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FFTF MODIFIED FERMII CONTROL ROD
DRIVE MECHANISM
CONCEPTUAL DESIGN STUDY

June 1969

AEC RESEARCH &
DEVELOPMENT REPORT

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CONCEPTUAL DESIGN STUDY

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FFTF MODIFIED FERMI CONTROL ROD
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J. R. McBride
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A. OBJECTIVE

The objective of this study was to develop a conceptual definition of shim/scram control rod drive mechanisms for the Fast Test Reactor (FTR), based on the Enrico Fermi Reactor safety rod concept.

B. BACKGROUND

The safety rod drive mechanism for the Enrico Fermi Fast Breeder Reactor^(1,2) served as a basis for the FTR control mechanisms conceptual design evaluated in this study. There is some deviation from the Enrico Fermi concept in the Modified Fermi Conceptual Design (MFCD) due to conditions unique to the FTR and improvements in technology since the Enrico Fermi Reactor was designed.

C. REACTOR CONTROL - GENERAL CONCEPT

The function of the reactor control rods is reactivity control. Reactivity is controlled by inserting or withdrawing neutron absorbing material (poison).

The shim/scram control rod has two modes of operation. In the shim mode the rod is inserted or withdrawn from the core with the drive to make adjustments in reactivity. When scrammed, the rod is released from the drive extension section by a mechanical latch and accelerated into the core by the combined forces of a spring and gravity. Rods are scrammed when an abnormal condition exists which endangers the reactor or auxiliary systems.

D. DESIGN PHILOSOPHY

The conceptual design was based on Core Concept VIII (SK-3-12881),* however, it is adaptable to other core concepts with a minimum of change. When a final core concept has been selected, it will be necessary to check the design against the specifications. To aid this review process, capabilities of components specified and critical areas in the design are outlined in this report. In addition, improvements in the design which may be made by changing the current specifications are pointed out.

E. DESCRIPTION

1. CONTROL MECHANISMS OPERATING CAPABILITIES

	<u>Design Criteria Requirements</u>	<u>Modified Fermi Conceptual Design</u>
<u>Physical Envelope</u>		
Diameter and length	7.5 in. diam x 72 in. from nozzle flange to top	7.5 in. diam x 71 in. from nozzle flange to top
<u>Drive Section</u>		
Stroke	38.0 in.	39.0 in.
Shim rate	9.0 in./min	9.0 in./min
Max. withdrawal rate	9.0 in./min	9.0 in./min
Max. insertion rate	Unspecified	90.0 in./min
Smallest jog increment	0.05 in.	0.001 in.
Capacity (push or pull)	1000 lb	1060 lb
Primary Position Indication**		
Smallest increment	0.010 in.	0.001 in.
Accuracy (full stroke)	0.100 in.	0.060 in.
Reproducibility	0.050 in.	0.006 in.
Secondary Position Indication**		
Smallest increment	Unspecified	0.022 in.
Accuracy (full stroke)	Unspecified	0.140 in.
Reproducibility	Unspecified	0.021 in.

* SK-numbers refer to Pacific Northwest Laboratory engineering drawings.

** With respect to drive mounting head, neglecting differential thermal expansion.

	<u>Design Criteria Requirements</u>	<u>Modified Fermi Conceptual Design</u>
<u>Poison Assembly</u>		
Scram Stroke	38.0 in.	37.0 in.
Maximum velocity	Unspecified	7.3 ft/sec
Scram time*	Unspecified	0.7 sec
Maximum acceleration	2 to 3 G	70.1 ft/sec ²
Poison Assembly Weight	300 lb	383 lb**

Environment

- At elevation 26 ft 4 in. (top of vessel head):

100 mr/hr gamma
 10^3 neutrons/cm²-sec
 250 °F

- At elevation 21 ft (bottom of plug):

3×10^5 r/hr gamma
 10^8 n/cm²-sec (less than 0.5 MeV)
 1100 °F

2. DESCRIPTION OF SECTIONSGeneral

The control rod assembly consists of three major sections which are:

- Drive section
- Drive extension section
- Poison section

The poison section is coupled to the lower end of the drive extension section with a mechanical latch. The whole assembly is raised and lowered with a translating nut type ball screw actuator powered with a stepping motor. The drive extension penetrates the shielding plug which is supported by

* Time from interruption of the electromagnet circuit to complete deceleration of rod by dashpot

** Seven-rod bundle, B₄C poison

a tube from the top of the guide tube. Due to the high temperature at the bottom of the shield plug (estimated 1100 °F), it does not appear feasible to use a sliding contact type seal. Instead, a flow of purge gas will be maintained from the upper side to the lower side of the shield plug to minimize the amount of sodium vapor entering the drive cavity. As a backup, the ball screw is enclosed in a bellows seal, and all joints are sealed with static seals.

A cylindrical cam closes the latch fingers on a spool that is attached to the poison section. Once the fingers are cammed in, the cam is held with an electromagnet. The cam is connected to the electromagnet with a latch rod that extends up through the drive extension section. When the electromagnet is de-energized, the cam drops and the fingers open releasing the poison section. The poison section is accelerated into the core by the combined forces of a spring and gravity. In the last 6 in. of stroke, it is decelerated by the dashpot type decelerator located at the bottom of the guide tube. The decelerator uses sodium as its damping medium.

The guide tube is supported by the reactor cover at the top, and the tube sheet at the bottom. In order to keep compressive loads on the guide tube low, a spring assembly built into the reactor cover is designed to carry two-thirds of the 1200 lb assembly weight with the other one-third carried by the tube sheet. The spring will accommodate 1 in. of differential thermal expansion between the reactor vessel and guide tube.

Specifica. Drive Section

The drive section is shown on Sheets 1 and 2 of SK-3-13278.* Control movement is accomplished with a translating nut type ball screw actuator driven by a stepping motor. Primary rod position indication comes from a digital rotary shaft encoder, and as a backup, rod position is indicated by a 10-turn potentiometer. Rod full-in and full-out positions are indicated by an adjustable 10-turn rotary limit switch.

The stepping motor is a versatile unit. A single stepping motor replaces the two motors, two speed reducers, two clutches, and a magnetic brake used on the Fermi drive, but flexibility of operation is not reduced. Stepping rate is adjustable from 50 to 1500 steps/sec which gives rod translational rates of 3 to 90 in./min, respectively. In normal operation the rod will move at 9 in./min (150 steps/sec). Upon scram, the drive will "chase" the poison section down at 90 in./min. Suitable control interlocks must be provided to ensure the rod cannot be withdrawn at more than 9 in./min.

In the Fermi Reactor, a control rod which was fully inserted buckled due to differential thermal expansion between the rod and guide tube. In order to avoid this problem in the FTR it is planned that the static holding torque of the stepping motor be reduced to a level which will allow the ball screw to back-drive the motor, thus relieving an excessive compressive load on the control rod. Reduction in holding torque can be accomplished by reducing the field coil excitation voltage with a fixed resistor in the field circuit. The resistor would be by-passed with a relay when the motor is stepped.

* See Appendix A for Drawings SK-3-13278 and SK-3-13288.

A rotary shaft angle encoder coupled directly to the stepping motor and working in conjunction with a bidirectional counter located in the control room serves as the primary control rod position indication system. The encoder generates 200 pulses per shaft revolution. With a 0.2 in. screw lead, 1 in. of control rod movement is equal to 1000 encoder pulses.

Secondary position indication comes from a ten-turn potentiometer. A planetary speed reducer with a 20:1 ratio converts the 200 screw revolutions required for 40 in. of linear travel into 10 revolutions of the potentiometer. A 10-turn adjustable rotary limit switch is coupled to the potentiometer to indicate when the rod is in the full-in and full-out positions.

b. Drive Extension Section

The drive extension section is shown in detail on Sheets 3 through 6 of SK-3-13278. The drive extension section consists of the latch rod electromagnet, latch rod, latch rod seal bellows, and control rod mechanical latch.

The following outline of the latching and scrambling sequences explains the operation of the drive extension section components.

Latching Sequence. With the poison section uncoupled and bottomed in the dashpot, the extension section is driven down. As the extension is driven down, the cocking tube seats on the poison section scram assist spring follower and begins to compress the spring. Driving further down, the latch cam contacts the spool bolt as shown in Figure 1A. The extension is driven further down causing differential motion between the latch fingers and cam, closing the fingers over the spool. At the same time, the electromagnet which is part of the drive extension, moves down to contact the armature. When the extension has moved 0.75 in. down from the point of initial

contact with the cam (Figure 1B), the electromagnet makes contact with the armature. To ensure good contact between the electromagnet and armature, the extension drives down another 0.25 in. compressing the electromagnet backup spring and actuating the limit switches which stop the drive and energize the electromagnet (Figure 1C). The drive is reversed and withdrawn 1 in. to the rod seated position (Figure 1D).

Scramming Sequence. With the poison section coupled to the drive extension and raised to the operating position, the following sequence of events take place when the rod is scrammed. Upon receipt of a signal to scram, the electromagnet is de-energized. The combination of the latch rod assembly weight, delatch assist spring force, and the resultant downward force on the cam caused by the outward force on the latch fingers causes the cam to move downward with respect to the fingers. As the cam moves downward, the acceleration spring and the weight of the poison section pull the latch spool out of the fingers. The cam moves further downward and cams the fingers out from the inside so that the fingers will fit over the spool when subsequently moved down for relatching.

There are several components in the drive extension which were changed from the Fermi concept in order to improve their performance.

To make alignment between the electromagnet and armature less critical, a self-aligning ball bushing was added to the armature. The angle on the bore of the cam (Figure 2) was increased from $2^{\circ} 26'$ used in the Fermi Reactor to 40° for the FTR. This increase in angle makes the latch self-opening when the latch magnet is released even if the delatch assist spring fails and the coefficient of friction is as high as 0.8. Increasing this cam angle increases the electromagnet

FIGURE 2. *Cam Angle for FTR*

holding force required. Required electromagnet holding force versus drive lifting load for coefficients of friction of 0.4 and 0.8^(3,4) is shown in Figure 3.

c. Poison Section

The Modified Fermi Conceptual Design for the FTR poison section is illustrated in Drawing SK-3-13288 (shown in the latched and fully retracted position). The original scrammable control rod poison section used in the Fermi Reactor is described in Reference 2. The basic components in the Modified Fermi Poison Section are the poison assembly and the dashpot. These basic components fit within the space envelope described by the guide tube. The major parts in the poison assembly are a latch spool, a scram assist spring assembly, a poison element and a ram. Parts in the dashpot area include the dashpot, the dashpot support tube, and the flow control orifice. A test section is illustrated in the Modified Fermi design drawing, but it may be eliminated in future work.

Since this was a conceptual design study, an effort was made to keep the design as flexible as possible to accommodate changes and to develop a general design basis that could be used to evaluate future modifications. In view of the fact that there were many unknowns pertaining to the poison section such as poison type and geometry, necessity of a test section, location of the poison during normal operation, required scram time, etc., it was necessary to choose a base design. This was done in order that a design description could be developed with sufficient detail to reveal feasibility problems.

The base design for this study contains a poison assembly with a 7-rod bundle B_4C poison element, a test section, a triple stepped ram, and a circular guide tube of variable cross section. The poison assembly is 19 ft 7 in. long and weighs approximately 383 lb. In the latched and fully

FIGURE 3. Latch Rod Electromagnet Holding Force Versus Latch Load for Coefficients of Friction of 0.4 and 0.8

retracted position, the latch spool is 20 in. below the sodium pool surface. Annular clearance between poison assembly alignment pads and the guide tube was scaled up from the Fermi reactor design and is 0.035 in. This clearance will accommodate a combined poison assembly and guide tube bow of 0.070 in./20 ft before jamming will be possible. In addition to the alignment pads, fluid dynamic lift forces tend to center the poison assembly in the guide tube.⁽⁵⁾ Flow control orifices will have to be sized experimentally when coolant requirements are determined. A series of orifices will reduce erosion and cavitation.

Materials were selected for all poison section components except the poison element. All other poison assembly components except the scram assist spring, spool, and poison assembly pads will be made of 304 stainless steel, which is considered the standard structural material for FFTF reactor internals. Colmonoy 4, which was used for the Fermi poison assembly pads, was used in the FFTF design. The spring material selected was Inconel X-750, but Inconel 718 may be a better choice if sufficient data can be generated on this new alloy (see Appendix B.)

For the base design it was necessary to make some assumptions as to the location of the poison section with respect to the core when the poison section is in the fully retracted position. The portion of total travel over which the scram assist force should act was also fixed in order to make the base design more definitive. The bottom of the poison section with the rod fully withdrawn was assumed to be 4 in. above the top of the core to reduce its effect on normal reactor operation. The first few inches of poison insertion into the core are the most significant in overcoming an excursion. On this basis, scram assist was provided for the first 10 in. of travel at which location the bottom of the poison will be

inserted 6 in. into the core. The poison is fully inserted into the core after a 37 in. scram stroke. Deceleration occurs over the last 6 in. of travel.

Maximum temperature seen by the poison section components was assumed to be 1200 °F (the ultimate operating bulk sodium outlet temperature) omitting gamma heating.

The base design is versatile enough to accommodate other poison types and geometries. A hexagonal guide tube and poison assembly represent a possibility if higher compactness is required. The test section could be eliminated with minor modifications. Changes in total travel, scram assist travel, and poison location in the fully retracted position could be accommodated but would require design modification. Changes in spring length would require only small modifications. Other scram assist devices such as pneumatic and hydraulic devices have been considered but would require considerable modification to the conceptual design.

Description of Scram Operation. The operation of the poison section will now be discussed. In normal reactor operation, the poison assembly is latched and withdrawn as required by the test program. Sodium coolant removes the heat generated in the poison section components due to radiation absorption. Sodium flows into the guide tube from the inlet plenum, through the flow control orifice, and past the dashpot and ram. Above the ram there are two parallel flow paths. One path is through the annular gap between the guide tube and the poison assembly. The other path is through the center of the poison assembly past the poison rods. When an excursion occurs, the poison assembly is unlatched and is accelerated into the core by gravitational and spring forces. It is retarded by fluid drag forces, bouyant forces, and sliding friction forces. In the last six inches of travel the ram enters the dashpot, pressure in the dashpot rises causing the assembly to decelerate to a smooth stop. Deceleration loads

on the dashpot are transmitted directly to the upper tube sheet thus reducing guide tube stress.

Description of Design Performance. A dynamic and kinematic analysis was made of the poison assembly design to determine approximate scram times, velocities, accelerations, drag forces, dynamic loads, scram assist requirements, etc. The method of analysis is described in Appendix B. The analysis resulted in two computer programs, RODDYN and DRAG, which compute poison assembly dynamics and poison assembly drag coefficients, respectively, for the Modified Fermi Control Rod Design. Listings of these programs are also included in Appendix B.

