main Bellows Failure: Separation of convolution due to wear against leadscrew extension shaft under severe misalignment test conditions. Contributing factor was wear of the lower guide bushing over the extended test duty cycle.

9. Control Rod Coupling Wear: Associated with corresponding wear in the Instrument Tree Guide Tube and the Control Assembly Handling Socket. Attributed to severe misalignment test.

TABLE 6

SUMMARY OF CRBR PCRS CHANGES vs FFTF CRS DESIGN

Change	Reason/Result
Driveline Length (and weight) Increase	CRBR system requirement to accommodate axial blankets
CRDM motor redesign	Increase load capacity for longer driveline, and maintain adequate static scram margin
Scram spring length increased	Provide additional scram assist capability for partial stroke scrams under increased system misalignments
Scram spring seat and actuating tube eliminated	Longer scram spring carried with driveline, and has no preload in extended condition. Improve scram assist for partial withdrawal and CRBR misaligned condition.
Driveline (Upper) disconnect eliminated	CRBR refueling scheme does not require a disconnect.
Driveline Maintenance Coupling added	Provide maintenance and lower driveline replacement capability for CRBR.
Welded assembly of leadscrew and upper driveline by supplier	Eliminates leak path and field assembly using conoseal
Number of bellows convolutions increased	Reduce bellows fatigue and improve life potential for 30 year operation
Added Rotational Joint to control assembly shaft, eliminated sleeved shaft	Eliminate torsional drag loads and relieve lateral misalignment drag loads in control assembly
Increase control assembly clearance	Accommodate increased misalignment and two year operating lifetime
Reduced number of absorber pins from 61 to 37	Reduce cost, improved scram performance
Added linear displacement transducer Position Indicator, eliminated switch type indicator	Improve accuracy to accommodate increased CRBR position indication requirements
Increased Rotor to Motor Tube clearance	Prevent contact and wear during latching under misaligned conditions
Clamped stator to CRDM nozzle	Reduce pressure boundary loads under increased CRBR seismic excitation and structural margin loading conditions

TABLE 7

CRBR PROTOTYPE SYSTEMS TEST DUTY CYCLE

	Temp.	SCRAM		Total Travel (ft)	Disconnects	REMARKS
		Full	Partial			
Part I Lead Unit 1	400°	280	1220	34,062	15 Min.	CRDM Life Test in air
Part II, Phase I Lead Unit 2	400°	12	---	4630	21	Sodium/argon environment travel @ 9 ipm
	600°	12	24			
	800°	--	36			
	1100°	24	36			
Part II Phase 2 Lead Unit 2	400°	24	12	6849	24	30 day hold
	600°	24	24			
	800°	62	56			
	1100°	25	48			
Part II Phase 3 Lead Unit 2	400°	48	24	5584	15	60 day hold
	600°	65	44			
	800°	14	40			
	1100°	40	60			
TOTALS	Lead Unit 1	280	1220	34,062	15	
	Lead Unit 2	350	404	17,063	60	
DESIGN REQUIREMENTS		750		17,000	60	

