Self-Actuated Shutdown System for a Commercial Size LMFBR

NP-846
Research Project 897-1

Final Report, August 1978

Prepared by

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DISCLAIMER

EPRI PERSPECTIVE

PROJECT DESCRIPTION

This final report for RP897-1, describing work performed by Combustion Engineering, Inc., presents a set of conceptual designs for a self-actuated shutdown system for commercial-size LMFBRs. Some of these designs are based on two patent disclosures made by L. Minnick of EPRI.

A self-actuated shutdown system is an inherent protection system actuated by the very occurrence of abnormal local conditions in an LMFBR core. Of particular concern was the loss of flow event with the postulate that the primary and secondary scram systems are unoperational. The majority of the conceptual designs presented in this report address protection against this postulated event. The basic concept involves the use of safety rods held up above the active core at surfaces sealed by the pressure of the normal flow of sodium in the core. If the inlet flow is reduced, the pressure drops and the safety rods fall into the core to effect a reactor shutdown. This happens without the operation of any sensing instrumentation or the control system. The project has developed two self-actuated shutdown devices employing this concept. Another shutdown system developed responds to an increase in temperature of the sodium coolant and in principle could provide protection against both the postulated loss of flow event and the transient overpower without scram event. The appendixes present some ideas on facilitating the insertion of safety rods in bowed or distorted channels.

This work is concerned with particularly significant aspects of LMFBR safety and licensing, since the postulated events impose the greatest burden on ensuring public safety. They can lead to untold complications in analysis (e.g., in describing core disruption and post-accident heat removal) and in design (e.g., in designing containment structures). A reliable self-actuated system could increase the probability of reactor shutdown to such an extent that postulates presently invoked may become unnecessary.

Similar types of self-actuated shutdown systems are also being designed by several vendors under DOE sponsorship. The levitated absorber ball concept being pursued at Atomics International is similar to the basic concept used here.

PROJECT OBJECTIVE

The objective of this one-year project was to develop conceptual designs of self-actuated shutdown systems for a commercial-size LMFBR that met the following major functional requirements: (1) the system should act fast enough that an appropriate amount of negative reactivity is introduced within the time required to prevent damage to the core for postulated fault conditions; (2) it should not be affected by movement of the top head of the LMFBR primary vessel relative to the core; (3) it should be testable in situ; (4) it should be resettable in situ; (5) it should be inherently reliable; (6) it should be able to function under the loads imposed by the design-basis seismic conditions; (7) it should not interfere with any mode of normal reactor operation (e.g., startup, shutdown, partial power with partial flow); (8) it should be possible to infer from reactor instrumentation the location of this system relative to the core; (9) it should have minimum impact on core physics and thermal-hydraulic performance (e.g., breeding gain, fissile inventory, hot channel factors, power peaking); (10) it should be replaceable; and (11) it should be made of materials able to withstand the LMFBR flux and coolant temperature environment over at least one life cycle of the core. The designs developed in the project were supposed to fit in a representative core designed under EPRI RP620, Design of the Prototype Large Breeder Reactor, and were supposed to combine the self-actuated feature with the secondary shutdown system in that core.

CONCLUSIONS AND RECOMMENDATIONS

The work performed has led to several interesting design concepts that satisfy the functional requirements and provide fast-acting systems in the range of 40% to 100% full power. Some of these employ bellows, which may be criticized as a possible source of system unreliability. The designs may also appear to be complicated; however, it is not axiomatic that complexity of design leads to unreliability. A large amount of testing will be required to refine (or simplify) the design and to establish the reliability of the self-actuation feature. It is recommended that this work be pursued in the future.

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ABSTRACT

A Self Actuated Shutdown System (SASS) is defined here as a reactor shutdown system in which sensors, release mechanisms and neutron absorbers are contained entirely within the reactor core structure, where they respond inherently to abnormal local process conditions, by shutting down the reactor, independently of the plant protection system (PPS). It is argued that a SASS, having a response time similar to that of the PPS, would so reduce the already very low probability of a failure-to-scram event that costly design features, derived from core disruptive accident analysis, could be eliminated. However, the thrust of this report is the feasibility and reliability of the in-core SASS hardware to achieve sufficiently rapid shutdown. A number of transient overpower and transient undercooling-responsive systems were investigated leading to the selection of a primary candidate and a backup concept. During a transient undercooling event, the recommended device is triggered by the associated rate of change of pressure, whereas the alternate concept responds to the reduction in core pressure drop and requires calibration and adjustment by the operators to accommodate changes in reactor power.

ACKNOWLEDGMENTS

Major contributions were made to this study by R. C. Noyes (Mgr. FBR Development), S. U. Zaman and D. W. Stuteville. Other C-E contributors were N. Guiggio and D. D. Mehta.

CONTENTS

ILLUSTRATIONS

SUMMARY

This report describes work performed by Combustion Engineering, Inc., under contract to EPRI, in the conceptual design of candidate self-actuated reactor shutdown systems for commercial-size LMFBRs. The self-actuated shutdown systems (SASS) pursued in this program are, with the exception of their associated reset hardware, entirely self-contained within the reactor core structure. They incorporate mechanisms that respond automatically to abnormal local process conditions (e.g., neutron flux, coolant flow) by releasing the safety rods, thus shutting down the core independently of the plant protection system (PPS).

The principal objective of this project is to provide a shutdown system that will automatically respond to abnormal local conditions, will be entirely self-contained within the reactor core control assemblies, and will be completely unobstructed by action of the PPS or any other external factor. It would thus be immune to power failures, structural dislocations between the head and the core, and wrong inferences of fuel conditions from combinations of indirect sensor measurements. Incorporation of such a shutdown system, having the same response time and negative reactivity insertion as the secondary PPS, will substantially reduce the probability of failure to scram in a timely manner and, consequently, will help avoid excessive licensing conservatism with respect to CDAs. These factors may be of substantial benefit to the reactor operator in reducing uncertainty about licensing requirements, which will in turn result in reduced plant costs.

Three systems described in the report--M, VO, and MM--are based on patent disclosures by L. Minnick of EPRI. The first two respond to pressure change and the third to the rate of pressure change during the loss of flow event. Another conceptual design, System A, responds to an increase in the sodium coolant temperature to perform the shutdown function. One of the appendixes describes some design ideas for facilitating the insertion of absorber rods in bowed or distorted control rod channels.