The kinematics for the reference case of the base design are illustrated in Figure 4. Total scram time for the reference case of the base design was calculated at 0.60 second for 37 in. of travel. The time required for the first 10 in. of travel was 0.18 sec. Maximum acceleration was 70.1 ft/sec^2 and maximum velocity 7.3 ft/sec . Maximum drag force prior to entering the dashpot was 465 lb. Constant deceleration was assumed in the dashpot and was calculated at 40.3 ft/sec^2 with an associated deceleration force of 867 lb. These values were based on an initial spring cocked force of 800 lb with a preload of 400 lb. However, for the reference case of the base design the spring was assumed to have relaxed 25% to a cocking force of 600 lb and a preload of 200 lb. For a description of the reference case of the base design refer to Appendix B.

F. DISCUSSION

One of the goals of this report is to guide future work so that a successful design results. In the course of the study several critical areas in the design have been noted. Also, it has been noted that some modification of the original specifications, if possible, could result in significant improvements in the design.

FIGURE 4. Base Design Poison Assembly Kinematics (Reference Case)

1. CRITICAL AREAS IN THE DESIGN

a. Scram Assist Spring

One of the most critical components in the MFCD affecting performance is the scram assist spring. The effects of irradiation, high temperature, and liquid sodium environment on the spring are not predictable, based on currently available spring materials data. There is data available on the effects of high temperature on spring materials, but only limited information on the effects of high temperature and high radiation combined. From the available thermal effects data, an Inconel X-750 spring, if used in the conceptual design, would not relax more than 10% in one year when subjected to a steady 1200 °F environment. However, if the combined effects of temperature and radiation are of the same magnitude as with Nimonic 80A,⁽⁶⁾ a similar alloy, spring relaxation could be 60% in one year. In the conceptual design, 60% relaxation would mean an increase of 20% in the time required to scram compared to a spring which had no relaxation.

It is important that two points concerning the spring be resolved. The required scram time must be established so that the need for scram assist can be determined and the combined effects of temperature and radiation on the spring material must be determined in order to make a decision on use of a spring for a scram assist device.

b. Seals

Seals are another critical area in the design. In the FTR three different sealing methods are used. A noncontacting purge type sealing arrangement is used to isolate the cavity above the shielding plug from the cover gas-sodium vapor atmosphere that exists below the shielding plug. Annular clearance requirements, purge gas velocity required, and methods for supplying and disposing of purge gas will have to be resolved through a development and testing program.

Two metal bellows type seals are specified in the design. One bellows is used to seal the latch rod penetration into the electromagnet case and the other bellows seals the ball screw. Bellows were used in a similar manner on the Fermi Reactor with success. In addition, tests on bellows in the FARET program showed that they can have quite a high cycle life.⁽⁷⁾ From experience gathered at the Enrico Fermi Reactor, bellows quality of manufacture is a large factor in successful performance. Reliability testing under simulated operating conditions is recommended. In addition, it is recommended that a pressure monitoring arrangement like that furnished on Fermi be used on the FTR to monitor seal integrity and to prevent an inflow of sodium vapor if a seal were to leak.

For static seals it is anticipated that "O"-ring type organic seals will be employed where temperatures and radiation levels permit. At higher temperatures and radiation levels metal seals will be used. Proper application of the seals and prototype testing under anticipated operating conditions should result in reliable seals.

c. Rod Position Indication During Scram

Rod position indication is tied to drive rotation. When scrammed, the poison section uncouples from the drive, and rod position indication is lost until the drive is run down to recontact the poison section in the full-in position. It is desirable to have rod position indication at all times, but it appears that any mechanical attachment to the poison section to give position readout during scram would reduce reliability of the system. Noncontacting position indication is a possibility if a sensor capable of withstanding the severe environment can be developed. One possible scheme would be to monitor the backpressure in a manifold that would supply sodium to a series of ports located along the guide tube. As the poison section moved down through the guide tube it would

close off the ports and thus increase the manifold backpressure. Backpressure could then be correlated to rod position. This scheme would depend upon the availability of a suitable pressure transducer and sufficient space for the manifold connecting the ports.

Future work on the Modified Fermi Conceptual Design should include consideration of possible continuous position indication schemes.

d. Lubrication

Certain components in the drive extension section and drive section must be lubricated. It is anticipated that those components below the drive coupling that require lubrication be treated with MoS_2 or other suitable dry lubricant. This includes the electromagnet armature self-aligning bearing, the electromagnet sliding surfaces, the ball screw, the ball nut, and the drive coupling. Those components above the drive coupling would be lubricated with high temperature, radiation resistant grease. Components above the drive coupling include the drive motor, shaft encoder, planetary speed reducer, potentiometer and rotary limit switch.

Ball screw life should be tested under anticipated environmental and lubrication conditions.

e. Lead Wires and Electrical Connectors

Lead wires and remote electrical connectors present a significant design problem. Lead wires from the electromagnet and limit switches must withstand the high temperature environment in the drive cavity and accommodate the 39 in. of relative movement between the electromagnet and the drive head. It is proposed that the lead cable be shielded with a stainless steel sheath which is coiled into a helical spring, one end attached to the drive head and the other attached to the electromagnet. The helical section is to be guided on the inside diameter with the ball nut reaction torque tube.

Additional design work is required on this concept and then a prototype assembly will be built and tested.

Connector requirements are dependent on whether or not remote handling is required. If manual connection is sufficient, commercially available sealed connectors should be suitable. However, if remote connection is required, special connectors will be necessary. In the remotely connected arrangement, connectors will be required to connect from the inner drive section cover to the connector mounted on the position readout component mounting frame, from the inner cover to the outer cover, and from the reactor room to the outer cover. The most difficult connector will be the unit which connects the inner and outer covers because it must accommodate 1 in. of movement between the two covers.

f. Latch Mechanical Interferences

The original Enrico Fermi Reactor latch design jammed, causing the fingers to be bent during in-sodium tests. The latch had been successfully operated in air and water prior to the sodium tests. Malfunction was traced to mechanical interferences which were the result of insufficient clearances between moving parts and insufficient bevel angles on interacting parts. Large scale layouts of the parts showed these interferences. When the parts were modified to eliminate these interferences, no further problems were encountered. On the Modified Fermi Reactor latch, large clearances have been allowed and interacting parts have been beveled to ease engagement. To validate satisfactory performance it is recommended that the latch be tested in sodium.

g. Assembly and Disassembly

Assembly and disassembly of the control rod components must be further refined. The approach taken was to build modules which could be gaged for various dimensional settings

and then combined to make up the overall assembly. It will be necessary to know what the requirements are concerning remote handling before the final assembly and disassembly sequences can be worked out for the control rod.

2. SUGGESTED SPECIFICATION MODIFICATIONS TO IMPROVE THE DESIGN

It is possible to make several improvements in the conceptual design by modifying the original specifications. These possible improvements are outlined so that they may be kept in mind if and when changes are made to the specifications.

a. Shorter Poison Section Stroke

Presently, specifications call for the bottom of the poison elements to be 4 in. above the core when the rod is fully withdrawn. If this could be changed to 4 in. below the top of the core for the safety rods, scram time could be reduced about 25%. In addition, the height of the drive assembly could be reduced by the 8 in. reduction in stroke.

b. Eliminate or Perforate Material Test Section

Reduction of fluid drag on the poison section by either eliminating or perforating the material test section between the ram and the poison elements would reduce scram time.

c. Increase Guide Tube Diameter Above the Top of the Sodium Pool

An increase in outside diameter of the guide tube from 5.25 to 6.25 in. by elimination of the guide liner tube would allow considerably more space for the drive and drive extension sections.

3. ALTERNATE COMPONENT DESIGN IDEAS

During the conceptual study a number of alternate component designs were considered. The following discussion describes alternate component designs considered and the reasons why they weren't used.

a. Reaction Torque Restraining Device

With a translating nut type linear actuator, the nut must be restrained from rotating in order to cause it to translate.

The first approach taken was to use trunnion mounted needle bearing cam followers running in guide slots. Insufficient diameter space made this approach unusable. The approach finally selected was to have a stationary hexagonally shaped tube guiding a sliding inner hexagonally shaped tube connected to the ball nut. In addition, this arrangement uses the two hexagonal tubes to guide the electromagnet lead wires.

b. Latch Rod Bellows Seal

The Enrico Fermi latch rod had an upper and lower bellows seal. The lower bellows was immersed in sodium. On the Modified Fermi design the lower bellows seal was eliminated. It was felt that the potential disadvantages associated with a bellows immersed in 1200 °F sodium would far outweigh the advantages of two bellows seals.

c. Spring Scram Assist

Alternatives to the single spring scram assist design are designs incorporating multiple springs in a nested or non-nested arrangement and acting in series or parallel. Both parallel and series arrangements of multiple springs can result in shorter lengths than a single spring arrangement for the same maximum shear stress, spring constant, stroke, preload, and envelope diameter. The reduction in length would mean that the bottom of the multiple spring arrangements could be located at a distance farther above the core than the single spring arrangement, and thus alleviate possible spring relaxation problems due to high irradiation.

This advantage is offset by the increase in complexity resulting from an increase in the number of springs, and the

problems associated with fastening them together and keeping them aligned. Another disadvantage of multiple springs is the increase in drag on the poison assembly due to a reduction in flow area.

The single spring arrangement was chosen for the conceptual design because of its inherent simplicity and lower drag. If spring relaxation due to irradiation proves to be too severe for the long single spring design, then a multiple spring design will have to be reconsidered.

G. RECOMMENDATIONS

1. At this time there are insufficient materials data to predict the scram assist spring's performance in an environment of sodium, high temperature (ultimate operating conditions), and radiation. Since the spring is an integral part of the Modified Fermi Conceptual Design, assurance that it will perform satisfactorily is essential. Therefore, it is recommended that alternate scram assist schemes be considered. This could mean using a device other than a spring or locating the spring out of the severe environment. The selection of an alternate scram assist scheme will probably mean a large modification of the drive design. Care must be taken to retain the desirable features now present in the design.

2. It is recommended that a study be undertaken to determine the effects of sodium, high temperature, and radiation on spring materials. If the study gives assurance that a spring will function satisfactorily in the environment, it would be possible to use it as originally planned.

3. To proceed to detailed design of a prototype control rod, the following points must be resolved.

- a. Maximum allowable scram time must be established.
- b. Those factors affecting scram time such as stroke, sodium flow rate, poison section geometry, and poison assembly weight must be finalized.

- c. Temperature and radiation profiles must be established to be sure that components selected are suitable.
- d. Remote handling requirements must be established.

4. Problem areas outlined in the discussion section must be resolved through a combined development and test program. Problem areas include seals, lubrication, lead wires and connectors, latch interferences, assembly-disassembly of the control rod, and position indication of the poison section during scram.

5. In order to determine design requirements for the scram assist device and decelerator, it is necessary to know the dynamics of the poison assembly along its full scram stroke. Analytical work and the resulting computer programs, RODDYN and DRAG, used to compute the poison assembly dynamics and kinematics of the Modified Fermi Control Rod Design have thus far been based on the assumption of constant drag force coefficients during a scram and constant deceleration in the dashpot (see Appendix B). This limits the ability to predict poison assembly performance and leaves no provision for the design of ram geometry. The effects of variable flow path geometry and variable friction factors on drag coefficients could be accounted for by computing the drag coefficients as a simultaneous part of the solution to the equations of motion. This will be done by integrating the DRAG program into the RODDYN program. The deceleration force in the dashpot should be derived and incorporated into the RODDYN computer program so deceleration performance could be predicted and ram geometry determined. Scram performance from any position of rod withdrawal could also be evaluated with this modification in the program.

To validate the relationships derived, it is recommended that the following tests be performed using water to simulate the sodium coolant.

- a. Measure pressure drop across the ram for different annular clearances, flow velocities, and ram insertion depths into the dashpot. This static test will be performed to determine the correctness of analytical relationships previously derived to describe the pressure drop across the ram in terms of annular clearance, flow velocity, and ram insertion depth.
- b. Perform dynamic tests with the goal of obtaining correlation between analytically predicted and actual performance. Drop tests will be performed with the ram and dashpot, during which ram dynamics for different ram entrance velocities, annular clearances, and weights could be monitored.
- c. To verify poison assembly pressure drop calculations, a simulated poison assembly should be statically tested for pressure drop at different flow velocities.
- d. A prototype poison assembly incorporating the optimized ram should be tested to verify predicted scram time.

APPENDIX A

DESIGN DRAWINGS

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SK-3-13278 Sheets 1 through 15

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E.E.T.E. CONTROL ROD
COCKED POSITION
13 IN
SCALE

CONCEPTUAL

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Scramble Control Rod Assembly

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Control Rod Assembly

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SECTION F-F

SECTION E-E

DETAIL D

CONCEPTUAL

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SECTION K-K

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SECTION P-P

SECTION N-N

SECTION M-M

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SECTION T-T

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SECTION V-V

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SECTION AA-AA

CONCEPTUAL

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APPENDIX B

ANALYSIS AND CALCULATIONS

APPENDIX B

ANALYSIS AND CALCULATIONS

DESIGN ANALYSIS

An analysis was made of the dynamics and kinematics of the poison section during a scram so that the performance of the base design and modifications to the design could be evaluated. The equations of motion for the poison assembly and the drag force on the assembly were derived. Computer programs were written to compute drag force coefficients and to numerically solve the equations of motion. In addition, a limited parametric study was made.

EQUATIONS OF MOTION FOR POISON ASSEMBLY

$$\sum \text{Forces} = \text{Time rate of change of momentum}$$

or

$$\sum F = \frac{d(MV)}{dt}$$

$$X = \int V dt$$

$$AC = \frac{dV}{dT}$$

where

$\sum F$ = Summation of forces on the assembly

AC = Acceleration of the assembly

V = Velocity of the assembly

X = Distance traveled by the assembly

M = Mass of the assembly

T = Time

There are several major forces which may act on the poison assembly. These are a spring force, the assembly weight, bouyant force, a sliding friction force, and a fluid drag force. A constant scram assist force was also included to make the analysis more general. Substituting, we have

$$\sum F = K(S - X) + W - F_b - F_{\text{frict}} + F_{\text{con}}$$

$$-F_{\text{drag}} = M \frac{dV}{dt}$$

where

$$F_{\text{drag}} = C_a \frac{dV_r}{dt} + C_v V_r^2, \quad V_r = V - V_{\text{fgt}}$$

and

K = Spring constant

S = Distance spring is compressed in the cocked position

W = Poison assembly weight

F_b = Bouyant force

F_{frict} = Sliding friction force

F_{con} = Constant scram assist force

F_{drag} = Fluid drag force

V_r = Velocity of poison assembly relative to the velocity of the fluid in the guide tube ahead of the assembly

V_{fgt} = Velocity of the fluid in the guide tube ahead of the assembly

C_a = Drag coefficient due to acceleration of the fluid with respect to time

C_v = Drag coefficient due to viscous fluid effects

G = Gravitational acceleration.