TABLE 8

CRBR PRIMARY CONTROL ROD SYSTEM TEST PROGRAM

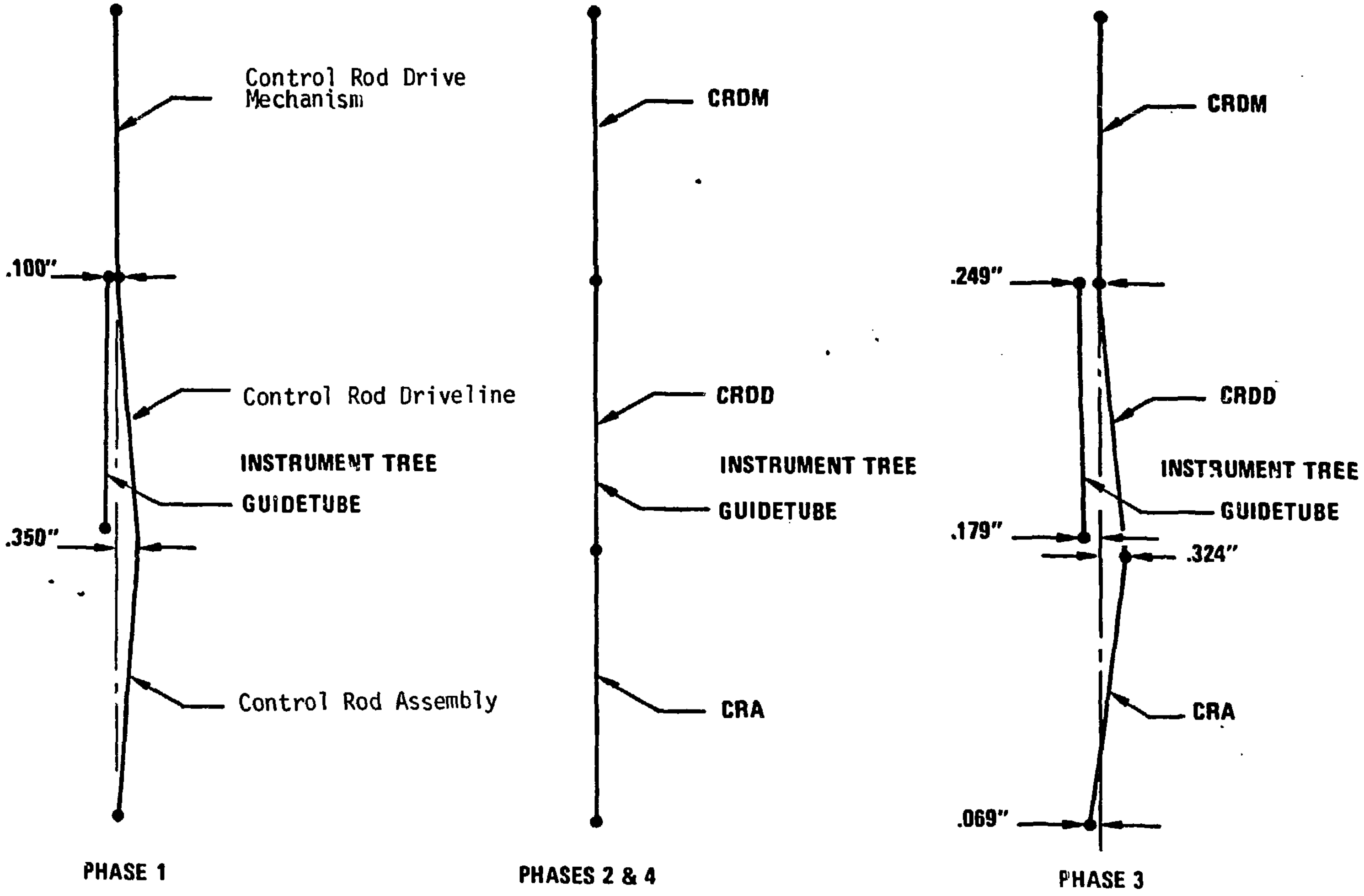
TASK	TEST OBJECTIVE	TEST DESCRIPTION	TEST STATUS	
Control Assembly Analytical Methods	Develop analysis to predict pin lifetime behavior and SCRAM performance characteristics under expected and abnormal operating conditions	The Analytical Codes will be updated and calibrated against test data to make extensive analytical investigations of SCRAM performance and pin lifetime behavior.	On-going activity. Completion expected in 1979 for PCA final design.	
CRBR Control Assembly Hydraulic Tests	Determine CA assembly hydraulic characteristics	Design verification test in water to determine pressure gradients, flow vibration potential, flow splits, and floatation potential.	Testing to start 12/77 with test completion in 1978.	
37 Pin Control Assembly Test in FFTF	Radiation test to confirm PCA performance under actual environmental conditions	Replace an FTR control assembly with a CRBR PCA modified to meet FTR constraints, and operate as an active control rod. Conduct post-irradiation inspections to verify radiation performance for two CRBR cycles.	Test assembly design and analysis has been initiated. Start of irradiation in FFTF targeted for 3/80	
PCRS: Control Assembly Rotational Joint Test	Verify the rotational joint will perform as specified under design basis operating conditions.	Impact tests, torque input vs torque output tests in sodium under aligned and misaligned conditions, and lifetime travel to verify the performance of the rotational joint design	Test completed successfully. Rotational Joint satisfied design requirements and eliminated outer duct wear.	
PCRS: Control Assembly Pin Compaction Test	Confirm analysis methods for pin bowing by determining interpin loads and pin-inner duct contact and loads for simulated bowed pin conditions	Pins will be prebowed to maximum anticipated bow and put in a bundle. Forces necessary to compact the pins to bundle dimensions will be measured and recorded	Testing to start 11/77 and will be completed early in 1978.	
Primary Control Rod System Prototype Test	Part I-PCRDM Prototype Accelerated Life Test - Verify wear service life and unlatching performance of the CRDM prior to plant unit fabrication. Evaluate wear and environmental influences during test Part II-PCRS Prototype Accelerated Environmental Test-Verify the PCRS will perform as specified under design basis conditions in the expected operating environment; evaluation of drag forces encountered, maintenance effects (change of control assembly and driveline), and disconnect joint.	Part I-Under accelerated conditions in air @400°F complete 1500 scrams (two anticpated lifetimes on the mechanism and measure unlatch time as an indicator of CRDM performance. Carefully inspect parts for wear after the first and second lifetime. Part II-Under prototypic operating conditions in sodium complete 750 scrams and 17,000 feet of travel on a prototypic driveline (twice anticipated life) and the same amount of scrams and travel	Testing to start 12/77 with completion early 1979.	