Section 1

INTRODUCTION

This report describes the conceptual design of candidate "self-actuated" reactor shutdown systems for commercial sized LMFBR's, which were developed by Combustion Engineering, Inc., under contract to the Electric Power Research Institute, during the period October 1976 through July 1977. The self-actuated shutdown systems (SASS), pursued during this program, are, with the exception of their associated reset hardware, entirely self-contained within the reactor core structure. They incorporate mechanisms which respond inherently to abnormal local process conditions (neutron flux, coolant flow) by releasing the safety rods, thus shutting down the core independently of the plant protection system (PPS).

Current LMFBR plant protection systems employ two reactor shutdown systems having redundancy of control rod worth and diversity of design. Some of the diversity occurs naturally due to the differing operational requirements of the two systems: the primary system controls reactivity during normal operation, whereas the secondary system is used only to shut down the reactor. Reactor scrams are initiated in response to certain combinations of off-normal signals from sensors which detect neutron flux, sodium temperature, pump speed, etc.. This involves a chain of sub-systems from the sensors, through the logic circuits, amplifiers, electro-magnetic actuators and control rod release mechanisms, culminating in the insertion of the control rods. However, despite proven component reliability, good inspection access and preventive maintenance, there may be a very low probability that an unacceptable change in the fuel element power level or cooling conditions does not result in reactor shutdown. It is argued that the failure of commonly affected links in both of the above-mentioned chains which could possibly occur, for example, during a severe earthquake, requires consideration of events involving inability to scram the reactor. With this possibility, combinations of occurrences could be postulated which might result in a core disruptive accident (CDA).

Particular faulted condition occurrences of interest are:

a. Pump loss with failure to scram, referred to as loss of flow (LOF) events, or to distinguish this condition from the light water reactor context, as transient undercooling (TUC) events.

b. Uncontrolled rod withdrawal with failure to scram, producing a transient overpower (TOP) event.

The principal objective of this project is to provide a shutdown system which will: inherently respond to the local, off-normal conditions accompanying these events; be entirely self-contained within the reactor core control assemblies; and, be completely unobstructed by action of the PPS or any other external effect. It would thus be immune to power failures, structural dislocations between the head and the core, or wrong inferences of fuel conditions from combinations of indirect sensor measurements. Incorporation of such a shutdown system, having the same response time and negative reactivity insertion as the secondary PPS, will substantially reduce the probability of failure to scram in a timely manner and, consequently, will help avoid excessive licensing conservatism with respect to CDA's. These factors may represent a substantial benefit to the reactor operator in the form of reduced uncertainty of licensing requirements, which will in turn result in reduced plant costs.

A further refinement of this philosophy, requested by EPRI during this study, involves the incorporation of the SASS hardware into a secondary control assembly such that control rod insertion can be initiated independently by the PPS and the SASS. In this way, the SASS does not penalize the core design by requiring additional non-fueled subassemblies. Other important operational criteria such as in-situ resettability and testability are addressed in Section 2.0 below.

During the initial proposal stage of this program, C-E offered seven alternative SASS devices, designed to respond to the power/flow mismatch which would occur during either a TUC or TOP event. A common feature of these devices was actuation of a release mechanism by the temperature increase produced by fuel situated upstream of the mechanism. At the time an EPRI patent disclosure (Reference 1) for a TUC-responsive device was also discussed. This idea was designated "System M". A modification of the latter to improve its response was suggested by C-E.

Subsequently, C-E was commissioned by EPRI to perform a parallel study of one of the TOP devices ("System A") and the modified TUC device (System MM"), with the objective of selecting one concept for further development during the remainder of the program. The design was to be based upon the CRBR pump coastdown flow history and a typical PLBR core specification.

This initial effort resulted in the following conclusions by C-E, which were later confirmed by EPRI:

1. The full licensing benefit of a SASS could not be realized with a device having substantially inferior performance to that of the secondary shutdown system (for example, 0.5-second release, 2-second full insertion time).

2. SASS protection to achieve this benefit was required only for TUC events, based upon CRBR estimates of their probability and energy content.

3. System MM met the performance objective of 1. for TUC events, but System A was slower, due to heat transfer delays inherent in indirect flow response devices, and more complex.

System M, mentioned above, and the modified version of it, System MM, incorporate an inherent hydraulic support principle in which a conventional poison pin bundle is held out of the active core region by the pressure drop developed at normal coolant flow rates. A reduction of flow releases the poison bundle, which then falls by gravity into the core region and shuts down the reactor. The upthrust on the poison bundle is not due to fluid levitation in the conventional sense, since the bundle pressure drop is too low. Instead, the upper end of the bundle has a seal plug which fits into an orificed constriction at the upper end of the control assembly duct. The upthrust on the poison bundle is thus, effectively, the product of the plug area and the orifice pressure drop and becomes negligible when the seal is broken.

In the case of System M, this is the basic principle of operation and results in a very simple configuration. However, if the device is sized for operation at 40% flow, there is an inherent delay at 100% flow due to the coastdown time between 100% and 40% flow. In contrast, System MM employs this principle as a backup at low flows and incorporates a means of breaking the seal at the plug, which is triggered by the rate of change of flow associated with a pump trip event. An inherent rate-of-change-pressure (RCP) sensor rapidly opens a valve across the plug if incipient coastdown occurs, at any flow level. However, this improved performence and versatility was achieved at the expense of simplicity, thus introducing questions of potential reliability. This situation gave rise to a proposal by EPRI (Reference 2) for an alternative modification of the original concept, in which the plug pressure drop could be adjusted to compensate for reactor operation at other than full flow. This version, designated "System VO" (variable orifice), was then investigated and developed to a degree comparable with that of System MM.

Following a final design review under the current program, the initial conclusions, stated above, emerged with a broader perspective. It became apparent that, depending upon the mode of reactor operation , all three TUC-responsive devices should be considered as prime candidates. For these reasons, prominence is given in this report to System M, System MM and System VO. In the following descriptions, the sequence departs from the chronological order because System VO is more closely related to System M than is System MM.