To simplify formulation of these equations, it was assumed that all of the spring coils were at the velocity of the poison assembly and that the drag force could be approximated as two linearly independent components, an acceleration component and a viscous component. The determination of the drag coefficients and drag force will be discussed later. Flow rate in the guide tube ahead of the poison assembly was assumed to be constant or zero. The control rod assembly was assumed to be in a vertical position.

The exact solution of these equations for location, velocity, acceleration, and drag force as a function of time is not known. An approximate solution was obtained by expressing the equations in finite difference form and programming a digital computer to perform the required numerical integrations and differentiations. In finite difference form we have:

$$K \left\{ S - \frac{[X(I) + X(I + 1)]}{2} \right\} + W - F_B - \text{Frict} + F_{\text{con}} \\ - C_a \left\{ \frac{V(I + 1) - V(I)}{\Delta T} \right\} - \frac{C_v}{4} [V(I) - V_{\text{fgt}} + V(I + 1) - V_{\text{fgt}}]^2 \\ = \frac{W}{G} \left\{ \frac{V(I + 1) - V(I)}{\Delta T} \right\},$$

$$X(I + 1) = X(I) + \left\{ [V(I + 1) + V(I)]/2 \right\} \Delta T.$$

$$AC(I + 1/2) = [V(I + 1) - V(I)]/\Delta T,$$

$$\Delta T = T(I + 1) - T(I),$$

where the spring force during a time increment, ΔT , is taken as the average of the force at $T(I + 1)$ and $T(I)$. The velocity used in calculating the viscous drag force is derived similarly. Substituting for $X(I + 1)$ and simplifying we can solve the resulting quadratic for $V(I + 1)$.

$$V(I + 1) = \frac{-B \pm \sqrt{B^2 - 4CA}}{2A}$$

where,

$$A = \frac{-C_v \Delta T}{4}$$

$$B = \frac{-K \Delta T^2}{4} - C_a - \frac{V(I) C_v \Delta T}{2} + V_{\text{fgt}} C_v \Delta T - \frac{W}{G}$$

$$C = K S \Delta T - K X(I) \Delta T - \frac{K V(I) \Delta T^2}{4} + W \Delta T - F_b \Delta T + C_a V(I)$$

$$\begin{aligned}
& - \frac{C_v \Delta TV(I)^2}{4} + C_v \Delta TV(I) V_{fgt} - C_v \Delta TV_{fgt}^2 \\
& + \frac{WV(I)}{G} - Frict \Delta T + Fcon \Delta T.
\end{aligned}$$

Of the two possible roots

$$V(I + 1) = \frac{-B - \sqrt{B^2 - 4CA}}{2A},$$

describes the velocity of the poison assembly.

Previous experimental work by Battelle-Northwest has shown that constant deceleration can be approximated during travel in the dashpot. The kinematic and dynamic analysis of the poison assembly was based on constant deceleration in the dashpot.

A listing of the computer program RODDYN, which calculates poison assembly kinematics and dynamics, is included (Figure B-1). Input variables with associated dimensional units are defined at the beginning of the listing. The accuracy of the numerical solution depends on the size of the time step. Time steps of 0.01 sec were shown to give a close approximation to the solution for cases solved in the parametric study. This was demonstrated by comparing the solutions for time steps of 0.01 and 0.001 sec.

FLUID DRAG FORCE

The fluid drag force on the poison assembly during a scram can only be determined exactly by actual experimentation. However, an approximation to the actual drag forces can be obtained by considering the fluid dynamics involved.

The force acting on a submerged body moving relative to an undisturbed stream is equal to the sum of the surface integral of normal pressure and the tangential shear stresses acting on it. The drag force is the component of that force in the direction of the flow of the undisturbed fluid relative to the body. The lift force is the component normal to the drag force.

100	1*	C	THIS PROGRAM CALCULATES POISON ASSEMBLY LOCATION, VELOCITY,
100	2*	C	ACCELERATION, AND DRAG FORCE AS A FUNCTION OF TIME BETWEEN
<hr/>			
100	3*	C	UNLATCHING AND ENTRY INTO THE DASHPOT. CONSTANT DECELERATION IS
100	4*	C	ASSUMED IN THE DASHPOT AND THE TIME REQUIRED TO TRAVERSE THE
100	5*	C	DASHPOT IS BASED ON THIS ASSUMPTION.
101	6*		
101	7*	C	IFIN = NUMBER OF CASES
101	8*		
101	9*	C	IMAX = NUMBER OF ALLOWABLE TIME STEPS SO THAT CASES REQUIRING
101	10*	C	AN UNREASONABLE AMOUNT OF TIME TO SCRAM CAN BE TERMINATED
101	11*		
101	12*	C	ICASE = CASE NUMBER
101	13*		
101	14*	C	DELT = TIME INCREMENT IN SECONDS
101	15*		
101	16*	C	VFGT = VELOCITY OF FLUID IN THE GUIDE TUBE AHEAD OF THE POISON
101	17*	C	SECTION IN FT/SEC . IT MUST BE ENTERED AS A NEGATIVE VALUE WHEN
101	18*	C	OPPOSITE IN DIRECTION TO THE MOTION OF THE POISON ASSEMBLY
101	19*		
101	20*	C	XDASH = DASHPOT LENGTH IN INCHES
101	21*		
101	22*	C	ST = DISTANCE SPRING IS COMPRESSED FROM ITS FREE LENGTH TO ITS
101	23*	C	LATCHED LENGTH IN INCHES
101	24*		
101	25*	C	S1 = DISTANCE SPRING EXPANDS WHEN UNLATCHED IN INCHES.
101	26*		
101	27*	C	S2 = DISTANCE TRAVELED BY THE POISON ASSEMBLY PRIOR TO ENTERING
101	28*	C	THE DASHPOT IN INCHES
101	29*		
101	30*	C	FRICT = FRICTIONAL FORCE DUE TO SLIDING IN LBS.
101	31*		
101	32*	C	FCON = ANY CONSTANT FORCE THAT MAY BE USED AS A SCRAM ASSIST IN
101	33*	C	LBS.
101	34*		

FIGURE B-1. RODDYN Computer Program Listing

```

01 35* C FB = BOUYANT FORCE ON ASSEMBLY IN LBS.
01 36*
01 37* C CV = VISCOUS DRAG FORCE COEFFICIENT IN LB*SEC**2/FT**2
01 38*
01 39* C CA = ACCELERATION DRAG FORCE COEFFICIENT IN LB*SEC**2/FT**2
01 40*
01 41* C SKR = SPRING CONSTANT LB/IN
01 42*
01 43* C W = WEIGHT OF POISON ASEMBLY INCLUDING THE SPRING IN LB
01 44*
01 45* C AC = ACCELERATION PRIOR TO ENTERING THE DASHPOT IN FT/SEC**2.
01 46*
01 47* C V = VELOCITY OF THE POISON ASSEMBLY IN FT/SEC.
01 48*
01 49* C X = DISTANCE TRAVELED BY THE POISON ASSEMBLY AT A GIVEN TIME IN
01 50* C INCHES
01 51*
101 52* C DELX = DISTANCE TRAVELED DURING A TIME INCREMENT IN INCHES.
101 53*
101 54* C ADASH = DECELERATION OF POISON ASSEMBLY IN THE DASHPOT IN FT/
101 55* C SEC**2.
101 56*
101 57* C TS2 = TIME REQUIRED FOR THE POISON ASSEMBLY TO TRAVEL DISTANCE S2
101 58* C IN SEC.
101 59*
1101 60* C TDASH = TIME REQUIRED TO TRAVERSE THE DASHPOT IN SECONDS.
1101 61*
1101 62* C TOTL = TOTAL TIME FOR SCRAM IN SECONDS.
1101 63*
1101 64* C FDRAG = DRAG FORCE ON THE ASSEMBLY IN LBS.
1101 65*
1101 66* DIMENSION T(1000), X(1000), V(1000), AC(1000), A(1000), B(1000),
1101 67* IC(1000), DELX(1000), FDRAG(1000)
1103 68* 1000 FORMAT (7E10.4)

```

FIGURE B-1. Cont'd RODDYN Computer Program Listing

```

0104 69* 1050 FORMAT (7I10)
0105 70*      READ (5,1050)  IFIN
0110 71*      READ (5,1050)  IMAX
0113 72*      10 CONTINUE
0114 73*      READ (5,1050)  ICASE
0117 74*      READ (5,1000)  DELT
0122 75*      READ (5,1000)  VFGT
0125 76*      READ (5,1000)  XDASH
0130 77*      READ (5,1000)  ST
0133 78*      READ (5,1000)  S1
0136 79*      READ (5,1000)  S2
0141 80*      READ (5,1000)  FRIC
0144 81*      READ (5,1000)  FCON
0147 82*      READ (5,1000)  FB
0152 83*      READ (5,1000)  CV
0155 84*      READ (5,1000)  CA
0160 85*      READ (5,1000)  SKR
0163 86*      READ (5,1000)  W
0166 87* 2051 FORMAT (1H , 'IFIN = ', I5)
0167 88* 2050 FORMAT (1H , 'IMAX = ', I5)
0170 89* 2052 FORMAT (1H0, 'ICASE = ', I5)
0171 90* 2000 FORMAT (1H , 'DELT = ', 1P5E15.5)
0172 91* 2001 FORMAT (1H , 'VFGT = ', 1P5E15.5)
0173 92* 2002 FORMAT (1H , 'XDASH = ', 1P5E15.5)
0174 93* 2003 FORMAT (1H , 'ST = ', 1P5E15.5)
0175 94* 2004 FORMAT (1H , 'S1 = ', 1P5E15.5)
0176 95* 2005 FORMAT (1H , 'S2 = ', 1P5E15.5)
0177 96* 2006 FORMAT (1H , 'FRIC = ', 1P5E15.5)
0200 97* 2007 FORMAT (1H , 'FCON = ', 1P5E15.5)
0201 98* 2008 FORMAT (1H , 'FB = ', 1P5E15.5)
0202 99* 2009 FORMAT (1H , 'CV = ', 1P5E15.5)
0203 100* 2010 FORMAT (1H , 'CA = ', 1P5E15.5)

```

FIGURE B-1. Cont'd RODDYN Computer Program Listing

```

00204 101* 2011 FORMAT (1H , 'SKR = ', 1P5E15.5)
00205 102* 2012 FORMAT (1H , 'W = ', 1P5E15.5)
00206 103* WRITE (6,2052) ICASE
00211 104* WRITE (6,2051) IFIN
00214 105* WRITE (6,2050) IMAX
00217 106* WRITE (6,2000) DFLT
00222 107* WRITE (6,2001) VFGT
00225 108* WRITE (6,2002) XDASH
00230 109* WRITE (6,2003) ST
00233 110* WRITE (6,2004) S1
00236 111* WRITE (6,2005) S2
00241 112* WRITE (6,2006) FRICF
00244 113* WRITE (6,2007) FCON
00247 114* WRITE (6,2008) FR
00252 115* WRITE (6,2009) CV
00255 116* WRITE (6,2010) CA
00260 117* WRITE (6,2011) SKR
00263 118* WRITE (6,2012) W
00263 119* INITIALIZE TIME,SPACE,VELOCITY,ACCELERATION,CONSTANTS,AND INDEXES
00266 120* G = 32.2
00267 121* I=0
00270 122* J=0
00271 123* T(1) =0.
00272 124* X(1)=0.
00273 125* V(1)=0.
00274 126* AC(1)=0.
00275 127* A(1) =0.
00276 128* B(1) =0.
00277 129* C(1) =0.
00300 130* DELX(1)=0.
00301 131* SK = SKR
00302 132* 100 I=I+1
00303 133* IF ( I.EQ. TMAX) GO TO 500
00303 134* INCREMENT TIME

```

FIGURE B-1. Cont'd RODDYN Computer Program Listing

```

00305 135*      T(I+1) = T(I) + DELT
00306 136*      A(I) = -CV*DELT/4.
00307 137*      B(I) = -3.*SK*DELT**2-CA-CV*V(I)*DELT/2.-W/G
00307 138*      1 +VFGT*CV*DELT
00310 139*      C(I) = SK*DELT*ST-SK*DELT*X(I)-3.*SK*V(I)*DELT**2.+W*DELT+CA*V(I)
00310 140*      1-CV*DELT*V(I)**2/4.+W*V(I)/G
00310 141*      2-FR*DELT-FRICT*DELT+FCON*DELT +CV*DELT*V(I)*VFGT -CV*DELT*VFGT**2
00311 142*      V(I+1) = ( -B(I)-SQRT(B(I)**2-4.*A(I)*C(I)))/(2.*A(I))
00312 143*      DELX(I) = 6.*(V(I+1)+V(I))*DELT
00312 144*      C CALCULATE THE DISTANCE TRAVELED BY THE POISON ASSEMBLY AT THE END
00312 145*      C OF THE CURRENT TIME INCREMENT
00313 146*      X(I+1) = X(I) +DELX(I)
00313 147*      C CALCULATE THE AVERAGE ACCELERATION DURING THE CURRENT TIME
00313 148*      C INCREMENT
00314 149*      AC(I) = (V(I+1)-V(I))/DELT

00315 150*      FDRAG(I+1) = CV*((V(I+1)+V(I))/2. )**2 + CA*AC(I)
00315 151*      C DETERMINE IF SPRING EXPANSION WILL TERMINATE BEFORE ONE HALF THE
00315 152*      C NEXT TIME STEP IF THE CURRENT VELOCITY IS MAINTAINED
00316 153*      XCHECK = X(I+1) +6.*V(I+1)*DELT
00316 154*      C CHECK FOR APPROXIMATE POINT AT WHICH SPRING FORCE IS ZERO
00317 155*      IF ( XCHECK .LT. S1) GO TO 100
00321 156*      SK = 0.
00322 157*      200 I=I+1
00323 158*      IF ( I .EQ. IMAX) GO TO 500
00323 159*      C INCREMENT TIME
00325 160*      T(I+1) = T(I) + DELT
00326 161*      A(I) = -CV*DELT/4.
00327 162*      B(I) = -CA-CV*V(I)*DELT/2.-W/G
00327 163*      1 +VFGT*CV*DELT
00330 164*      C(I) = W*DELT + CA*V(I)-CV*DELT*V(I)**2/4. + W*V(I)/G
00330 165*      1-FR*DELT-FRICT*DELT+FCON*DELT +CV*DELT*V(I)*VFGT -CV*DELT*VFGT**2
00331 166*      V(I+1) = ( -B(I)-SQRT(B(I)**2-4.*A(I)*C(I)))/(2.*A(I))