TABLE 8 (contd)

TASK	TEST OBJECTIVE	TEST DESCRIPTION	TEST STATUS	
PCRS Prototype Test (contd)		on three control assemblies (approximately five times anticipated life). System wear and performance will be closely monitored. Evaluate performance of Disconnect Actuating Tool and Maintenance Equipment.		
CRD Seismic Dynamic Friction Couples	To obtain fluid coupling and effective friction data under simulated seismic conditions for use in scram insertion analyses.	Rod drop times through a set of bushings simulating the driveline will be measured under various misaligned, flow, accelerating, vibration, and environmental conditions to confirm the seismic analyses emphasizing the magnitude of fluid coupling effects.	Test completed. Analyses initiated to evaluate test results.	
Extended Dynamic Friction Couple Tests	To provide data for typical PCRS geometries on fluid coupling and thin film effects under seismic vibration conditions that can be combined with analysis to establish design margins for scram insertion during seismic events.	Rod drop times of various geometric configurations with different misalignments, flows, and vibration inputs will be measured.	Testing extending from 12/77 to early 1979.	
Drag Force for Bowed Duct Test	Provide test data to substantiate analysis which will show duct bowing has low potential CMF.	Drag load measurements of insertion and withdrawal will be made under various bow configurations and environments to include bows beyond worst case design basis to verify safety margins.	Test completed. Test results confirm pretest predictions for magnitude of drag forces versus duct bow. Further analyses planned to check two-dimensional calculations for drag force predictions.	
CRDM Seismic Test	To confirm reliable operation of the CRDM unlatching and leadscrew release under simulated seismic events.	CRDM and simulated leadscrew is mounted in test fixture and coupled to a vibration generator. The unlatch and release reliability will be assessed by measuring leadscrew release times with various vibration inputs.	Test rig under construction. Testing to begin late 1978.	
Pin Rupture Test	Generate data which combined with analysis will verify insertion failure due to pin rupture has low potential to cause scram insertion failures.	Rupture pins at center and wall locations within a duct and determine resulting duct deformations. Pin holes to worst anticipated failures (2" slots) will be tested.	Single pin rupture tests in duct completed. Testing of fall pin assembly initiated with completion expected early 1978.	

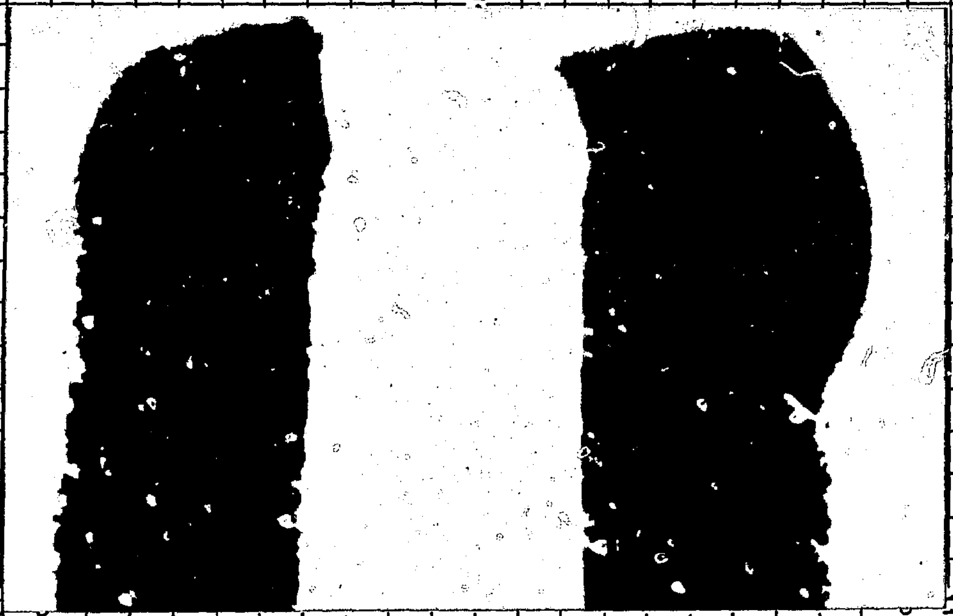
TABLE 8 (contd)