The work on System A (transient overpower device) and a side study of modifications to rod bundle poison configurations for improved insertability are summarized in the appendices (Appendix D and Appendix E, respectively).

The course of this investigation has been punctuated by design reviews, attended by representatives of the EPRI-PLBR Project Office, PLBR Contractors, ANL and DOE/RRT. The valuable contributions and guidance, received from EPRI management and other active participants, are, hereby, acknowledged.

Section 2

FUNCTIONAL REQUIREMENTS

The functional requirements were specified by EPRI as follows:

"The self-actuated shutdown system has to satisfy the following functional requirements: (a) it should have sufficient worth, and should be sufficiently fast-acting such that an appropriate amount of negative reactivity is introduced within the time required to prevent damage to the core for postulated faulted conditions: (b) it should not be affected by movement of the top head of the LMFBR primary vessel relative to the core; (d) it should be testable in-situ; (e) it should be resettable in situ; (f) it should be inherently reliable; (g) it should be able to function under the loads imposed by the design-basis seismic conditions: (h) it should not interfere with any mode of normal reactor operation, e.g., startup, shutdown, partial power with partial flow, etc. (i) it should be possible to infer from reactor instrumentation the location of this system relative to the core; (j) it should have minimum impact on the core physics and thermal-hydraulic performance, e.g., the breeding gain, fissile inventory, hot channel factors, power peaking, etc.; (k) it should be replaceable, and (l) it should be built of materials which can withstand the LMFBR flux and coolant temperature environment over at least one life cycle of the core."

The above functional requirements were studied by C-E and developed into a set of quantified design criteria (Appendix A), which served as guidelines for the conceptual design study. As the study progressed, those criteria which were specifically aimed at System MM and System A became insufficiently general to embrace the new concepts introduced during the design reviews. The following requirement summary represents an attempt to maintain the intent of the Appendix A material and, at the same time, address the later ideas.

1. The Self-Actuated Shutdown System (SASS) shall offer, redundantly, the same degree of protection to the plant and public as the primary or the secondary shutdown systems. For conceptual design purposes the protection requirements

and pump coastdown performance of the CRBRP shall apply. Specifically, a 0.5 second release time and 1.5 second insertion time shall be target values. The core design shall be based upon Phase I PLBR designs.

2. The SASS hardware shall be integrated with that of the secondary control rod assemblies but the design shall insure that release by SASS and PPS action is entirely independent and that failure of one system has no effect on the other.

3. The system shall be testable in-situ. Provision shall be made for testing the SASS release and speed of response by appropriate flow variation during reactor shutdowns. Low power reactor operation may be necessary for measurements of rod worth.

4. The system shall be capable of being withdrawn and reset after insertion in accordance with normal startup procedures.

5. The system shall be replaceable or repairable using normal refueling equipment during a refueling shutdown without adverse effect on plant availability.

6. The system should allow reactor operation over the range of 40% to 100% of normal power and flow, without imposing operational limitations, while retaining capability to scram in the self-actuating mode.

7. The SASS shall not be affected by lateral displacement, thermal expansion or distortion of the upper internals or the rotating plugs, during normal or accident conditions. The SASS portion of the shutdown system shall be wholly contained in the hex duct above the core and disconnected from the control rod drive so that no interference of the poison rod is experienced due to motion of the rotating plug, the control rod drive or the upper internals. No external connections which can be used to bypass the SASS, intentionally or inadvertently, shall be provided.

8. The system shall position the poison material fully withdrawn from the reactor core zone for reactor operation and fully inserted for reactor shutdown. Necessary instrumentation shall be provided to detect and ensure the full-in and full-out positions of the poison rod. The poison assembly

shall remain structurally intact and provide repeated scram capability during normal, upset, emergency or faulted reactor operating conditions including OBE and SSE. The assembly shall be designed to prevent control rod ejection from the core.

9. The system shall be fail safe.

10. During reactor operation, the coolant temperature at the control assembly exit shall be as close as possible to the mixed mean outlet temperature of the adjacent fuel assemblies. This is to minimize the temperature gradient across the assembly nozzles and the upper internals of the reactor vessel.

Section 3

DESIGN DESCRIPTIONS

The hydraulic systems considered and described in the following are:

1. System M
2. System VO
3. System MM

These systems respond to a loss of flow and, therefore, protect against TUC events. They were developed to satisfy the requirements of high speed of response, reliability, in-situ testability, resettability and PPS trip capability to ensure prevention of core damage subsequent to an TUC event.

The basic hydraulic support concept appears in an EPRI patent disclosure by L.E. Minnick (Reference 1). The poison assembly is held out of the core during normal operation by the pressure drop across a support seal at its upper end. Upon loss of flow associated with a TUC event, when the hydraulic pressure becomes insufficient to hold up the poison assembly, the assembly drops by gravity into the core for reactor shutdown.

The variable orifice (VO) concept is based on another EPRI patent disclosure by L.E. Minnick (Reference 2) for maintaining a constant pressure drop across the support seal, at any operating flow rate, so that the coastdown delay, inherent in the first concept, is avoided.

System MM is similar to the above systems in hydraulic support but the hydraulic actuator is sensitive to the rate of change of pressure (RCP). The RCP actuator controls a valve which, upon opening, reduces the differential pressure across the support seal to effect a rapid rod release for reactor shutdown. No operator initiated adjustment or control is required on the actuator during reactor operation.

3.1 SYSTEM M

The System M concept relies on coolant pressure to keep the poison assembly suspended above the core during reactor operation. Upon loss of pressure during flow coastdown, the assembly is released for reactor shutdown.

In the proposed concept, as illustrated in Figure 3-1, the upper end of the poison assembly is formed to make a hydraulic seal with the upper section of the assembly duct. Flow passages through the seal provided for an adequate poison rod coolant flow. The normal operating coolant pressure drop across the seal is sufficient to suspend the poison assembly weighing approximately 90 kg (200 lb.). The control rod drive shaft, shown in Figure 3-2 extending from the central chamber of the assembly, is used to position the assembly during reactor operation in the control mode. In the SASS mode, the shaft is used to raise the assembly duct. The drive shaft is then lowered so that the poison assembly is free to insert upon decrease in the seal differential pressure for reactor scram.