```

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FIGURE B-1. Cont'd RODDYN Computer Program Listing

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```

00332 167*      DELX(I) = 6.*(V(I+1)+V(I))*DELT
00332 168*      C      CALCULATE THE DISTANCE TRAVELED BY THE POISON ASSEMBLY AT THE END
00332 169*      C      OF THE CURRENT TIME INCREMENT
00333 170*      X(I+1) = X(I) + DELX(I)
00333 171*      C      CALCULATE THE AVERAGE ACCELERATION DURING THE CURRENT TIME
00333 172*      C      INCREMENT
00334 173*      AC(I) = (V(I+1)-V(I))/DELT
00335 174*      FDRAG(I+1) = CV*((V(I+1)+V(I))/2.)**2 + CA*AC(I)
00335 175*      C      DETERMINE IF THE POISON ASSEMBLY HAS ENTERED THE DDASHPOT.
00336 176*      XCHECK = X(I+1)
00337 177*      IF ( XCHECK .LT. S2) GO TO 200
00337 178*      C      ASSUME CONSTANT VELOCITY V(I+1) FROM S2 AND CALCULATE TIME
00337 179*      C      REQUIRED TO TRAVERSE DISTANCE S2
00341 180*      TS2 = T(I+1) - (X(I+1)-S2)/(12.*V(I+1))
00342 181*      JI = I+1
00343 182*      WRITE (6,5000)
00345 183*      5000 FORMAT (1H0, 'VALUES PRIOR TO ENTERING THE DASHPOT: /)
00346 184*      WRITE (6,3001)
00350 185*      3001 FORMAT (1H , 5X, 'TIME', 10X, 'DISTANCE', 5X, 'DELX', 9X, 'VELOCITY',
00350 186*      1 2X, 'ACCELERATION', 2X, 'DRAG FORCE', 5X, 'A', 12X, 'B', 12X, 'C', 11X,
00350 187*      2 'J')
00351 188*      WRITE (6,3002)
00353 189*      3002 FORMAT (1H , 5X, 'SEC ', 10X, 'IN ', 5X, 'IN ', 9X, 'FT/SEC ',
00353 190*      1 2X, 'FT/SEC**2 ', 2X, 'LBS ', 10X, ' / ')
00354 191*      3000 FORMAT (1H , 1P9E13.3, 15)
00355 192*      WRITE (6,3000) (T(J), X(J), DELX(J), V(J), AC(J), FDRAG(J), A(J), B(J),
00355 193*      10(J), J, J=1, JT)
00374 194*      4000 FORMAT (1H0, 5X, 'TS2 = ', 1P9E15.5)
00375 195*      WRITE (6,4000) TS2
00375 196*      C      ASSUME CONSTANT DECELERATION IN THE DASHPOT AND CALCULATE THE
00375 197*      C      TIME REQUIRED TO TRAVERSE THE DASHPOT AND THE DECELERATION
00375 198*      C      REQUIRED

```

FIGURE B-1. Cont'd RODDYN Computer Program Listing

```

00400 199*      TDASH = XDASH/(6.*V(I+1) )
00401 200*      ADASH = V(I+1)/TDASH
00402 201*      TOTT = TDASH + TS2
00403 202*      WRITE (6,5050)
00405 203*      5050 FORMAT (1H0, 'VALUES IN THE DASHPOT,/')
00406 204*      WRITE (6,6001) TDASH
00411 205*      6001 FORMAT (1H , 5X, 'TDASH = ', 1P5E15.5)
00412 206*      6002 FORMAT (1H , 5X, 'ADASH = ', 1P5E15.5)
00413 207*      WRITE (6,6002) ADASH
00416 208*      WRITE (6,6003) TOTT
00421 209*      6003 FORMAT (1H , 5X, 'TOTAL TIME = ', 1P5E15.5 , '/')
00422 210*      IF (ICASE .LT. IFIN) GO TO 10
00424 211*      500 STOP
00425 212*      END

```

FIGURE B-1. Cont'd RODDYN Computer Program Listing

The drag force can be broken into two categories. The first is the pressure or form drag due to a pressure difference across parallel projected surface areas of the body. The second is the shear drag which is caused by the friction of the fluid on the surface of the body.

If the poison assembly scram occurred at constant velocity, the drag force would be due to viscous effects only and steady state viscous fluid dynamics could be applied. However, the scram is unsteady and therefore the effects of acceleration of the fluid with respect to time must be considered. The major effect of fluid acceleration with respect to time is to alter the steady state form drag with some interaction with the shear drag.

The simultaneous solution for the drag force due to acceleration and viscous effects is complex. In order to simplify the problem the viscous effects were treated independently of the acceleration effects. The drag force was thus broken into two components, a steady state viscous component and an unsteady state nonviscous component.

VISCOUS FORCE COMPONENT

The steady state viscous component will now be discussed. The total steady state viscous component is made up of the two categories, form drag and shear drag. However, the total

viscous drag force on the poison assembly, F_{pa} , and the guide tube, F_{gt} , is opposed by an equal and opposite force on the fluid column surrounding the poison assembly, or

$$F_{pa} + F_{gt} = (P_1 - P_2) A_2.$$

The viscous drag on the poison section is

$$F_{pa} = (P_1 - P_2) A_1 = F \text{ (viscous)},$$

where A_1 is defined as the cross sectional area between the center of the guide tube and the line in the annular gap between the poison assembly and the guide tube on which the shear stresses are zero. For cases where the annular gap is small, this line may be taken at the center of the gap without causing significant error in the viscous drag force. The total pressure drop across the assembly is the sum of the pressure drops across various locations along the assembly.

$$\begin{aligned} P_1 - P_2 &= \left(\sum \frac{\rho K}{2g} V_f^2 + \sum \frac{\rho f l}{D} \frac{V_f^2}{g} \right)_{\text{annulus}} \\ &= \left(\sum \frac{\rho K}{2g} V_f^2 + \sum \frac{\rho f l}{D} \frac{V_f^2}{g} \right)_{\text{Central flow path}}, \end{aligned}$$

where V_f is the fluid velocity relative to the assembly at a particular location. The guide tube was assumed to move at the velocity and acceleration of the assembly to simplify the formulation of both viscous and acceleration force components.

Using the continuity relationship we can solve for the pressure drop in terms of the velocity of the assembly relative to the fluid ahead of the assembly in the guide tube, V_r . Upon substitution, the viscous component of the drag force is derived in terms of a constant times V_r^2

$$F \text{ (viscous)} = C_v V_r^2.$$

ACCELERATION FORCE COMPONENT

The unsteady state nonviscous drag force component can be derived similarly. This force component is equal to the pressure difference across the assembly times the cross sectional area, Aax of the assembly.

$$F \text{ (acceleration)} = (P_1 - P_2) Aax$$

The pressure drop across the assembly is equal to the sum of the pressure drops across various locations along the assembly;

$$\begin{aligned} P_1 - P_2 &= \sum \rho L AC_f \text{ (Annulus)} \\ &= \sum \rho L AC_f \text{ (central flow path)}, \end{aligned}$$

where AC_f is the absolute acceleration of the fluid at a particular location.

Differentiating the continuity relation, we can solve for the pressure drop in terms of the acceleration of the poison assembly relative to the fluid in the guide tube ahead of the assembly, AC .

$$F \text{ (acceleration)} = C_a AC$$

The calculation of the drag coefficients has been programmed on a digital computer and a listing of the program DRAG is included (Figure B-2). Input, including dimensional units, is described in the listing.

COMPARISON OF ANALYSIS TO EXPERIMENTAL RESULTS

In order to evaluate the accuracy of the design analysis, an analysis was made of an experimental decelerator test stand used in a previous study and compared to experimental data. The test stand consisted of a vertical guide tube, a simulated poison section, a scram assist spring, and a dashpot to decelerate the simulated poison section. A velocity of

00101	1*		
00101	2*	C	THIS PROGRAM CALCULATES THE VISCOUS DRAG COEFFICIENT CV AND THE
00101	3*	C	ACCELERATION DRAG COEFFICIENT CA WHERE THE DRAG FORCE IS EXPRESSED
00101	4*	C	AS A FUNCTION OF ASSEMBLY VELOCITY AND ACCELERATION.
00101	5*	C	DRAG FORCE = CV*VELOCITY **2 + CA*ACCELERATION
00101	6*		
00101	7*	C	IN ORDER TO SIMPLIFY THE FORMULATION OF THE EQUATIONS USED IN THIS
00101	8*	C	PROGRAM IT WAS ASSUMED THAT THE PRESSURE DROP DUE TO VISCOUS
00101	9*	C	EFFECTS WAS INDEPENDENT OF THE PRESSURE DROP DUE TO ACCELERATION.
00101	10*		
00101	11*		DIMENSION AA(10), AKA(10), AB(10), AKB(10), AK(10), BK(10),
00101	12*		1SLA(10), SLB(10), DA(10), DB(10)
00101	13*		2,DELPVA(10), DELPKA(10), DELPVB(10), DELPKB(10)
00101	14*		3,FFA(10), FFB(10)
00101	15*		4,AALOSS(10), AAF(10), ABLOSS(10), ABF(10) , AACEL(10), BACEL(10)
00101	16*		5,DELPAA(10), DELPAB(10),
00101	17*		6FORVIS(10),FORVIK(10),AKVIS(10),AVIS(10),
00101	18*		7 FACELL(10),FBCELL(10),ACCEL(10),BCCEL(10)
00103	19*		
00103	20*	C	IMAXD = TOTAL NUMBER OF CASES
00103	21*		
00103	22*	C	ICASE = CASE NUMBER
00103	23*		
00103	24*	C	IKAIN = NUMBER OF LOCATIONS IN ANNULAR FLOW PATH AT WHICH
00103	25*	C	EXPANSION, CONTRACTION, AND ETC. TYPE PRESSURE DROPS OCCUR
00103	26*		
00103	27*	C	IKBIN = NUMBER OF LOCATIONS IN CENTRAL FLOW PATH AT WHICH
00103	28*	C	EXPANSION, CONTRACTION, AND ETC. TYPE PRESSURE DROPS OCCUR
00103	29*		
00103	30*	C	IAAIN = NUMBER OF LOCATIONS IN ANNULAR FLOW PATH AT WHICH
00103	31*	C	FL/D TYPE PRESSURE DROPS OCCUR
00103	32*		
00103	33*	C	IABIN = NUMBER OF LOCATIONS IN CENTRAL FLOW PATH AT WHICH
00103	34*	C	FL/D TYPE PRESSURE DROPS OCCUR
00103	35*		

FIGURE B-2. DRAG Computer Program Listing

00103	36*	C	ML = MAXIMUM OF IKAIN, IKBIN, IAAIN, IABIN
00103	37*		
00103	38*	C	DEN = DENSITY OF THE FLUID IN THE GUIDE TUBE--(LB/FT**3)
00103	39*		
00103	40*	C	AGT = FLOW AREA IN THE GUIDE TUBE AHEAD OF THE POISON ASSEMBLY
00103	41*	C	(IN**2)
00103	42*		
00103	43*		
00103	44*	C	AVIS(I) = THE PORTION OF THE FLOW AREA IN THE GUIDE TUBE
00103	45*	C	WHICH IS USED TO CALCULATE THE DRAG FORCE COEFFICIENT DUE TO
00103	46*	C	VISCOUS EFFECTS CORRESPONDING TO DELPVA(I).
00103	47*	C	IT IS THE AREA LOCATED BETWEEN THE CENTER OF THE GUIDE TUBE AND A
00103	48*	C	POINT IN THE ANNULAR GAP (FORMED BY THE POISON ASSEMBLY AND THE
00103	49*	C	GUIDE TUBE) AT WHICH THE FLUID SHEAR STRESS IS ZERO. FOR A SMALL
00103	50*	C	ANNULAR GAP AREA RELATIVE TO GUIDE TUBE AREA ONLY A SMALL ERROR
00103	51*	C	IN VISCOUS DRAG FORCE WILL RESULT BY ASSUMING ZERO SHEAR STRESS
00103	52*	C	EXISTS AT THE CENTER OF THE ANNULAR GAP. (IN**2)
00103	53*		
00103	54*	C	AKVIS(I) = THE PORTION OF THE FLOW AREA IN THE GUIDE TUBE
00103	55*	C	WHICH IS USED TO CALCULATE THE DRAG FORCE COEFFICIENT DUE TO
00103	56*	C	VISCOUS EFFECTS CORRESPONDING TO DELPKA(I).
00103	57*	C	IT IS THE AREA LOCATED BETWEEN THE CENTER OF THE GUIDE TUBE AND A
00103	58*	C	POINT IN THE ANNULAR GAP (FORMED BY THE POISON ASSEMBLY AND THE
00103	59*	C	GUIDE TUBE) AT WHICH THE FLUID SHEAR STRESS IS ZERO. FOR A SMALL
00103	60*	C	ANNULAR GAP AREA RELATIVE TO GUIDE TUBE AREA ONLY A SMALL ERROR
00103	61*	C	IN VISCOUS DRAG FORCE WILL RESULT BY ASSUMING ZERO SHEAR STRESS
00103	62*	C	EXISTS AT THE CENTER OF THE ANNULAR GAP. (IN**2)
00103	63*		
00103	64*	C	ACCEL(I) = CROSS SECTIONAL AREA OF THE POISON ASSEMBLY AT
00103	65*	C	LOCATION (I) USED IN CALCULATING THE DRAG FORCE LOSS COEFFICIENT
00103	66*	C	DUE TO ACCELERATION CORRESPONDING TO DELPAA(I). (IN**2)
00103	67*		
00103	68*	C	BCCEL(I) = CROSS SECTIONAL AREA OF THE POISON ASSEMBLY AT
00103	69*	C	LOCATION (I) USED IN CALCULATING THE DRAG FORCE LOSS COEFFICIENT
00103	70*	C	DUE TO ACCELERATION CORRESPONDING TO DELPAB(I). (IN**2)

FIGURE B-2. Cont'd DRAG Computer Program Listing

00103	71*		
00103	72*	C	AA(I) = FLOW AREA AT LOCATION (I) IN ANNULAR FLOW PATH USED TO
00103	73*	C	DETERMINE FL/D TYPE PRESSURE DROP--(IN**2)
00103	74*		
00103	75*	C	AB(I) = FLOW AREA AT LOCATION (I) IN CENTRAL FLOW PATH USED TO
00103	76*	C	DETERMINE FL/D TYPE PRESSURE DROP--(IN**2)
00103	77*		
00103	78*	C	AKA(I) = FLOW AREA AT LOCATION (I) IN ANNULAR FLOW PATH USED TO
00103	79*	C	DETERMINE EXPANSION, CONTRACTION, AND ETC. TYPE PRESSURE DROP--
00103	80*	C	(IN**2)
00103	81*		
00103	82*	C	AKB(I) = FLOW AREA AT LOCATION (I) IN CENTRAL FLOW PATH USED TO
00103	83*	C	DETERMINE EXPANSION, CONTRACTION, AND ETC. TYPE PRESSURE DROP--
00103	84*	C	(IN**2)
00103	85*		
00103	86*	C	AK(I) = LOSS COEFFICIENT CORRESPONDING TO AREA AKA(I)
00103	87*		
00103	88*	C	BK(I) = LOSS COEFFICIENT CORRESPONDING TO AREA AKB(I)
00103	89*		
00103	90*	C	SLA(I) = FLOW PATH LENGTH AT LOCATION (I) IN ANNULAR FLOW PATH
00103	91*	C	CORRESPONDING TO AREA AA(I)--(IN)
00103	92*		
00103	93*	C	SLB(I) = FLOW PATH LENGTH AT LOCATION (I) IN CENTRAL FLOW PATH
00103	94*	C	CORRESPONDING TO AREA AB(I)--(IN)
00103	95*		
00103	96*	C	FFA(I) = FRICTION FACTOR AT LOCATION (I) IN ANNULAR FLOW PATH
00103	97*	C	CORRESPONDING TO AREA AA(I)--(NUMERIC)
00103	98*		
00103	99*	C	FFB(I) = FRICTION FACTOR AT LOCATION (I) IN CENTRAL FLOW PATH
00103	100*	C	CORRESPONDING TO AREA AB(I)--(NUMERIC)
00103	101*		
00103	102*	C	DA(I) = HYDRAULIC DIAMETER AT LOCATION (I) IN ANNULAR FLOW PATH
00103	103*	C	CORRESPONDING TO AREA AA(I)--(IN)
00103	104*		
00103	105*	C	DB(I) = HYDRAULIC DIAMETER AT LOCATION (I) IN CENTRAL FLOW PATH
00103	106*	C	CORRESPONDING TO AREA AB(I)--(IN)

FIGURE B-2. Cont'd DRAG Computer Program Listing