TASK	TEST OBJECTIVE	TEST DESCRIPTION	TEST STATUS	
Duct Impact Test	Verify that scram arrest has low potential to cause failure to scram	Simulate scram impact by dropping a weight on the end of an irradiated EBR-II duct, measure strain and observe cracking (if any). Analytically correlate data to CRBR duct.	Test completed with no duct damage under impact loads in excess of design basis. Analyses planned for correlation to CRBR conditions.	
System Level Tests ● Hold time tests ● Failed bellows tests	Confirm scram reliability of a PCRS in the operating environment simulating a Row 4 operating profile with inactive periods to help evaluate the limited time dependent failure mechanisms that may exist. Determine the potential for flow vibration of the PCRS. Confirm reliable operation of the PCRS with a failed bellows and determine potential CRDM failures resulting from bellows failure. Evaluate potential failure modes at the design basis limits of misalignment and other operating parameters.	750 scrams from various withdral heights and 17,000 ft. of travel will be performed on each unit with inactive periods as specified to simulate the service of Row 4 control rod. Inactive periods will provide realistic evaluation of self-welding and other time dependent failures in the reactor environment. Wear will be carefully assessed after test completion. Scrams from various heights under different flow and temperature conditions with misalignments at maximum design basis. Intentionally fail the bellows and operate the CRDM and driveline, normally operated to a pure argon environment, exposed to sodium vapor. Instrument the control rod and driveline with accelerometers, determine flow vibration at various flow rates and withdrawal positions. Full scale in sodium.	Test rig and test article fabrication near completion. Testing expected 4/78 to 1/80.	