In lifting the poison assembly to the fully withdrawn (sealed position), the circular sealing surfaces are centered with respect to each other by the action of centering vanes on the control rod drive shaft. When the drive shaft is lowered, any lateral motion between the seals allows bypass flow past the seats, resulting in a reduction of the differential pressure, and the poison assembly is released. This feature provides for reactor scram during lateral motions associated with earthquakes. Ordinary flow induced vibrations do not cause significant seal displacement due to its self centering features, and therefore, such inadvertent scrams are avoided.

Sealing between the circular sealing surfaces can be maintained if there is no distortion of the duct and/or the assembly: however, in a high temperature and high fluence LMFBR environment, significant duct distortions are probable. Such distortions could lead to difficulty in obtaining a hydraulic seal between the two surfaces. A spherical seal arrangement, as illustrated in Figure 3-3, should maintain the hydraulic seal with expected duct distortions. The spherical seat can also be used for self-alignment during resetting of the assembly. A seat angle of 63.4° to the vertical was selected to ensure alignment even with a coefficient of friction of 2 (extreme design value used in CRBR analysis).

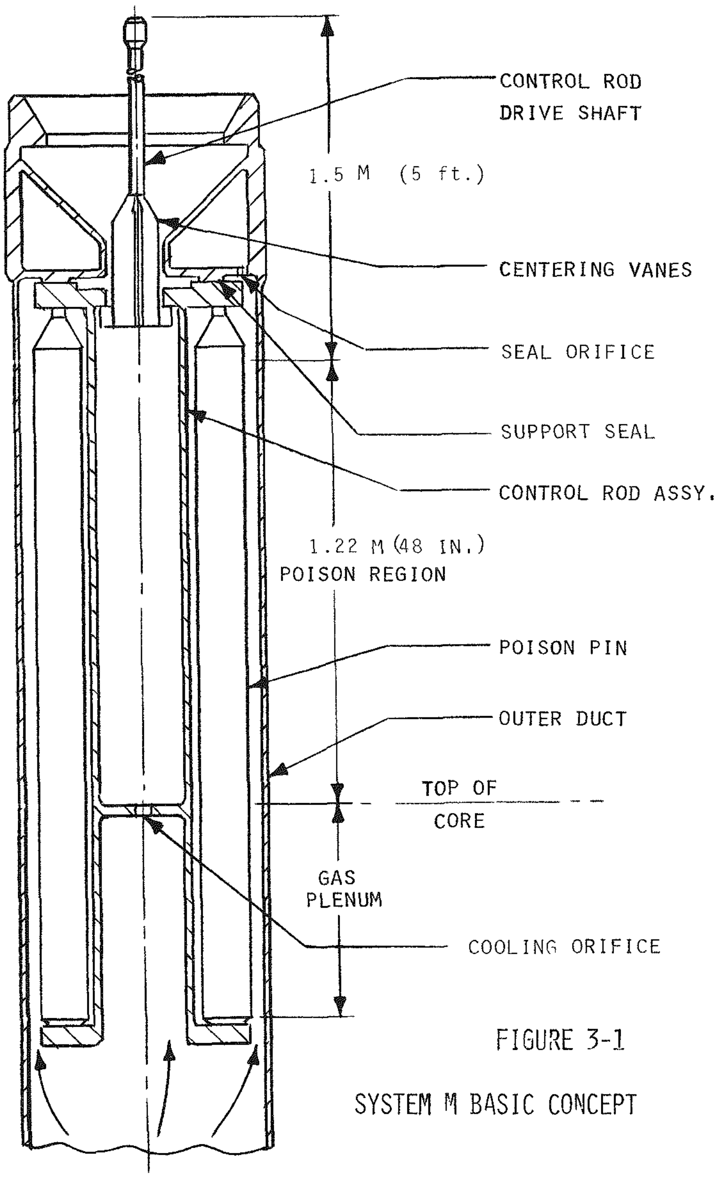


FIGURE 3-1

SYSTEM M BASIC CONCEPT

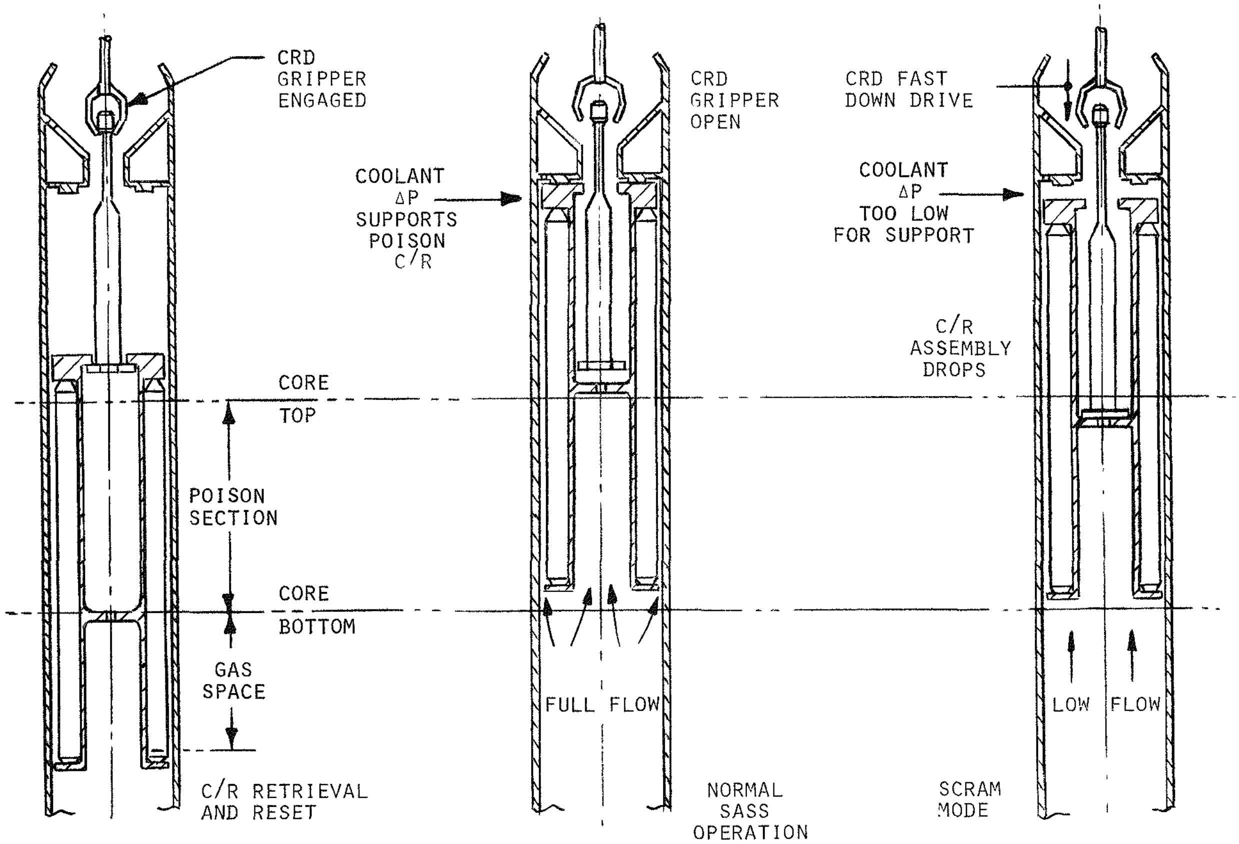


FIGURE 3-2 SYSTEM M MODES OF OPERATION

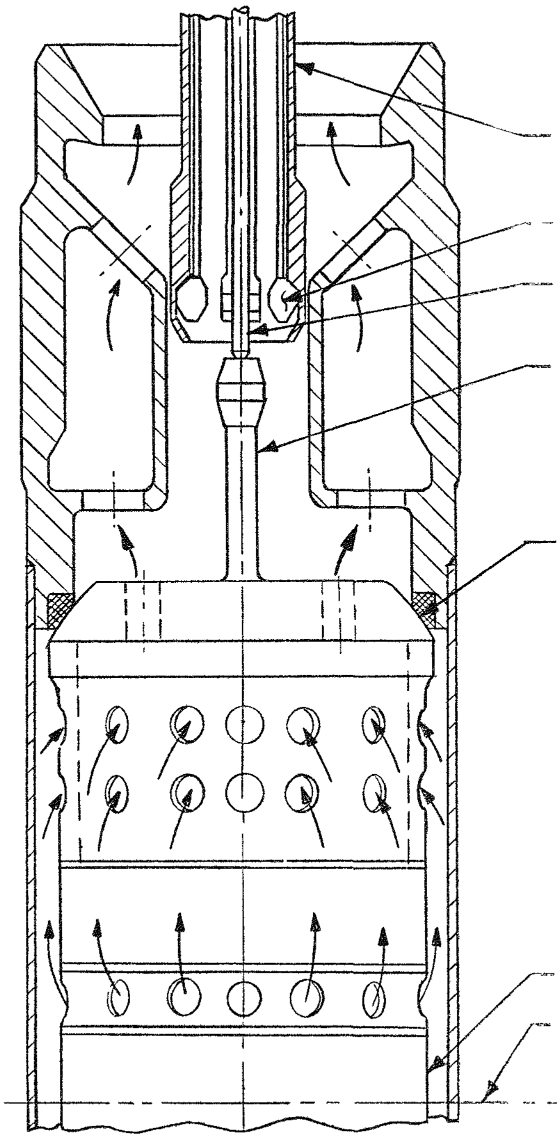


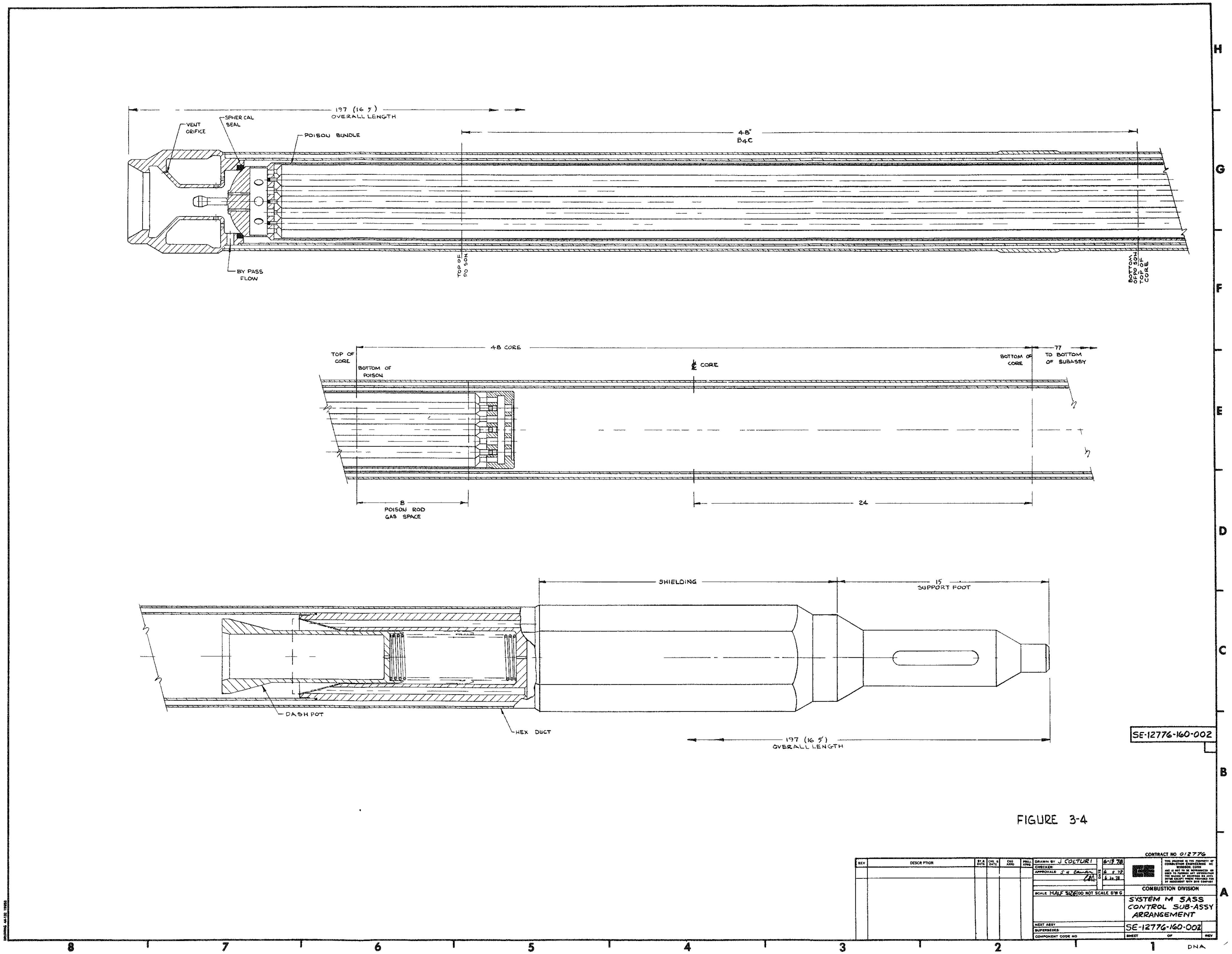
FIGURE 3-3 SYSTEM M DETAILED CONCEPT