```

00103 107*
00103 108*      1000 FORMAT (7E10.5)
00104 109*      5000 FORMAT (1H ,1P8E15.5)
00105 110*      1050 FORMAT (7I10)
00106 111*      2050 FORMAT (1H ,8I10)
00106 112*      C      READ IN INPUT
00107 113*      READ (5,1050)      IMAXD
00112 114*      5      READ (5,1050)      ICASED
00115 115*      READ (5,1050)      IKAIN
00120 116*      READ (5,1050)      IKBIN
00123 117*      READ (5,1050)      IAAIN
00126 118*      READ (5,1050)      IABIN
00131 119*      READ (5,1050)      ML
00134 120*      IKA = IKAIN
00135 121*      IKB = IKBIN
00136 122*      IAA= IAAIN
00137 123*      IAB = IABIN
00140 124*      LM = ML
00141 125*      READ (5,1000)      DEN
00144 126*      READ (5,1000)      AGT
00147 127*      READ (5,1000)      (AVIS(I), I=1,IAA)
00155 128*      READ (5,1000)      (AKVIS(I), I=1,IKA)
00163 129*      READ (5,1000)      (ACCEL(I), I=1,IAA)
00171 130*      READ (5,1000)      (BCCEL(I), I=1,IAB)
00177 131*      READ (5,1000)      (AA(I), I=1,IAA)
00205 132*      READ (5,1000)      (AB(I), I=1,IAB)
00213 133*      READ (5,1000)      (AKA(I), I=1,IKA)
00221 134*      READ (5,1000)      (AKB(I), I=1,IKB)
00227 135*      READ (5,1000)      (AK(I), I=1,IKA)
00235 136*      READ (5,1000)      (BK(I), I=1,IKB)
00243 137*      READ (5,1000)      (SLA(I), I=1,IAA)
00251 138*      READ (5,1000)      (SLB(I), I=1,IAB)
00257 139*      READ (5,1000)      (FFA(I), I=1,IAA)
00265 140*      READ (5,1000)      (FFB(I), I=1,IAB)
00273 141*      READ (5,1000)      (DA(I), I=1,IAA)
00301 142*      READ (5,1000)      (DB(I), I=1,IAB)

```

FIGURE B-2. Cont'd DRAG Computer Program Listing

00307	143*	1350	FORMAT (1H0, 10X, 'IMAXD	= ' ,6I10)
00310	144*	1351	FORMAT (1H , 10X, 'ICASED	= ' ,6I10)
00311	145*	1400	FORMAT (1H , 10X, 'IKA	= ' ,6I10)
00312	146*	1401	FORMAT (1H , 10X, 'IKB	= ' ,6I10)
00313	147*	1402	FORMAT (1H , 10X, 'IAA	= ' ,6I10)
00314	148*	1403	FORMAT (1H , 10X, 'IAB	= ' ,6I10)
00315	149*	1404	FORMAT (1H , 10X, 'ML	= ' ,6I10)
00316	150*	1500	FORMAT (1H , 10X, 'DEN	= ' ,1P6E15.5)
00317	151*	1501	FORMAT (1H , 10X, 'AGT	= ' ,1P6E15.5)
00320	152*	1996	FORMAT (1H , 10X, 'AVIS(I)	= ' ,1P6E15.5)
00321	153*	1997	FORMAT (1H , 10X, 'AKVIS(I)	= ' ,1P6E15.5)
00322	154*	1998	FORMAT (1H , 10X, 'ACCEL(I)	= ' ,1P6E15.5)
00323	155*	1999	FORMAT (1H , 10X, 'BCCEL(I)	= ' ,1P6E15.5)
00324	156*	2000	FORMAT (1H , 10X, 'AA(I)	= ' ,1P6E15.5)
00325	157*	2001	FORMAT (1H , 10X, 'AB(I)	= ' ,1P6E15.5)
00326	158*	2002	FORMAT (1H , 10X, 'AKA(I)	= ' ,1P6E15.5)
00327	159*	2003	FORMAT (1H , 10X, 'AKB(I)	= ' ,1P6E15.5)
00330	160*	2004	FORMAT (1H , 10X, 'AK(I)	= ' ,1P6E15.5)
00331	161*	2005	FORMAT (1H , 10X, 'BK(I)	= ' ,1P6E15.5)
00332	162*	2006	FORMAT (1H , 10X, 'SLA(I)	= ' ,1P6E15.5)
00333	163*	2007	FORMAT (1H , 10X, 'SLB(I)	= ' ,1P6E15.5)
00334	164*	2008	FORMAT (1H , 10X, 'FFA(I)	= ' ,1P6E15.5)
00335	165*	2009	FORMAT (1H , 10X, 'FFB(I)	= ' ,1P6E15.5)
00336	166*	2010	FORMAT (1H , 10X, 'DA(I)	= ' ,1P6E15.5)
00337	167*	2011	FORMAT (1H , 10X, 'DB(I)	= ' ,1P6E15.5)
00340	168*		WRITE(6,1350) IMAXD	
00343	169*		WRITE(6,1351) ICASED	
00346	170*		WRITE(6,1400) IKA	
00351	171*		WRITE(6,1401) IKB	
00354	172*		WRITE(6,1402) IAA	
00357	173*		WRITE(6,1403) IAB	
00362	174*		WRITE(6,1404) ML	
00365	175*		WRITE(6,1500) DEN	
00370	176*		WRITE(6,1501) AGT	

FIGURE B-2. Cont'd DRAG Computer Program Listing

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00373 177*      WRITE(6,1996) (AVIS(I), I=1,IAA)
00401 178*      WRITE(6,1997) (AKVIS(I), I=1,IKA)
00407 179*      WRITE(6,1998) (ACCEL(I), I=1,IAA)
00415 180*      WRITE(6,1999) (BCCEL(I), I=1,IAB)
00423 181*      WRITE (6,2000)      (AA(I), I=1,IAA)
00431 182*      WRITE (6,2001)      (AB(I), I=1,IAB)

00437 183*      WRITE (6,2002)      (AKA(I),I=1,IKA)
00445 184*      WRITE (6,2003)      (AKB(I),I=1,IKB)
00453 185*      WRITE (6,2004)      (AK(I), I=1,IKA)
00461 186*      WRITE (6,2005)      (BK(I), I=1,IKB)
00467 187*      WRITE (6,2006)      (SLA(I), I=1,IAA)
00475 188*      WRITE (6,2007)      (SLB(I), I=1,IAB)
00503 189*      WRITE (6,2008)      (FFA(I), I=1,IAA)
00511 190*      WRITE (6,2009)      (FFB(I), I=1,IAB)
00517 191*      WRITE (6,2010)      (DA(I), I=1,IAA)
00525 192*      WRITE (6,2011)      (DB(I), I=1,IAB)
00533 193*      TALOSS = 0.
00534 194*      TAAF = 0.
00535 195*      TBLOSS = 0.
00536 196*      TABF = 0.
00537 197*      TAAC = 0.
00540 198*      TBAC = 0.
00541 199*      FORVKT = 0.
00542 200*      FORVST = 0.
00543 201*      FBCELT = 0.
00544 202*      FACELT = 0.
00544 203*      CALCULATE PRESSURE DROP AND FORCE TO VISCous FRICTION
00545 204*      DO 100 I=1,IKA
00550 205*      AALOSS(I) = AK(I)*(AA(1)/AKA(I))**2
00551 206*      TALOSS= TALOSS + AALOSS(I)

```

FIGURE B-2. Cont'd DRAG Computer Program Listing


```

00552 207* 100 CONTINUE
00554 208*      DO 200 I=1,IAA
00557 209*      AAF(I) = (FFA(I)*SLA(I)/DA(I))*(AA(1)/AA(I))**2
00560 210*      TAAF = TAAF + AAF(I)
00561 211* 200 CONTINUE
00563 212*      DO 300 I=1,IKB
00566 213*      ABLOSS(I) = BK(I)*(AKB(1)/AKB(I))**2
00567 214*      TBLOSS = TBLOSS + ABLOSS(I)
00570 215* 300 CONTINUE
00572 216*      DO 400 I=1,IAB
00575 217*      ABF(I) = (FFB(I)*SLB(I)/DB(I))*(AKB(1)/AB(I))**2
00576 218*      TABF = TABF + ABF(I)
00577 219* 400 CONTINUE
00601 220*      AAN = TALOSS + TAAF
00602 221*      ABC = TBLOSS + TABF
00603 222*      VAVB = SQRT(ABC/AAN)
00604 223*      VBRAM = AGT/(VAVB*AA(1) + AKB(1))
00605 224*      VARAM = VBRAM*VAVB
00606 225*      DELPV = .5/(144.*32.2) *DEN*ABC*VBRAM**2
00606 226*      CALCULATE PRESSURE DROP AND FORCE DUE TO ACCELAERATION
00607 227*      DO 500 I=1,IAA
00612 228*      AACEL(I) = SLA(I)* AA(1)/AA(I)
00613 229*      TAAC = TAAC + AACEL(I)
00614 230* 500 CONTINUE
00616 231*      DO 501 I=1,IAB
00621 232*      BACEL(I) = SLB(I)*AB(1)/AB(I)
00622 233*      TBAC = TBAC + BACEL(I)
00623 234* 501 CONTINUE
00625 235*      AABA = TBAC/TAAC
00626 236*      ABRAM = AGT/(AABA*AA(1) + AB(1))
00627 237*      AARAM = ABRAM*AABA
00630 238*      DELPA = 1./((32.2*1728.)*TBAC*ABRAM*DEN
00631 239*      DO 600 I=1,IKA

```

FIGURE B-2. Cont'd DRAG Computer Program Listing

```

00634 240*      600 DELPKA(I) = .5/(144.*32.2)*DEN*AALOSS(I)*VARAM**2
00636 241*      DO 610 I=1,IAA
00641 242*      610 DELPVA(I) = .5/(144.*32.2)*DEN*   AAF(I)*VARAM**2
00643 243*      DO 620 I=1,IKB
00646 244*      620 DELPKB(I) = .5/(144.*32.2)*DEN*ABLOSS(I)*VBRAM**2
00650 245*      DO 630 I=1,IAB
00653 246*      630 DELPVB(I) = .5/(144.*32.2)*DEN*   ABF(I)*VBRAM**2
00655 247*      DO 640 I=1,IAA
00660 248*      640 DELPAA(I) =1./(32.2*1728.)*DEN*(AACEL(I)*AARAM-SLA(I))
00662 249*      DO 650 I=1,IAB
00665 250*      650 DELPAB(I) =1./(32.2*1728.)*DEN*(BACEL(I)*ABRAM-SLB(I))
00667 251*      DO 50 I=1,IAA
00672 252*      FACELL(I) = DELPAA(I)*ACCEL(I)
00673 253*      50 FACELT = FACELL(I) + FACELT
00675 254*      DO 51 I=1,IAB
00700 255*      FBCELL(I) = DELPAB(I)*BCCFL(I)
00701 256*      51 FBCELT = FBCELL(I) + FBCELT
00703 257*      CA      = FBCELT + FACELT
00704 258*      DO 102 I = 1,IKA
00707 259*      FORVIK(I) = DELPKA(I)*AKVIS(I)
00710 260*      102 FORVKT = FORVIK(I) + FORVKT
00712 261*      DO 103 I = 1,IAA
00715 262*      FORVIS(I) = DELPVA(I)*AVIS(I)
00716 263*      103 FORVST = FORVST + FORVIS(I)
00720 264*      CV      = FORVST + FORVKT
00721 265*      3010 FORMAT (1H0, 5X, 'DRAG FORCE = ', 1PE14.3, '*VELOCITY**2 + ',
00721 266*      1, 1PE14.3, '*ACCELERATION')
00722 267*      WRITE(6,3010) CV,CA
00726 268*      IF ( ICASED .GE. IMAXD ) GO TO 3333
00730 269*      GO TO 5
00731 270*      3333 STOP
00732 271*      END

```

FIGURE B-2. Cont'd DRAG Computer Program Listing

10 ft/sec after 17.2 in. of travel was taken from experimental data. The design analysis predicted a velocity of 11.1 ft/sec. The difference between the calculated and the experimental values is due to two main effects. First, sliding friction was assumed to be zero in the analysis. Second, drag coefficients were difficult to predict because of the problems associated with determining pressure drop loss coefficients (entrance, exit, turning) for the geometry of the simulated poison section. The entrance, exit and turning losses were significantly larger than the friction (f_l/d) losses in this case. In cases where f_l/d type losses are as great or greater than exit, entry, and turning losses, the method of analysis should predict better results, since f_l/d type losses can be determined more accurately. Poison assemblies analyzed in the parametric study are of this latter case.