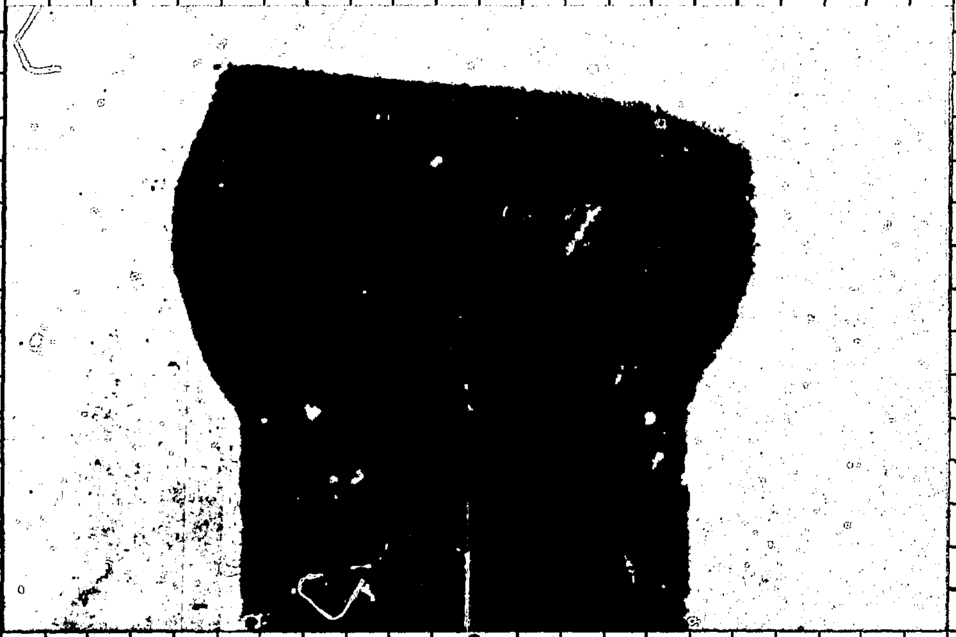


FFTF ENVIRONMENTAL LIFE TEST

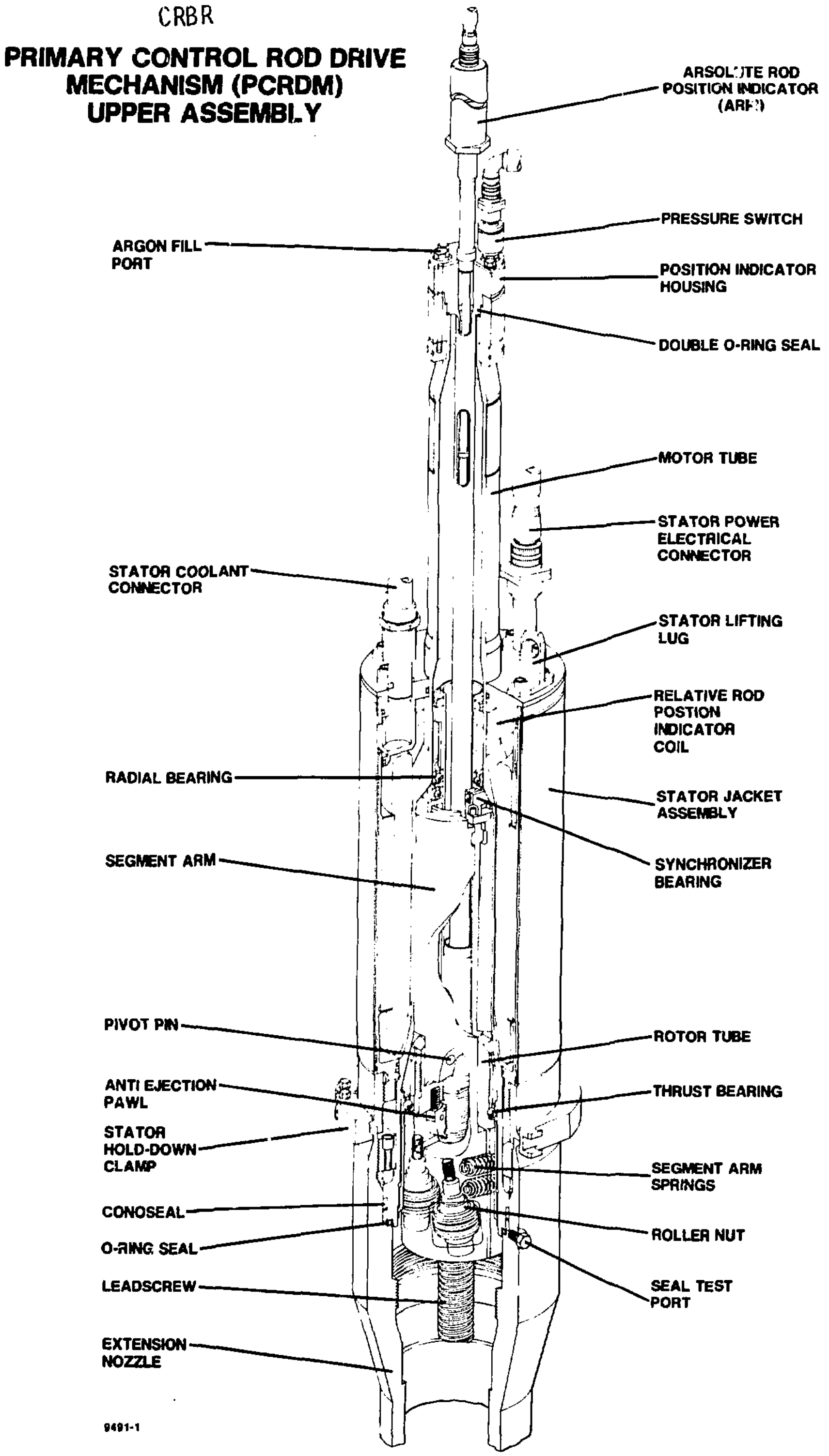
Figure 1 - CONTROL ROD COMPONENT ALIGNMENT CONFIGURATION



1st BELLOWS CONVOLUTION SHOWING PLATE SEPARATION DUE TO WEAR.