The drive shaft was replaced by a handling head in order to reduce the CRD stroke from 2.74 m (108") to 1.22 m (48"). This also improves the maximum poison loading for the assembly as no central hole is required for the drive shaft. The problem of possible interference of the drive shaft with the free fall of the assembly is also avoided. The control assembly arrangement for this system is shown in Figure 3-4.

Typical (CRBRP) coastdown curves are shown in Figure 3-5. It is estimated a 83 kPa (12 psi) differential pressure is required across a 127 mm (5") diameter seal to support an assembly weighing about 79.4 kg (175 lb.). These parameters are compatible with PLBR assembly dimensions. The nominal seal differential pressure, therefore, varies from 83 kPa (12 psi) to 517 kPa (75 psi) as the flow is varied in the operating range of 40% to 100%, as illustrated in Figure 3-5. In order to permit operation at 40% flow without inadvertent trips, the trip point is set 5% below the 40% flow, i.e., at the 35% flow rate. This corresponds to a trip pressure of about 62 kPa (9 psi). Hence, upon loss of flow from an initial 100% flow condition, it would take about 8 seconds before the poison assembly is released. This delay in the release time, combined with the time for insertion into the core, results in an excessive delay relative to the 2-second objective.

Alternatively, if the reactor operation is planned at 100% flow only, the operating seal differential pressure could be set at 83 kPa (12 psi) at 100% flow. The trip pressure of 62 kPa (9 psi), therefore, will result in only a 1 second delay in rod release.