PARAMETRIC ANALYSIS

Various modifications to the poison section base design are possible. In order to evaluate and compare the performance of a few possible cases, a limited parametric study was made. A reference case of the base design was selected for a common point of comparison. The dynamics and kinematics for each case were calculated using the RODDYN and DRAG computer programs.

Reference Case of the Base Design

The reference case of the base design is the 7-rod bundle B₄C assembly weighing 383 lb. Friction factors used to compute the viscous drag coefficient for this case were based on commercial steel roughness and a Reynolds number of 5×10^4 . There is a tapered section in the guide tube 8 in. above the core. The guide tube is circular above and below the taper (see Drawing SK-3-13288). Flow path lengths in the annulus vary due to the difference in guide tube cross sectional area above and below the taper in the guide tube.

As the poison assembly moves past the tapered section the annular flow path in the small section increases and the annular flow path in the large section decreases. To simplify the drag coefficient calculations for this geometry it was necessary to assume fixed flow path lengths in the annulus. They were based on poison section geometry after 10 in. of poison assembly travel. Drag on the scram assist spring assembly was neglected due to the large flow area in that section. Sodium properties were based on 1000 °F. The spring for the reference case has a free length of 97.5 in. The spring is assumed to be relaxed 25% to a cocking force of 600 lb and a preload of 200 lb, from an initial cocking force of 800 lb and a preload of 400 lb. Sliding friction forces were assumed to be zero. The assembly was assumed to be in a vertical position. Fluid velocity ahead of the assembly in the guide tube was assumed to be zero. Figure 4 of the reference case is typical of the kinematics of the cases compared.

Results of Parametric Study

The results of the parametric study are presented as plots of distance traveled by the poison assembly versus time. These will now be discussed.

Figure B-3 illustrates four different poison element geometries which contain two different poison materials, Boron Carbide (B_4C) and Tantalum (Ta). These two materials represent the most probable poison materials for the FFTF. The differences illustrated in Figure B-4 are due to assembly weight and fluid drag force which is geometry dependent. For the reference case, the poison assembly and the small and large sections of the guide tube are circular. In the other cases the poison assembly and the small section of the guide tube are hex-shaped, with the large section of the guide tube remaining circular. A more compact geometry is possible with the hex-shape.

7-Rod Bundle B_4C 7-Rod Bundle Ta
 Rod OD - 1.1283 in. Rod OD - 1.3 in.
 Poison Element Length - 90.5 in. Poison Element Length - 35.625 in.

61-Rod Bundle B_4C Billet Ta
 Rod OD - 0.416 in. Central Hole ID - 0.75 in.
 Poison Element Length - 90.5 in. Poison Element Length - 35.625

General: Poison Tube Wall Thickness - 0.1875 in.
 Guide Tube Wall Thickness - 0.150 in.
 Large Section of Guide Tube OD - 5.250 in.
 Small Section of Guide Tube: OD (Circular) - 4.52 in.
 Across outside flats (Hex) - 4.52 in.
 Poison Tube: OD (Circular) - 4.010 in.
 Across outside flats (Hex) - 4.095 in.

FIGURE B-3. Various Poison Section Cross Sections

FIGURE B-4. Distance Versus Time for Various Poison Elements with Scram Assist

Figure B-5 illustrates the effect on scram time of poison assembly surface roughness for the base design. If surface roughness used in predicting friction factors cannot be determined exactly for a particular case, predicted scram time could be bracketed by calculations based on smoothest and roughest possible cases.

Figure B-6 demonstrates the effect of spring relaxation on scram time. Approximately ten percent relaxation is anticipated due to thermal effects at 1200 °F in the base design. However, it may be much larger due to combined effects of radiation and temperature.

The effect of reducing spring length is shown in Figure B-7. The neutron flux decreases as the distance above the core increases. The lower end of the spring is in a relatively high flux region. Therefore, removing the lower portion of the spring could reduce possible spring relaxation due to irradiation effects. Figure B-7 also illustrates the effect of eliminating the entire scram assist spring assembly. This would simplify the design if required scram times could be achieved by free fall.

A few comments will summarize. Drag forces in the cases studied are the major retarding force and are highly geometry dependent. The reference case scram assist reduced scram time 1/3 from the free fall case. However, elimination of the scram assist would simplify the design. A review of the equations of motion show that increased assembly weight decreases acceleration when scram assist forces are greater than retarding forces. It increases acceleration when scram assist forces are less than retarding forces. Therefore, weight could be added to reduce the scram time of a free fall design.

FIGURE B-5. Distance Versus Time for Base Design for Commercial Steel and Smooth Tube Surface Roughness

FIGURE B-6. Distance Versus Time for Various Percentage Relaxation of Scram Assist Spring for Base Design

FIGURE B-7. Distance Versus Time for Various Free Lengths of Scram Assist Spring for Base Design

SPRING DESIGN

Base Design Spring Description

A scram assist device may be required to obtain the necessary scram time in the FFTF. In keeping with the Fermi concept, the scram assist selected for the base design 7-rod bundle B₄C poison assembly is a single spring. It is shown on Drawing SK-3-13278, Sheets 7,8, and 9. The material is Spring Temper Inconel X-750 which after cold coiling is solution treated at 2100 °F for 2 hr and aged at 1550 °F for 24 hr and 1300 °F for 20 hr. The spring was designed for a cocked force of 800 lb with a resulting torsional shear stress of 28,300 lb/in.² and a preload of 400 lb at an operating temperature of 1200 °F. Preloading gives the maximum amount of scram assist energy for a given amount of spring expansion and cocked force.

Since the modulus of rigidity changes with temperature the cocked force at room temperature is 1085 lb. This may tax the drive if cocking is required at room temperature since the maximum downward force available is 1060 lb plus the weight of part of the drive extension (approximately 100 lb). This force must cock the scram assist spring and also compress the magnet spring (100 lb maximum). If room temperature tests are to be used to simulate reactor operation at high temperature, then another spring will have to be designed to give the simulated cocking force. Relaxation due to thermal effects is estimated at less than 10% for 1 year's operation at 1200 °F. This estimate was obtained by linearly extrapolating data taken up to 4300 hr.⁽⁸⁾ Relaxation due to the combined effects of high temperature and irradiation are not known.

The spring could be modified to accommodate different poison sections or different scram assist forces. However, relaxation problems may be increased if the modification calls for higher torsional shear stresses. Relaxation due to the combined irradiation and high temperature effects may be

reduced by eliminating the lower portion of the spring which will be exposed to higher neutron flux than the upper portion. The effect of shorter length springs and relaxation on base design kinematics and dynamics are discussed in the parametric analysis section. Modifications should not require the spring to operate at the sodium pool cover gas interface because of impurity deposition and thermal stress problems.

Spring Materials Selection

Six spring materials were considered for the design. These were Inconel 718, Inconel X-750, A-286, S-816, Rene-41 and L-605. The last three are cobalt alloys and were eliminated because of potential problems in mass transport and handling radioactive materials. The first three are listed in order of their resistance to relaxation from thermal effects of 1200 °F in their optimum heat treatment condition.⁽⁸⁻¹³⁾ Very limited data on Inconel 718 show it to be significantly more resistant to relaxation due to thermal effects than Inconel X-750.⁽⁸⁻¹³⁾ Significantly more relaxation data due to thermal effects is available on Inconel X-750 than the other two alloys, and it has seen reactor use including the Fermi Reactor. On this basis, it was selected for the base design.

There is not enough information on the relaxation of spring materials under the combined effects of irradiation and high temperature to assume that the scram assist spring design will meet FTR requirements. Neutron flux in the FTR at the bottom of the spring with the poison assembly in the fully withdrawn position has been estimated at 5×10^7 n/cm²-sec with energies of $10 > \text{MeV} > 0.39$.⁽¹⁴⁾ Temperatures to 1200 °F are possible. Irradiation effects on the relaxation of Inconel X-750 at 600 °F and an integrated flux of 4.2×10^{19} nvt fast are discussed by Mehan.⁽¹⁵⁾ However, extrapolation of this data to 1200 °F does not appear feasible. Irradiation of a similar spring material Nimonic 80A showed relaxations of over

60% after 3800 hr in a fast fluence (0.6 to 5.9×10^{19} n/cm²) at 525 °C. (~976 °F).⁽⁶⁾

Relaxation is considered the major spring design problem. However, it is possible that a spring material could fail due to stress rupture if the material was highly relaxation resistant under irradiation and high temperature. The stress rupture properties of Inconel X-750 and A-286 under high temperature and irradiation are discussed by Collins.⁽¹⁶⁾

RAM AND DASHPOT DESIGN

The function of the ram and dashpot is to decelerate the poison assembly to a smooth stop during the last 6 in. of travel. Minimum dynamic loading of the poison section will occur if the dashpot and ram are designed for constant deceleration of the poison assembly.

Previous experimental work by BNW has indicated that it may be possible to approach constant deceleration with a triple stepped piston. The function of the steps is to decrease the flow area between the ram and dashpot as the ram moves further into the dashpot. The pressure force on the ram plus the drag force on components other than the ram act with the other retarding forces to decelerate the assembly. The major force is the pressure force on the ram. Constant deceleration could therefore be obtained by maintaining constant retarding forces on the ram. This can be approximated by proper sizing of the ram step diameter and length.

Additional analysis is required to develop a basis for sizing the ram steps. The approach to formulate this basis would be to develop a relationship for the pressure in the dashpot and force on the ram as a function of ram location, velocity, and deceleration. This force relationship could be substituted into the equations of motion by modifying the RODDYN computer program. Deceleration performance of specific ram geometries could then be evaluated.

STRESS AND BUCKLING ANALYSIS

Stress Analysis

Stress analysis of the poison section was limited to static and dynamic loading of the base design. Thermal strains and stresses and their effect on low cycle fatigue, fretting, etc., could be significant especially during the transient scram conditions. However, they were not evaluated during this study. All parts of the base design are adequately designed to accommodate the static and dynamic loads placed on them. Modifications from the base design would have to be analyzed to insure their reliable operation. Only the most highly stressed components of the base design will be discussed.

The latch spool bolt is the most highly stressed component under static loading. The maximum static load would occur under the improbable occurrence of freeing a stuck poison assembly. The maximum load would be a drive lift force of 1060 lb plus a cocked scram assist force of 800 lb. The stress under these conditions is 3480 lb/in^2 .

The dashpot support tube and dashpot wall are the most highly stressed components under dynamic loading. For the 383 lb base design assembly entering the dashpot at 6.3 ft/sec, a maximum load of 867 lb is imposed on the dashpot. Dashpot pressure is 123 lb/in^2 . Resulting dashpot support tube compressive stress is 740 lb/in^2 . Hoop stress in the dashpot wall is 734 lb/in^2 .

Available data on stainless steel 304⁽⁶⁾ suggest that there is a considerable margin of safety for the above loadings under the expected high temperatures and fast flux irradiation in the FTR.

Buckling Analysis

Buckling of the poison assembly under static and dynamic loading is not a problem for the base design. The ratio of the length of the assembly to the radius of gyration is less than 56.0. A compressive stress greater than 90,000 lb/in² would be required to cause buckling. Stress this high is not anticipated under dynamic loading. Yielding or crushing would probably occur at stresses below this value.

APPENDIX C

DESIGN CALCULATIONS

APPENDIX C
DESIGN CALCULATIONS

CONTROL ROD DRIVE CAPACITY

From curves on Slo-Syn HS 400B motor, at 150 steps/sec
 (9 in./minimum linear translation)

$$T = 600 \text{ oz.-in.}$$

For a ballscrew,

$$T = \frac{F \ell}{2\pi e}$$

$$F = \frac{T 2\pi e}{\ell}$$

$$e = 0.9 \quad (\text{ball screw manufacturer's recommendations})$$

$$\ell = 0.2 \text{ in.} \quad (\text{Saginaw 0875-0200-SRT or equivalent})$$

$$F = \frac{\frac{600 \text{ oz.-in.}}{16 \text{ oz/lb}} 2\pi(0.9)}{0.2 \text{ in.}}$$

$$F = 1060 \text{ lb} \leftarrow$$

at 1500 step/sec (90 in./minimum linear translation)

$$T = 220 \text{ oz.-in.}$$

$$F = \frac{\frac{220}{16} 2\pi(0.9)}{0.2} = 388 \text{ lb} \leftarrow$$

GUIDE TUBE SPRING CALCULATIONS

<u>Item</u>	<u>Weight, lb</u>
1. Guide tube	294
2. Dash pot	9.2
3. Drive assembly	
mounting head	36.3
motor	12.5
motor cov.	16.5
ball screw	10.6
4. Ball nut and ext.	
tube	20.3
electromagnet	
case	17.3
magnet	13.5
latch rod	15.8
5. Extension tube	45.5
6. Latch	40.0
7. Shielding	
tube	127.5
shielding	48.2
8. Control rod	400.0
Total	1107.2 lb

For miscellaneous items, add 15%

$$W_T = 1.15(1107.2) = 1270 \text{ lb}$$

SPRING SIZE CALCULATIONSStroke

Stroke necessary is equal to difference in expansion between guide tube and reactor vessel.

Assume 300 °F difference in temperature between guide tube and reactor vessel.

Guide tube length ≈ 439 in.

$$\delta = \alpha \Delta T \ell$$

$$\ell = 439 \text{ in.}$$

$$\Delta T = 300 \text{ °F}$$

$$\alpha = 9.0 \times 10^{-6} \text{ in./in./°F}$$

$$\delta = (9.0 \times 10^{-6}) (300) (439)$$

$$\delta = 1.185 \text{ in.}$$

Make stroke = 2 in.