[illegible] BELLOWS CONVOLUTION [illegible] TION


CRBR

PRIMARY CONTROL ROD DRIVE MECHANISM (PCRDM) UPPER ASSEMBLY

Figure 3A

CRBR

PRIMARY CONTROL ROD DRIVE MECHANISM (PCRDM) LOWER ASSEMBLY

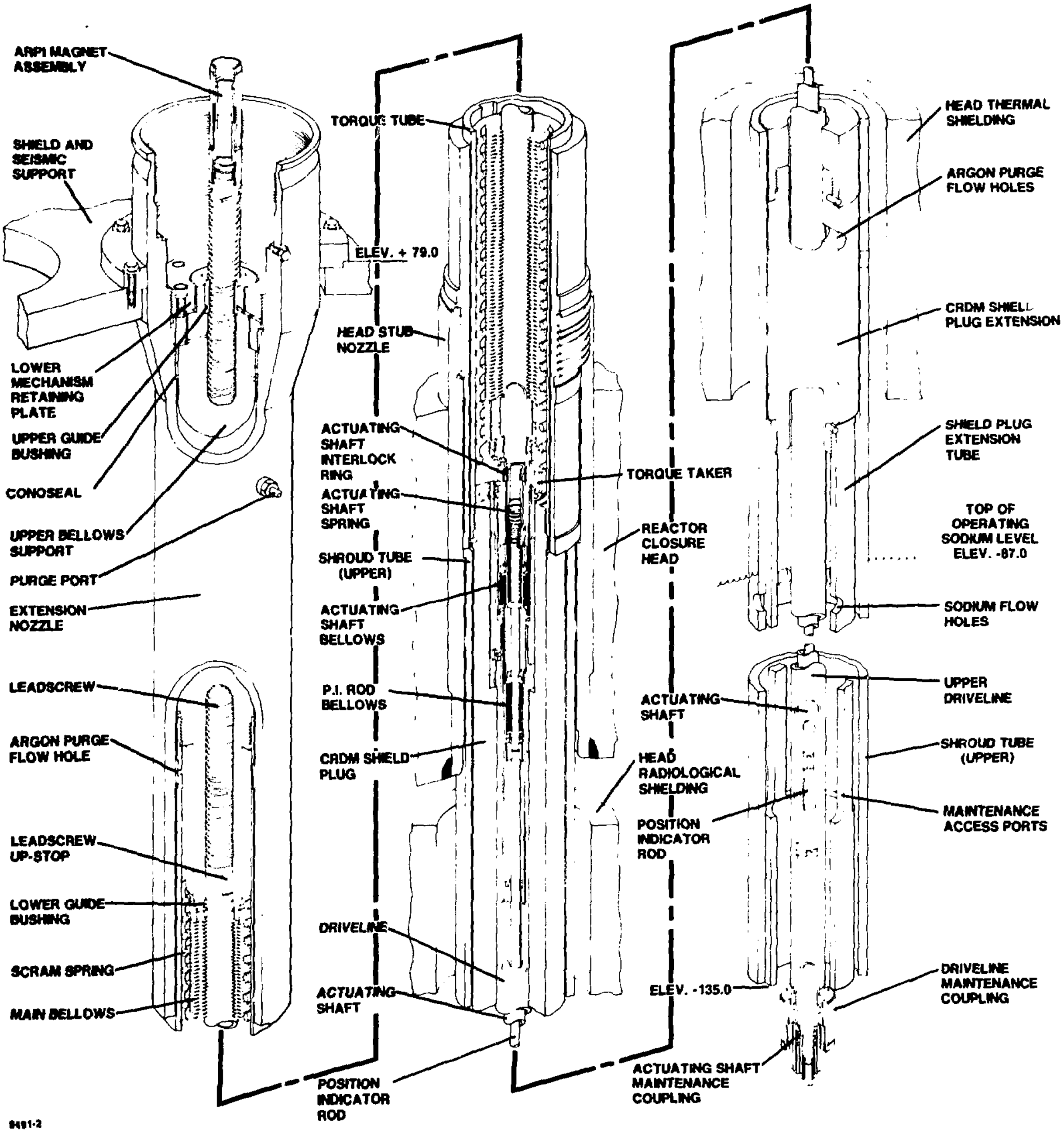


Figure 3B

CRBR

PRIMARY CONTROL ROD DRIVELINE (PCRD)