A 21 kPa (3 psi) margin between the operating and the trip pressure is adequate protection against inadvertent reactor shutdown due to mechanical shocks or low level seismic vibrations of up to 0.5g. If this margin is reduced to about 8.9 kPa (1.3 psi), a release time of 0.5 second (target value) is obtained, but the mechanical shock resistance is decreased to 0.15g. This follows from the nature of the seal design in which momentary axial movement of the poison assembly causes an irreversible (until reset) loss of hydraulic support. A simple modification to avoid this problem is shown in Figure 3-6. The spherical seat is replaced with a piston-like plug which under steady operating conditions is fully inserted in the cylinder. During an oscillatory disturbance, the piston floats in the cylinder, due to the inertia of the poison assembly, and eventually returns to its steady state position when the disturbance decays to less than the 0.15% level. The length of the piston engagement is determined from the



197 (16.5') OVERALL LENGTH
VENT ORIFICE
SPHERICAL SEAL
POISON BUNDLE
48" B4C
BY PASS FLOW
TOP OF POISON
BOTTOM OF POISON TOP OF CORE
48 CORE
TOP OF CORE
BOTTOM OF POISON
℄ CORE
BOTTOM OF CORE
77 TO BOTTOM OF SUBASSY
8 POISON ROD GAS SPACE
24
SHIELDING
15 SUPPORT FOOT
DASH POT
HEX DUCT
197 (16.5') OVERALL LENGTH
SE-12776-160-002
CONTRACT NO 012776
REV
DESCRIPTION
BY & DATE
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ENG APPD
PROJ. APPD
DRAWN BY J COLTURI 6-19-78
CHECKER
APPROVALS
SCALE HALF SIZE
DO NOT SCALE DWG
COMBUSTION DIVISION
SYSTEM M SASS CONTROL SUB-ASSY ARRANGEMENT
NEXT ASSY
SUPERSEDES
COMPONENT CODE NO
SE-12776-160-002
SHEET OF
REV