For static loads,

$$S_s = K_s \frac{8FD}{\pi d^3}$$

$$F = \frac{2}{3} (1270) = 8471b \left(\begin{array}{l} \text{Design spring to carry } 2/3 \\ \text{of total weight, let tube} \\ \text{sheet carry other } 1/3 \end{array} \right)$$

$$D \approx 6 \text{ in.}$$

$$K_s \approx 1$$

$$S_s = 70,000 \text{ psi} \left(\begin{array}{l} \text{Inconel "X" 5\% relaxation in} \\ \text{7 days per page 40} \\ \text{Huntington Alloy Bulletin T-35} \end{array} \right)$$

Solve for d

$$d^3 = \frac{K_s 8FD}{\pi S_s}$$

$$d = 0.57 \text{ in.}$$

If 0.625 in. rod is used,

$$d = 0.625 \text{ in.}$$

$$D = 6.125 \text{ in.}$$

$$F = 847 \text{ lb}$$

$$K_s = 1 + \frac{.5}{C}$$

$$C = \frac{D}{d} = \frac{6.125}{0.625} = 9.8$$

$$K_s = 1 + \frac{.5}{9.8} = 1.051$$

$$S_s = \frac{(1.051)(8)(847)(6.125)}{\pi (0.625)^3}$$

$$S_s = 57,000 \text{ psi}$$

NUMBER OF ACTIVE COILS

$$y = \frac{8FD^3N}{d^4 G}$$

$$N = \frac{yd^4G}{8FD^3}$$

$$y = 2 \text{ in.}$$

$$d = 0.625 \text{ in.}$$

$$G = 10.5 \times 10^6 \text{ psi}$$

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$$F = 847 \text{ lb}$$

$$D = 6.125 \text{ in.}$$

$$N = 2.07$$

Increase deflection to 4 in.

$$y = 4 \text{ in.}$$

$$N = \frac{4}{2} 2.07 = 4.14 \text{ active coils}$$

DRIVE EXTENSION COLUMN LOAD CAPACITY CALCULATIONS

Critical load was calculated assuming two different end conditions:

1. Ends hinged
2. Ends fixed

1. Ends hinged

at

$$x = 0, L$$

$$\omega = 0$$

$$\frac{d^2 \omega}{dx^2} = 0$$

Equation of equilibrium

$$\frac{EI_1 d^2 \omega_1}{dx^2} + P \omega_1 = 0 \quad \text{when } 0 \leq x \leq L_1,$$

$$\frac{EI_2 d^2 \omega_2}{dx^2} + P \omega_2 = 0 \quad \text{when } L_1 \leq x \leq L$$

$$\text{Let } K_1^2 = \frac{P}{EI_1} \quad \text{and } K_2^2 = \frac{P}{EI_2}$$

$$\omega_1 = C_1 \sin K_1 x + C_2 \cos K_1 x \quad \text{when } 0 \leq x \leq L_1$$

$$\omega_2 = C_5 \sin K_2 x + C_6 \cos K_2 x \quad \text{when } L_1 \leq x \leq L_2$$

where C_1 , C_2 , C_5 , and C_6 are constants of integration.

Substitution of end conditions and simultaneous solution results in the following:

$$\frac{\tan K_1 L_1}{\tan K_2 L_2} = - \frac{K_1}{K_2}$$

Let
$$per = \frac{m^2 EI_2}{L^2}$$

where m^2 is a numerical factor depending on the ratios

$$\alpha_1 = \frac{L_1}{L} \text{ and } \alpha_2 = \sqrt{\frac{I_2}{I_1}}$$

substituting,

$$\frac{\tan m\alpha_1\alpha_2}{\tan m(1 - \alpha_1)} = - \alpha_2$$

$$L_1 = 39 \text{ in.}$$

$$L = 84 \text{ in.}$$

$$\alpha_1 = 0.464$$

$$I_1 = 0.0265 \text{ in.}^4 \text{ (Ball screw)}$$

$$I_2 = 0.537 \text{ in.}^4 \text{ (Extension tube)}$$

$$\alpha_2 = 4.5$$

substituting,

$$\frac{\tan 2.09m}{\tan 0.536m} = -4.5$$

By trial and error solution,

$$m = 0.935$$

$$P_{cr} = \frac{m^2 EI_2}{L^2}$$

$$E = 30 \times 10^6 \text{ psi}$$

$$P_{cr} = 1990 \text{ lb}$$

2. Ends fixed

Equations of Equilibrium

$$\frac{EI_1 d^2 \omega_1}{dx^2} + P\omega_1 = M_0 \quad \text{for } 0 \leq x \leq L_1$$

$$\frac{EI_2 d^2 \omega_2}{dx^2} + P\omega_2 = M_0 \quad \text{for } L_1 \leq x \leq L$$

Again, letting $K_1^2 = \frac{P}{EI_1}$ and $K_2^2 = \frac{P}{EI_2}$

General solution is;

$$\omega_1 = C_1 \sin K_1 x + C_2 \cos K_1 x + C_3$$

$$\omega_2 = C_5 \sin K_2 x + C_6 \cos K_2 x + C_7$$

where C_1, C_2, C_3, C_5, C_6 and C_7 are constants of integration.

Substitution of end conditions and simultaneous solution results in the following:

$$\frac{\left(\tan K_1 L_1\right) \left(\tan \frac{K_1 L_1}{2}\right)}{\tan \frac{K_2 L_2}{2}} = -\frac{K_1}{K_2}$$

Let $P_{cr} = \frac{m^2 EI_2}{L^2}$

where m^2 is a numerical factor depending on the ratios

$$\alpha_1 = \frac{L_1}{L} \quad \text{and} \quad \alpha_2 = \sqrt{\frac{I_2}{I_1}}$$

substituting,

$$\frac{\left(\tan m \alpha_1 \alpha_2\right) \left(\tan \frac{m \alpha_1 \alpha_2}{2}\right)}{\tan \frac{m (1-\alpha_1)}{2}} = -\alpha_2$$

$$L_1 = 39 \text{ in.}$$

$$L = 84 \text{ in.}$$

$$\alpha_1 = 0.464$$

$$I_1 = 0.0265 \text{ in.}^4 \text{ (Ball screw)}$$

$$I_2 = 0.537 \text{ in.}^4 \text{ (Extension tube)}$$

$$\alpha_2 = 4.5$$

$$\frac{(\tan 2.09 \text{ in.})(\tan 1.045 \text{ in.})}{\tan 0.268 \text{ in.}} = -4.5$$

By trial and error solution,

$$m = 1.47$$

$$E = 30 \times 10^6 \text{ psi}$$

$$P_{cr} = \frac{m^2 EI_2}{L^2}$$

$$P_{cr} = 4,930 \text{ lb}$$

$$F = KB^2A$$

$$K = \frac{1}{7.213 \times 10^7}, \quad \frac{\text{lb-in.}^2}{\text{line}^2}$$

$$B = \text{Flux density, lines/in.}^2$$

$$A = \text{Cross sectional area, in.}^2$$

$$F_{max} = 600 \text{ lb (based on latch load of 1900 lb)}$$

$$NI = \frac{B\ell}{\mu}$$

$$\ell = \text{Effective path length, in.}$$

$$\mu = \text{Permeability}$$

$$NI = \text{Magnetomotive force, amp-turns}$$

$$A_2 = \frac{\pi D_2^2}{4}$$

$$\frac{\pi D_2^2}{4} = \frac{\pi(D_o^2 - D_i^2)}{4}$$

$$D_2^2 = D_o^2 - D_i^2$$

Let $D_o = 3.5$ in.

$$D_2 = 2.2$$
 in.

$$D_i = 2.72$$
 in.

$$A_t = 7.7$$
 in.²

Solve for B required

$$B = \sqrt{\frac{F}{KA}}$$

$$F = 600$$
 lb

$$K = \frac{1}{7.213 \times 10^7} \left(\frac{\text{lb-in}^2}{\text{line}^2} \right)$$

$$B = 7.49 \times 10^4 \text{ lines/in.}^2 = 1.16 \times 10^4 \text{ lines/cm}^2$$

$$= 11.6 \text{ K - GAUSS}$$

From Armco Iron data,

$$B = 11.6 \text{ K-GAUSS}$$

$$H = 4 \text{ Oersteds}$$

$$\ell_i = 11.2$$
 in.

$$\ell = 0.005$$
 in. (air gap)

$$NI = H_i \ell_i + 2(0.313B\ell)$$

$$= 325.6$$
 amp-turns

$$NI = 325.6$$
 amp-turns

Calculate number of turns for different size wires

Cross sectional area

$$A_c = \left(\frac{D_i - D_o}{2} \right) h$$

$$D_i = 2.7 \text{ in.}$$

$$D_o = 2.2 \text{ in.}$$

$$h = 3.375 \text{ in.}$$

$$A_c = 0.843 \text{ in.}^2$$

Assume close packing,

$$A_w = A_c f$$

$$A_c = \text{cross sectional area of space}$$

$$A_{wt} = \text{cross sectional area of wires}$$

$$f = \text{packing factor} = 0.907$$

$$A_{wt} = 0.762 \text{ in.}^2$$

$$n = \frac{A_{wt}}{A_{wi}}$$

$$A_{wi} = \frac{\pi D_o^2}{4}$$

$$n = \frac{A_{wt}}{\frac{\pi D_o^2}{4}}$$

$$h = \frac{4 A_{wt}}{\pi D_o^2}$$

$$n = \frac{0.973}{D_o^2}$$

Solve for length of wire

$$V_c = \frac{\pi (D_i^2 - D_o^2)}{4} \ell$$

$$V_c = 6.5 \text{ in.}^3$$

$$V_w = f V_c$$

$$V_w = 5.87 \text{ in.}^3$$

$$\ell_w = \frac{V_w}{A_{wi}}$$

$$\ell_w = \frac{V_w}{\frac{\pi D_o^2}{4}}$$

$$\ell_w = \frac{0.623}{D_o^2} \text{ ft}$$

$$NI = 325.6 \text{ amp-turns}$$

$$I = \frac{325.6}{n}$$

$$E = IR$$

$$E = \frac{325.6}{n} R$$

<u>Size, AWG</u>	<u>n, turns</u>	<u>R¹, ohm^(a)</u>	<u>R¹/n</u>	<u>E</u>
20	885	9.7	0.011	3.58
21	1093	15.0	0.0137	4.46
22	1380	24.2	0.0176	5.72
23	1710	37.6	0.022	7.16
24	2150	60.7	0.0282	9.18

a. 600 °F, $\alpha = 2.18 \times 10^{-3}/^{\circ}\text{F}$ for copper

Current Requirements

<u>Size, AWG</u>	<u>R, ohm</u>	<u>E, volt</u>	<u>I, amp</u>
20	9.7	3.58	0.369
21	15.0	4.46	0.297
22	24.2	5.72	0.236
23	37.6	7.16	0.190
24	60.7	9.18	0.152

LATCH ROD COLUMN CALCULATIONS

$$P_{cr} = \frac{\pi^2 EI}{\ell^2}$$

$$P_{cr} = (\text{f.s.}) P$$

$$P = 432 \text{ lb}$$

$$I = 0.310 \text{ in.}^4 \quad (1 \frac{1}{2} \text{ schedule } 40)$$

$$E = 29 \times 10^6 \text{ psi (SS)}$$

$$\ell = 89.5 \text{ in.}$$

Solve for f.s.

$$\text{f.s.} = \frac{\pi^2 EI}{P \ell^2}$$

$$\text{f.s.} = 2.57$$

STRESS-LATCH FINGER

$$F_{\max} = \frac{F_{\text{latch}}}{3}$$

The divisor of 3 is to account for 3 fingers

$$F_{\text{latch}} = F_s + F_d$$

$$F_s = 600 \text{ lb} \left(\begin{array}{l} \text{Safety rod} \\ \text{accelerating} \\ \text{spring 3G} \\ \text{acceleration} \end{array} \right)$$

$$F_d = 1300 \text{ lb} \left(\begin{array}{l} \text{Drive lifting} \\ \text{capacity} \end{array} \right)$$

$$F_{\max} = 833 \text{ lb} \left(\begin{array}{l} \text{Would occur} \\ \text{with stuck rod} \end{array} \right)$$

Section A

$$\sigma_A = \frac{F}{A} + \frac{Mc}{I}$$

$$F = 833 \text{ \#}$$

$$A = (0.5)(0.375) = 0.1875 \text{ in.}^2$$

$$M = Fd$$

$$d = 0.5 \text{ in.}$$

$$M = 583 \text{ in.-lb}$$

$$c = \frac{0.375}{2} = 0.1875 \text{ in.}$$

$$I = \frac{bh^3}{12} = 0.0022 \text{ in.}^4$$

$$\begin{aligned} \sigma_A &= \frac{833}{0.1875} + \frac{583(0.1875)}{0.0022} \\ &= 4,450 + 49,700 \end{aligned}$$

$$\sigma_A = 54,150 \text{ psi}$$

For Stellite 6B

$$\sigma_{YP} = 60,600 \text{ psi at } 1250^\circ\text{F, short term}$$

P 14 Union Carbide wear

$$\sigma_{ULT} = 115,000 \text{ psi resistant alloys data book}$$

Stress-Latch Finger

$$f.s._{YP} = \frac{\sigma_{YP}}{\sigma} = \frac{60,600}{54,150} = 1.12$$

$$f.s._{ULT} = \frac{115,000}{54,150} = 2.12$$

Note: Once finger yields slightly, load on cam would be redistributed with the cam surface absorbing the bending moment leaving only the direct tensile load.