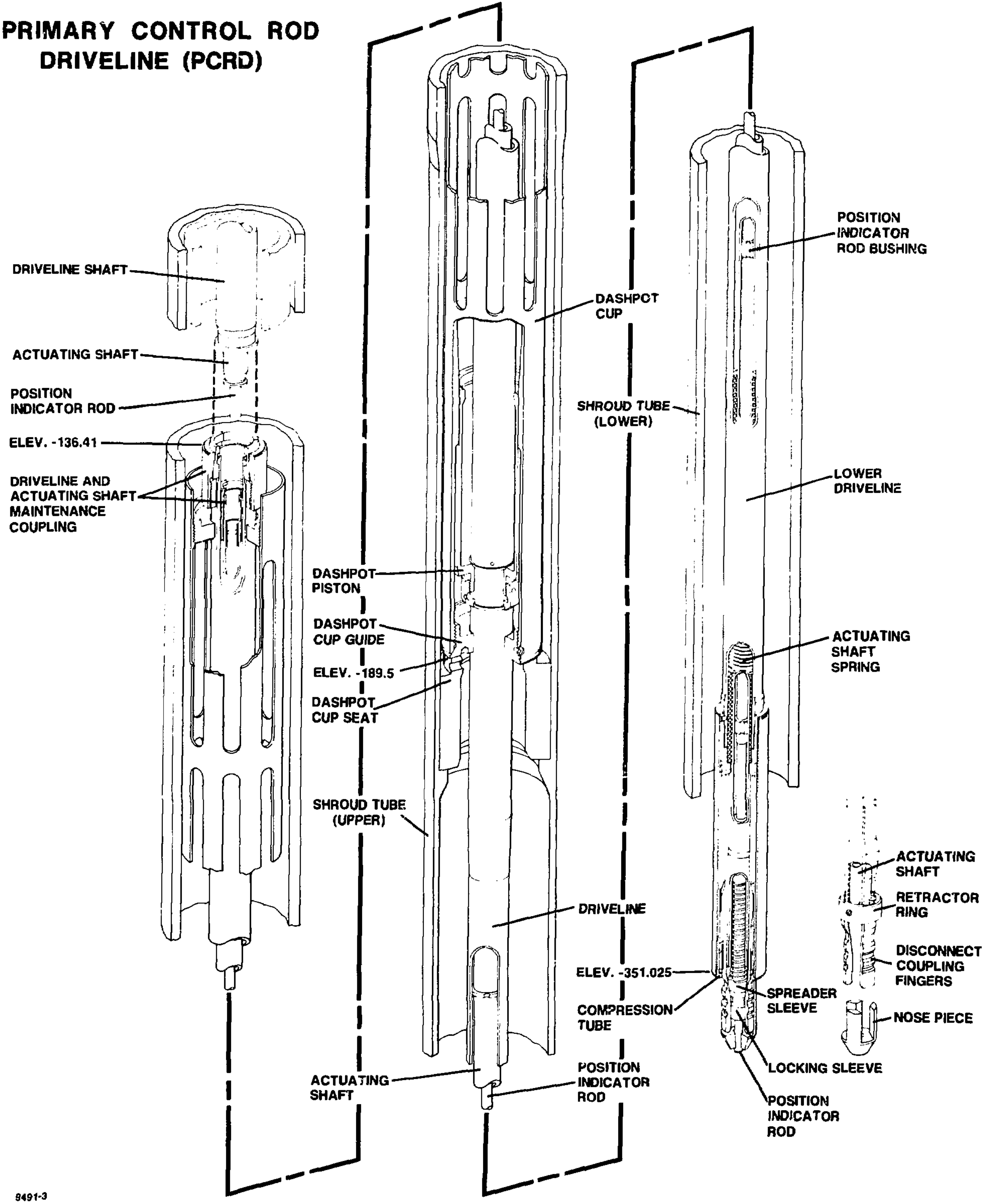


Figure 3C

CRBR

PRIMARY CONTROL ASSEMBLY

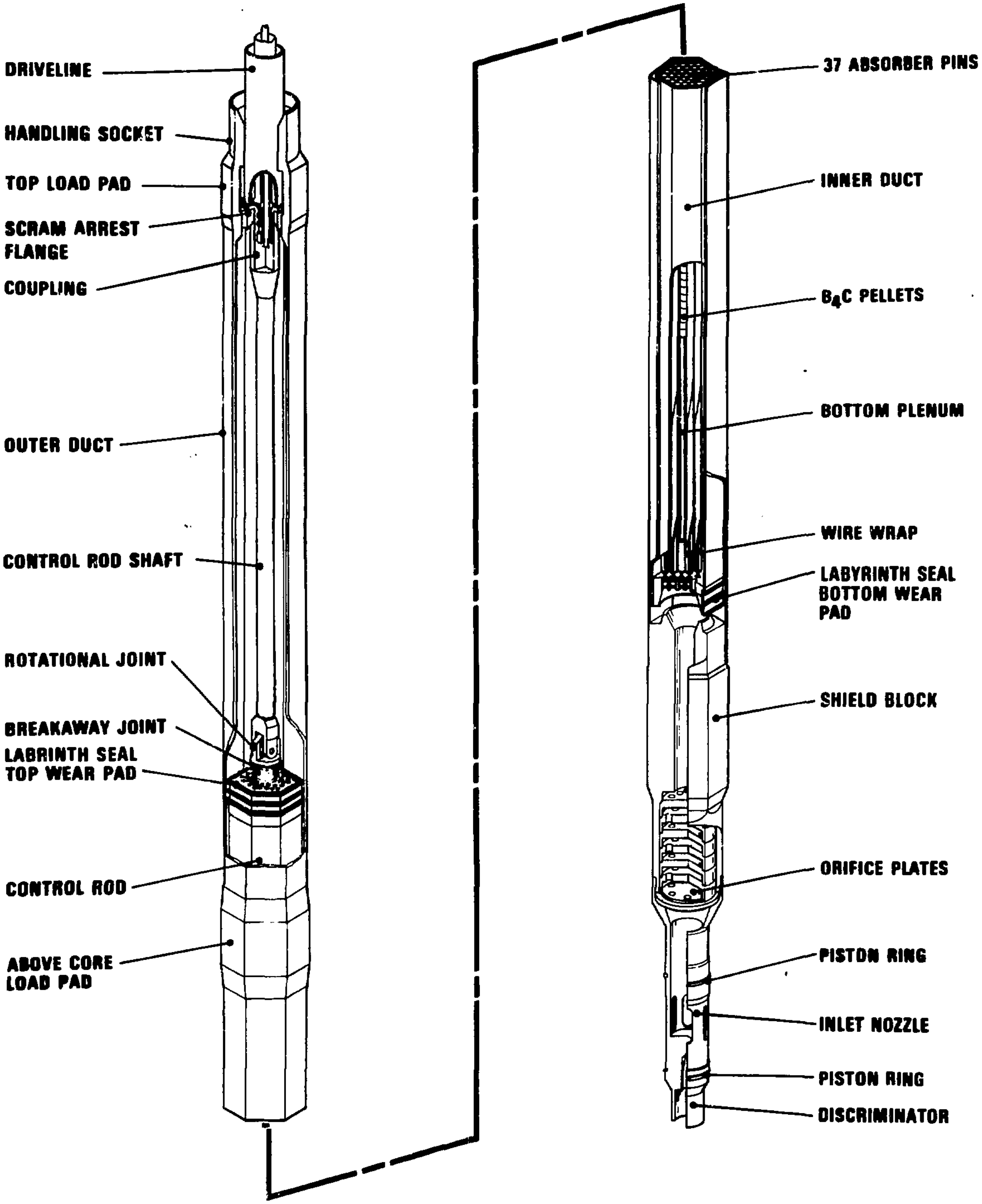