FIGURE 3-4

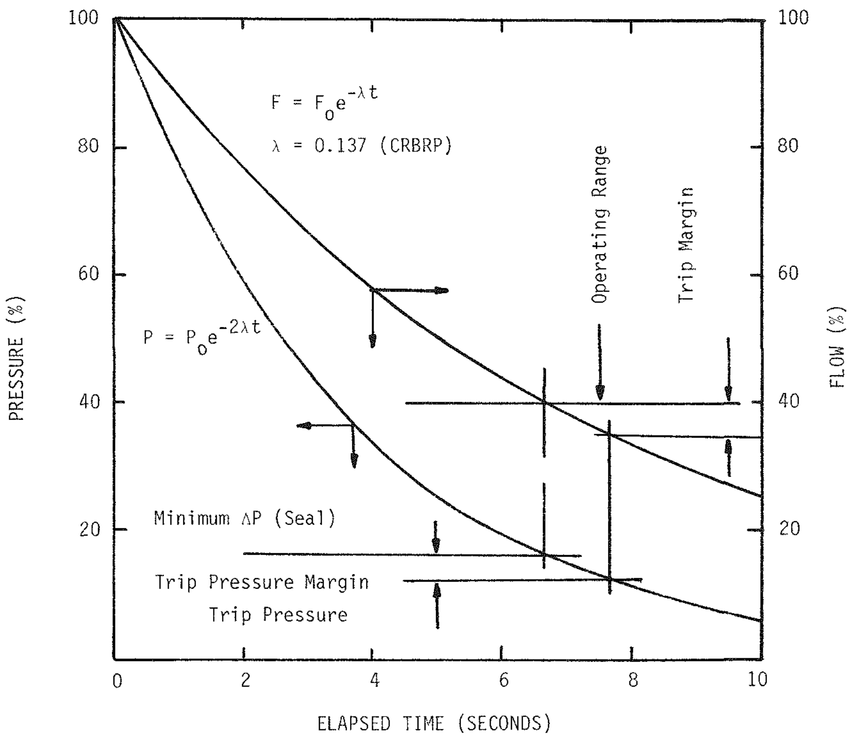


FIGURE 3-5 PUMP COASTDOWN CHARACTERISTICS

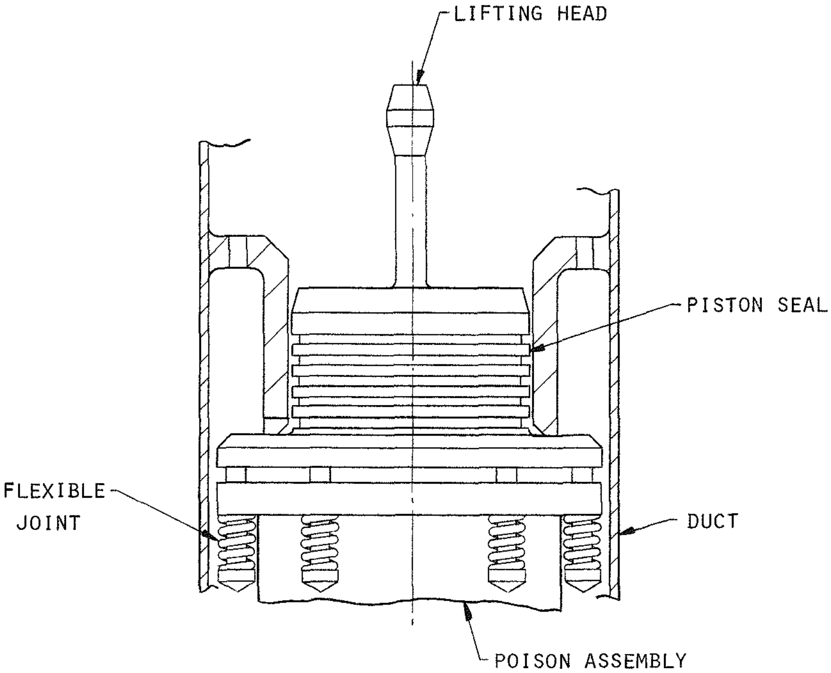


FIGURE 3-6 SYSTEM M PISTON SEAL CONCEPT

seismic amplitude. For example, a 50 mm engagement, based upon a typical OBE amplitude, causes a release delay of 0.5 seconds but, even without over-pressure, will also protect against a -3% pressure pulse over 1 second. This penalty can, therefore, be minimized by reducing the over-pressure to allow for only steady departures from the nominal pressure drop. This modification does not preclude the use of System M as a scram device for severe seismic events.

Self-alignment, to account for duct and poison assembly distortion, is not provided by the plug and socket support seal, but instead, the assembly is articulated just below the plug feature. The articulation is flexible enough to cause minimal sidethrust on the socket but is also self centering to allow easy location during retrieval by the CRD gripper.

3.2 SYSTEM VO

The operating principle of System of System VO is the same as that of System M. It does, however, incorporate a fundamental improvement, which allows the system to provide the same performance at 100% reactor coolant flow rate as at 40% flow. This is achieved by remote adjustment of a variable orifice (VO), which is adjacent to the support seal and serves to vary a bypass flow around it, so that the seal pressure difference is held constant at slightly more than the minimum support value.

The arrangement is shown in circuit diagram form in Figure 3-7, where the principal pressure drops are given for the reactor flow rate range. These pressures are used for design purposes only, and are not used by the operators for adjustment. Instead, an indicator on the VO actuator mechanism, at the operating floor, is used to relate the valve setting to the control rod release point, based upon calibrations made at incremental flow levels in the operating range.

3.2.1 System Description

The basic conceptual arrangement of System VO is shown in Figure 3-8. The poison assembly and support seal detail is similar to that of System M, except that the main coolant flow path bypasses the seal via the variable orifice assembly, situated above it. This device consists of a number of orifices, axially disposed along the cylindrical baffle which closes off the upper end of the control assembly duct, and a closely fitting sleeve inside of it, which forms the lower end of the