After yielding,

$$\sigma = 4,450 \text{ psi}$$

$$f.s._{YP} = \frac{60,600}{4,450} = 13.6$$

$$f.s._{ULT} = 25.9$$

Section B

$$\sigma_B = \frac{F}{A} + \frac{Mc}{I}$$

$$F = 833 \text{ lb}$$

$$A = (0.5)(0.625) = 0.3125 \text{ in.}^2$$

$$M = Fd$$

$$d = 0.7 \text{ in.}$$

$$C = 0.3 \text{ in.}$$

$$I = \frac{bh^3}{12} = 0.0102 \text{ in.}^4$$

$$\sigma = \frac{833}{0.3125} + \frac{(833)(0.7)(0.3)}{0.0102}$$

$$\sigma = 19,870 \text{ psi}$$

$$f.s._{YP} = \frac{60,600}{19,870} = 3.04$$

$$f.s._{ULT} = \frac{115,000}{19,870} = 5.8$$

Under normal operating conditions,

$$F = \frac{F_{\text{rod normal}}}{3} = \frac{F_{RN}}{3}$$

$$F_{RN} = F_S + W$$

$$F_S = 600 \text{ lb (accelerating spring)}$$

$$W = 200 \text{ lb (safety rod weight)}$$

$$F_{RN} = 600 + 200 = 800 \text{ lb}$$

$$F = \frac{800}{3} = 266 \text{ lb}$$

For Section A

$$f.s._{YP} = \frac{833}{266} 1.12 = 3.51$$

$$f.s._{ULT} = \frac{833}{266} 2.12 = 6.34$$

For Section B

$$f.s._{YP} = \frac{833}{266} (3.04) = 9.53$$

$$f.s._{ULT} = \frac{833}{266} (5.8) = 18.2$$

CONTACT STRESSES

Surface 1

$$\sigma = \frac{P}{A}$$

$$P = F \sin 45^\circ$$

$$F = 833 \text{ lb (maximum load)}$$

$$A = (0.3)(0.5) \\ = 0.15 \text{ in.}^2$$

$$\sigma = \frac{833 \sin 45}{0.15} = 3920 \text{ psi}$$

Surface 2

$$\sigma = \frac{P}{A}$$

$$P = F = 833 \text{ lb (maximum load)}$$

$$A = (0.2)(0.5) = 0.1 \text{ in.}^2$$

$$\sigma = \frac{833}{0.1} = 8,330 \text{ psi}$$

Factor of safety based on yield point

$$f.s._1 = \frac{60,600}{3920} = 15.4$$

$$f.s._2 = \frac{60,600}{8,330} = 7.26$$

$$\Sigma F_Y = F_m - F_o - W + F_{fy} = 0$$

$$F_m = F(\sin 45^\circ)^2(\cos \theta)$$

$$F_f = \mu F_m$$

$$\mu = 0.4 \text{ to } 0.8 \text{ (coefficient of friction} \\ \text{stellite 6B on 6B)}$$

$$F_{fy} = \mu F(\sin 45)^2(\cos \theta)^2$$

$$F_o = F_m \sin \theta \quad F_o \quad F_{fy}$$

$$F_m = W + F(\sin 45)^2(\cos \theta)(\sin \theta) - F(\sin 45)^2(\cos \theta)^2$$

$$= W + F(\sin 45)^2(\cos \theta)^2 \left(\frac{\sin \theta}{\cos \theta} - \mu \right)$$

$$= W + F(\sin 45)^2(\cos \theta)^2(\tan \theta - \mu)$$

LATCH OPENING FORCES

Calculate $\frac{F_m - W}{F}$ for different θ 's

holding $\mu = 0.4$

$$\begin{aligned}\frac{F_m - W}{F} &= (\sin 45)^2 (\cos \theta)^2 [(\tan \theta) - \mu] \\ &= (0.707)^2 (\cos \theta)^2 [(\tan \theta) - 0.4] \\ &= 0.5 (\cos \theta)^2 [(\tan \theta) - 0.4]\end{aligned}$$

θ	$\frac{F_m - W}{F}$
5°	-0.154
10°	-0.107
15°	-0.61
20°	-0.0175
25°	+0.029
30°	+0.68
35°	+0.101
40°	+0.128

for $\mu = 0.8$

θ	$\frac{F_m - W}{F}$
5	-0.354
10	-0.301
15	-0.248
20	-0.194
25	-0.137
30	-0.082
35	-0.034
40	+0.018
45	+0.05

ESTIMATE-LATCH ROD ASSEMBLY WEIGHT

$$W = \left[\frac{\pi D_o^2 \ell_1}{4} - \frac{\pi D_i^2 \ell_2}{4} \right] \rho$$

$$\rho = 0.303 \text{ lb/in.}^3 \text{ (Stellite 6B)}$$

$$W = 9.58 \text{ lb}$$

Latch rod

$$W = \ell \omega$$

$$\ell = 20 \text{ ft (approx.)}$$

$$\omega = 2.7 \text{ lb/ft (1 1/2 in. SS Sched. 40 pipe)}$$

$$W = 54 \text{ lb}$$

Magnet Armature

$$W = \left[\frac{\pi D_1^2 \ell_1}{4} + \frac{\pi D_2^2 \ell_2}{4} \right] \rho$$

$$\rho = 0.28 \text{ lb/in.}^3 \text{ (Armco Iron)}$$

$$W = 16.9 \text{ lb}$$

Partial total

$$W_{pt} = 9.6 + 54 + 16.9 = 80.5$$

add about 20% miscellaneous,

$$\begin{aligned} \text{total} \\ \text{weight} &= W_{tot} \approx 100 \text{ lb} \end{aligned}$$

SCRAM TIME CALCULATION

There are 3 phases in scram cycle:

1. Decay of magnetic flux
2. Delatch
3. Rod travel into core

1. Decay of magnetic flux

Estimated 0.050 sec

2. Delatch

$$s = \frac{1}{2} at^2$$

$$t = \sqrt{\frac{2s}{a}}$$

$$F = ma$$

$$a = \frac{F_a}{m}$$

$$t = \sqrt{\frac{25m}{F_a}}$$

$$s = 0.75 \text{ in.}$$

$$m = \frac{W}{g}$$

$$W = 60 \text{ lb (Latch rod, armature, cam)}$$

$$g = 386 \text{ in./sec}^2$$

$$F_a = W + \frac{F_s}{2}$$

$$F_s = 100 \text{ lb}$$

$$F_a = 110 \text{ lb}$$

$$t = 0.046 \text{ sec}$$

3. Travel

From Figure 4,

$$\text{time} = 0.6 \text{ sec}$$

$$\begin{aligned} \text{total time} &= 0.050 + 0.046 + 0.6 \\ &= 0.696, \text{ or about } 0.7 \text{ sec} \end{aligned}$$

SCRAM ASSIST SPRING CALCULATIONS

Design Parameters

$$\text{Cocked force, } F_{C_{1200 \text{ } ^\circ\text{F}}} = 800 \text{ lb}$$

$$\text{Preload, } F_{PL_{1200 \text{ } ^\circ\text{F}}} = 400 \text{ lb}$$

$$\text{Maximum Operating Temp, } T_o = 1200 \text{ } ^\circ\text{F}$$

$$\text{Modulus Rigidity, } G_{1200 \text{ } ^\circ\text{F}} = 8.1 \times 10^6 \frac{\text{lb}}{\text{in.}^2}$$

$$G_{80 \text{ } ^\circ\text{F}} = 11 \times 10^6 \frac{\text{lb}}{\text{in.}^2}$$

Material, Inconel X-750

Relaxation of Inconel X-750 at 1200 °F and 30,000 lb/in.²
is approximately 10%/year due to thermal effects.

Allowable Torsional Shearing

Stress, $\tau_{1200 \text{ } ^\circ\text{F}} = 30,000 \text{ lb/in.}^2$

Irradiation effects on relaxation not known.

Design Equations

$$\tau = \frac{K 8 F_C D}{\pi d^3}, \quad K = \frac{4C-1}{4C-4} + \frac{0.615}{C}$$

$$C = D/d$$

D = Mean spring diameter

d = Wire diameter

$$y = \frac{8 F_C D^3 N}{4 d G}$$

y = Distance spring is compressed

N = Number of active coils

$$L = Nd + N^1 d + (N^1 + N - 1) CL + y$$

L = Free length

N^1 = Number of dead coils

CL = Clearance between coils when spring is compressed.

Solution for Spring Size by Trial and Error

Assume

$$d = 0.70, \quad D = 4.0$$

$$C = \frac{4.0}{0.7} = 5.72$$

$$K = \frac{22.8 - 1}{22.8 - 4} + \frac{0.615}{22.8} = 1.16 + 0.027$$

$$= 1.19$$

For 1200 $^\circ\text{F}$ operating conditions

$$d^3 = \frac{1.19(8)(800)(4)}{\pi 30,000} = 0.323$$

$$d'' = 0.685$$

Therefore solution for d lies between 0.685 and 0.70.

Use d = 0.70 for conservative design.

$$N = \frac{20(0.7)^4(8.1)(10^6)}{(8)(800)(4)^3} = 95$$

$$\tau_{1200 \text{ } ^\circ\text{F}} = \frac{1.19(800)(8)(4)}{\pi(0.7)^3} = 28,300 \text{ lb/in.}^2$$

Assume

$$N^1 = 2$$

$$C_L = 0.1 \text{ in.}$$

Free length

$$\begin{aligned} L &= 95(0.7) + 2(0.7) + 20 + 96(0.1) \\ &= 97.5 \text{ in.} \end{aligned}$$

Preload Length,

$$L_{PL} = 87.5 \text{ in.}$$

Cocked length,

$$L_C = 77.5 \text{ in.}$$

For room temperature conditions

$$\begin{aligned} \tau_{80 \text{ } ^\circ\text{F}} &= \tau_{1200 \text{ } ^\circ\text{F}} \left(\frac{G_{80 \text{ } ^\circ\text{F}}}{G_{1200 \text{ } ^\circ\text{F}}} \right) = 28,300 \left(\frac{11 \times 10^6}{8.1 \times 10^6} \right) \\ &= 38,400 \text{ lb/in.}^2 \end{aligned}$$

$$\begin{aligned} F_{C_{80 \text{ } ^\circ\text{F}}} &= F_{C_{1200 \text{ } ^\circ\text{F}}} \left(\frac{G_{80 \text{ } ^\circ\text{F}}}{G_{1200 \text{ } ^\circ\text{F}}} \right) = 800 \left(\frac{11 \times 10^6}{8.1 \times 10^6} \right) \\ &= 1085 \text{ lb} \end{aligned}$$

POISON SECTION ALLOWABLE BOW CALCULATIONSAnnular Clearance

Fermi $C_L = 0.020$ in.

Scaling up to FTR

FTR $C_L = 0.035$ in.

Assume: (Conservative Assumptions)

Distance between front pad and cocking shoulder
to be 20 ft.

Distance between front pad and central land to
be 10 ft.

Allowable Bow = 0.070 in./20 ft

POISON SECTION STRESS CALCULATIONS

<u>Component</u>	<u>Cross Sectional Area</u>
Spool bolt	0.535 in. ²
Spring guide tube	1.3 in. ²
Poison tube and test section	2.2 in. ²
Dashpot support tube	1.17 in. ²

	<u>Wall Thickness</u>
Dashpot wall	0.25 in.

Maximum Static Load

Occurs at spool bolt during the unlikely occurrence of trying to free a stuck control rod. It is equal to the maximum drive lift force of 1060 lb plus spring force of 800 lb.

Maximum Static Load = 1860 lb

Maximum Dynamic Load

Occurs due to deceleration of the poison assembly.

$$L_{\text{Dynamic}} = \text{Weight} + \text{Mass} \times \text{Deceleration}$$

For the conceptual design base design reference case

$$V = 6.375 \text{ ft/sec (Velocity at entrance to the dashpot)}$$

$$S = 6 \text{ in. (Travel in the dashpot)}$$

$$A = \frac{V^2}{2S} = \frac{6.375^2 \text{ ft}^2/\text{sec}^2 \times 12 \text{ in./ft}}{2 \times 6 \text{ in.}} = 40.6 \text{ ft/sec}^2$$

$$W = 383 \text{ lb (Weight of assembly)}$$

Dynamic Load

$$L_D = 383 + 383 \times \frac{40.6}{37.2} = 867 \text{ lb}$$

Pressure in the Dashpot

Inside Dashpot Diameter = 3 in.

$$P = \frac{F}{A} = \frac{867 \text{ lb}}{\frac{\pi}{4}(3)^2 \text{ in.}^2} = 123 \text{ lb/in.}^2$$

Stress on Most Highly Stressed Components

Spool bolt

Tensile Stress, $\sigma = L_D/A$

$$\sigma = \frac{1860 \text{ lb}}{0.535 \text{ in.}^2} = 3480 \text{ lb/in.}^2$$

Dashpot Support Tube

Compressive stress, $\sigma = L_D/A$

$$\sigma = \frac{867}{1.17} = 740 \text{ lb/in.}^2$$

Dashpot wall

Hoop stress, $\sigma = \frac{PD}{t}$

$$\sigma = \frac{123(3)}{0.5} = 734 \text{ lb/in.}^2$$

POISON ASSEMBLY BUCKLING CALCULATIONS

Assume the poison assembly is a column made up of the spring guide tube 20 ft long without perforations. (Conservative assumption)

Buckling Relations

1. Assuming pinned ends

$$P/A = \frac{\pi^2 E}{(L/K)^2}$$

$$E = 30 \times 10^6 \text{ lb/in.}^2$$

$$L = 240 \text{ in.}$$

$$K = \sqrt{I/A}$$

$$A = \frac{\pi}{4} (\gamma_2^2 - \gamma_1^2)$$

$$I = \frac{\pi}{4} (\gamma_2^4 - \gamma_1^4)$$

$$\gamma_1 = 2.8875$$

$$\gamma_2 = 3.1875$$

$$A = \pi/4 (10.2 - 8.35) = 1.45 \text{ in.}^2$$

$$I = \pi/4 (103.5 - 69.7) = 26.5 \text{ in.}^4$$

$$K = \sqrt{I/A} = \sqrt{\frac{26.5}{1.45}} = 4.28 \text{ in.}$$

$$L/K = \frac{240}{4.28} = 56.0$$

$$P/A = \sigma = \frac{\pi^2 E}{(L/K)^2}$$

$$= \frac{\pi^2 (30 \times 10^6)}{(56)^2} = 94,250 \text{ lb/in.}^2$$

Buckling will not be possible for stresses under 94,250. Stresses this large under dynamic loading is not anticipated. Yielding or crushing would occur before buckling.

BNWL-970

APPENDIX D

COMPONENT SPECIFICATIONS

APPENDIX D

COMPONENT SPECIFICATIONS

Specifications for the major purchased components selected for the Modified Fermi Conceptual Design are outlined so that their capabilities may be reviewed when operating conditions are better defined.

1. Potentiometer

Type	Fairchild Type 990
Resistance Range	5000 Ω
Independent Linearity	0.2% F.S. (294 Ω alloy)
Resolution	0.015% F.S.
Resistance Tolerance	2%
Power Dissipation @ 85%	2W
Electrical Angle	3600° + 4° - 2°
Mechanical Rotation	3600° + 10° - 0°
Torque	0.35 in./oz
Backlash	1°
Ambient Operating Temperature	150 °C (300 °F)
Radiation	Unknown

2. Potentiometer Speed Reducer

Type	PIC U2-5
Ratio	20:1
Max. Output Torque	65 oz-in.
Backlash	0.5°
Ambient Operating Temperature	250 °F
Radiation	Unknown

3. Shaft Encoder

Type	Dynamics Research Corp. Model 29
Mechanical Shaft Speed, Max.	3000 rpm
Shaft Angular Acceleration	10^6 radian/sec ² max.
Ambient Operating Temperature	140 °F
Operating Life, Min.	2×10^8 rev or 10,000 hr
Count Cycles per Shaft Rev.	200
Radiation	Unknown

4. Stepping Motor

Type	Slo-Syn HS-400B
Holding Torque	850 oz-in.
Max. Stepping Rate	1670 steps/sec
Steps per Revolution	200
Max. Running Torque	600 oz-in. at 250 steps/sec
Stepping Accuracy	$\pm 0.090^\circ$ nonaccumulative
Ambient Operating Torque	100 °C (212 °F) Radiation Resistant Model
	130 °C (266 °F) High Temperature Model
Radiation	3000 Mrads (Radiation Resistant Model)

5. Ball Screw

Type	Saginaw 0875-0200-SRT
Lead of Thread	0.200 in.
Thread	Right Hand, Rolled
Operating Load Cap.	1000 lb for 10^6 in.
Max. Static Load	9,800 lb
Lead Accuracy	0.0015 in./in.
Backlash	0.005 in.
Material	AISI 8620

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