Figure 3D

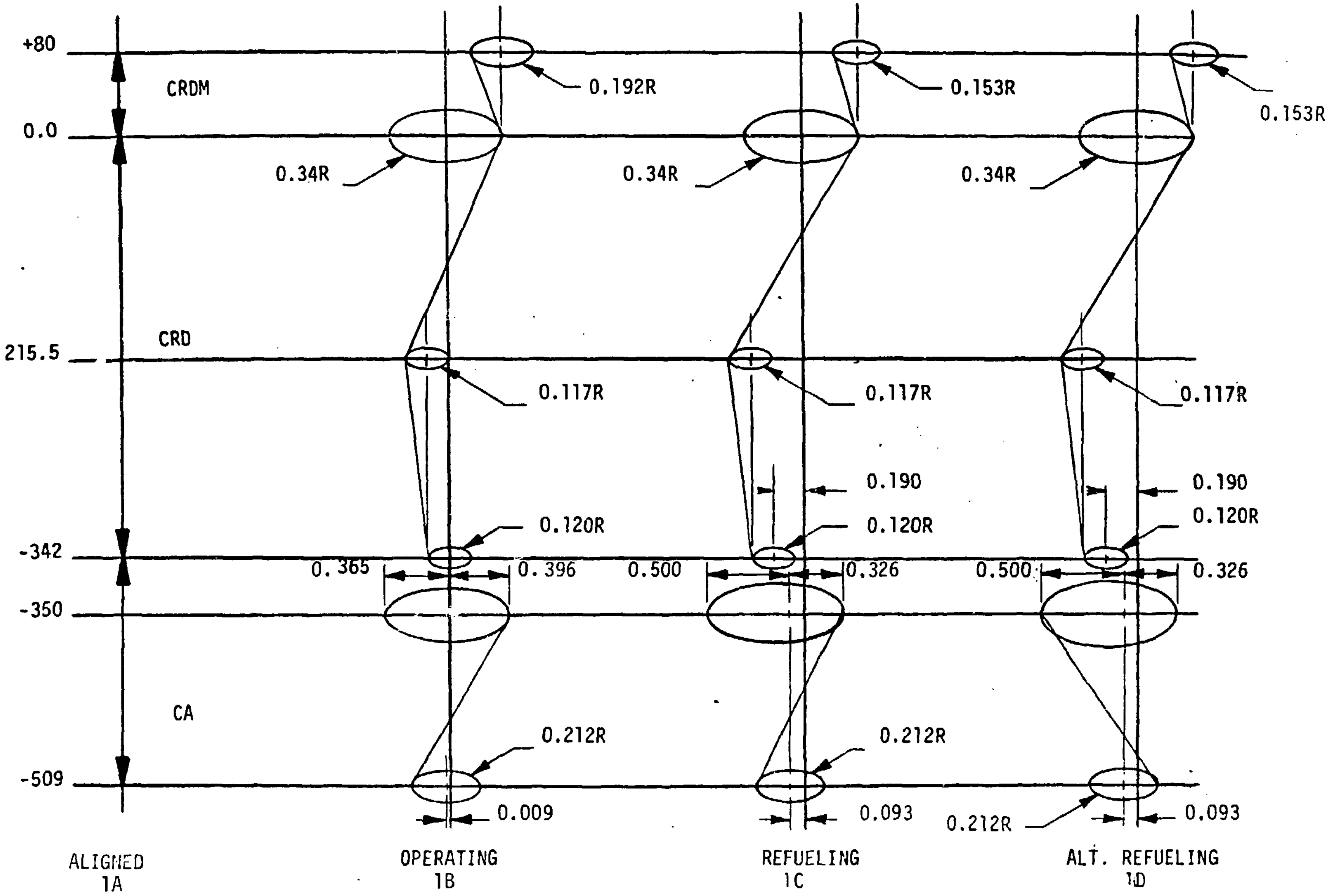


Figure 4

CRBR PROTOTYPE TEST MISALIGNMENT CONDITIONS