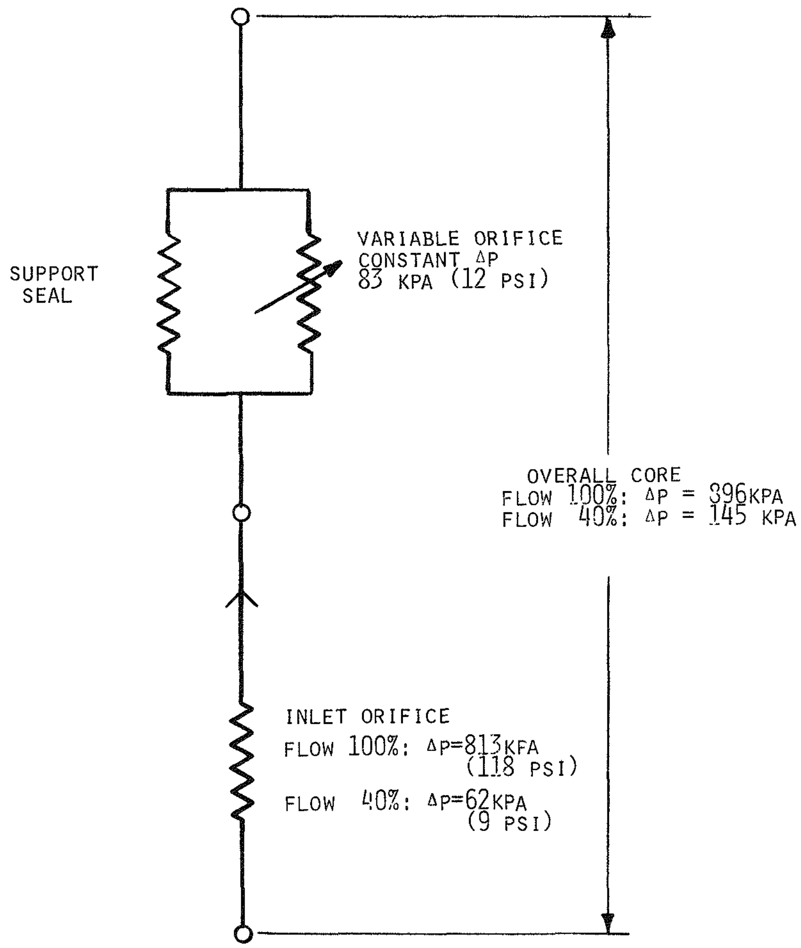


FIGURE 3-7 SYSTEM VO HYDRAULIC CIRCUIT DIAGRAM

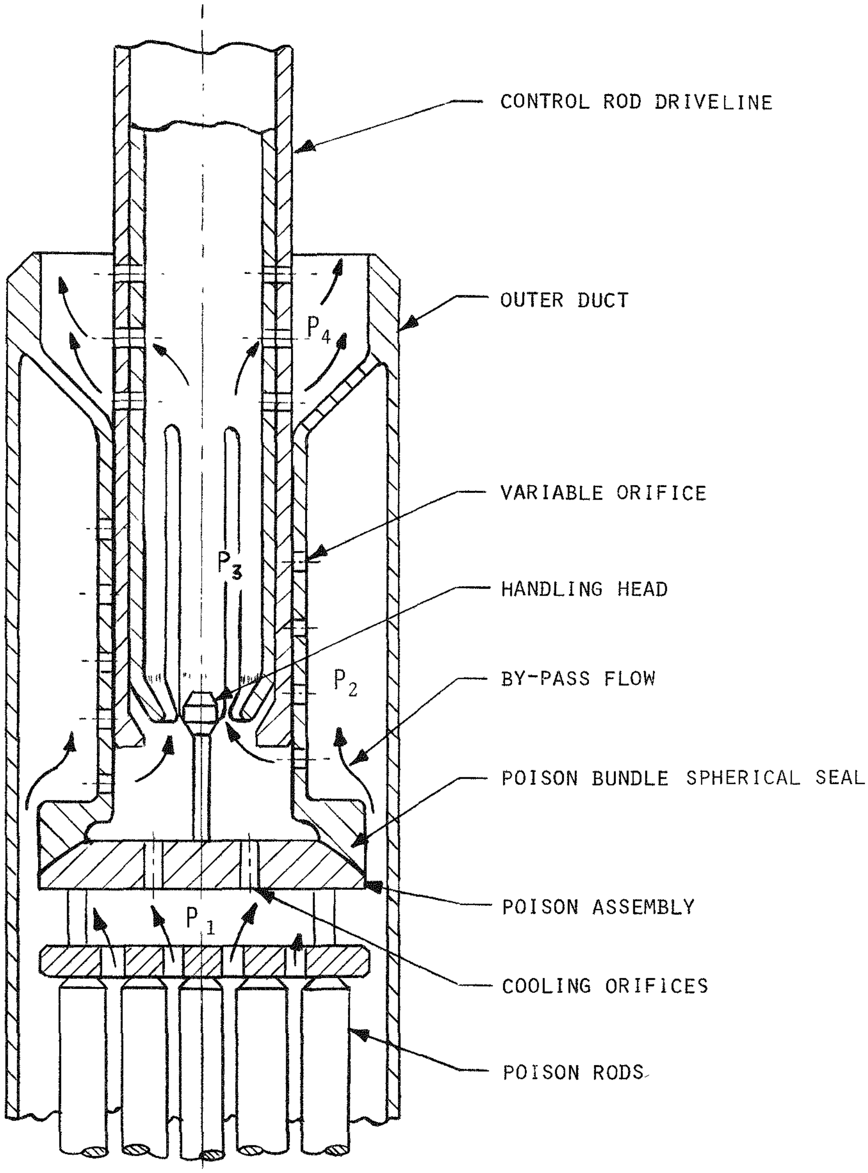


FIGURE 3-8 SYSTEM VO BASIC CONCEPT

control rod driveline (CRD). The pressure difference across the seal may, therefore, be controlled by axial movement of the CRD. The associated control rod drive mechanism, having positional readout, is state-of-the-art equipment which is beyond the scope of this investigation.

The minimum number of orifice steps required is determined by the need to maintain both an acceptable release time and support pressure margin at any flow rate in the operating range. Figure 3-9, shows the performance given by a VO design having twelve 6.4 mm diameter orifice steps, and illustrates how stepwise orificing and the minimum support margin contribute to the response time. The mean response time of approximately 1 second lies within an error band width of approximately 1 second.

Not included in the error band shown is the uncertainty in the relative position of the orifices and the movable sleeve. Clearly, utilization of the CRD gripper tube for orifice control should take account of the relative thermal growth and irradiation swelling of the duct with respect to the CRD. It is estimated that approximately 45 mm allowance for growth, as illustrated in Figure 3-10, is required for the variable orifice control sleeve if calibration were restricted to annual refueling shutdowns. The orifices would, therefore, be spaced approximately 50 mm apart to compensate for these effects and require extension of the length of the VO assembly to more than 60 cm (24 in.). This would violate the requirement that the SASS be contained entirely within the core structure envelope. One solution to this problem is frequent recalibration which will increase the scheduled unavailability of the plant. However, other sources of relative axial movement between the CRD and the control assembly are accidental rotation to the top head relative to the core and movement due to design basis seismic conditions. Although these events have a low probability of occurrence, they represent the kind of phenomena for which a SASS should be immune.

A solution to the operational and safety problems, described above, is to isolate the orifice control sleeve from the axial movement of the CRD when it is not being used for adjustment. This approach was taken in developing the detailed design of System VO, shown in Figure 3-11. The control sleeve is held in the desired location by a U-shaped spring detent within the orifice cylinder. The CRD incorporates a gripper which engages the sleeve for setting but is normally retracted, as shown in the figure. A total of twelve 6.4 mm diameter orifices, spaced 9.5 mm apart in a helical array, are used for flow adjustment and a further

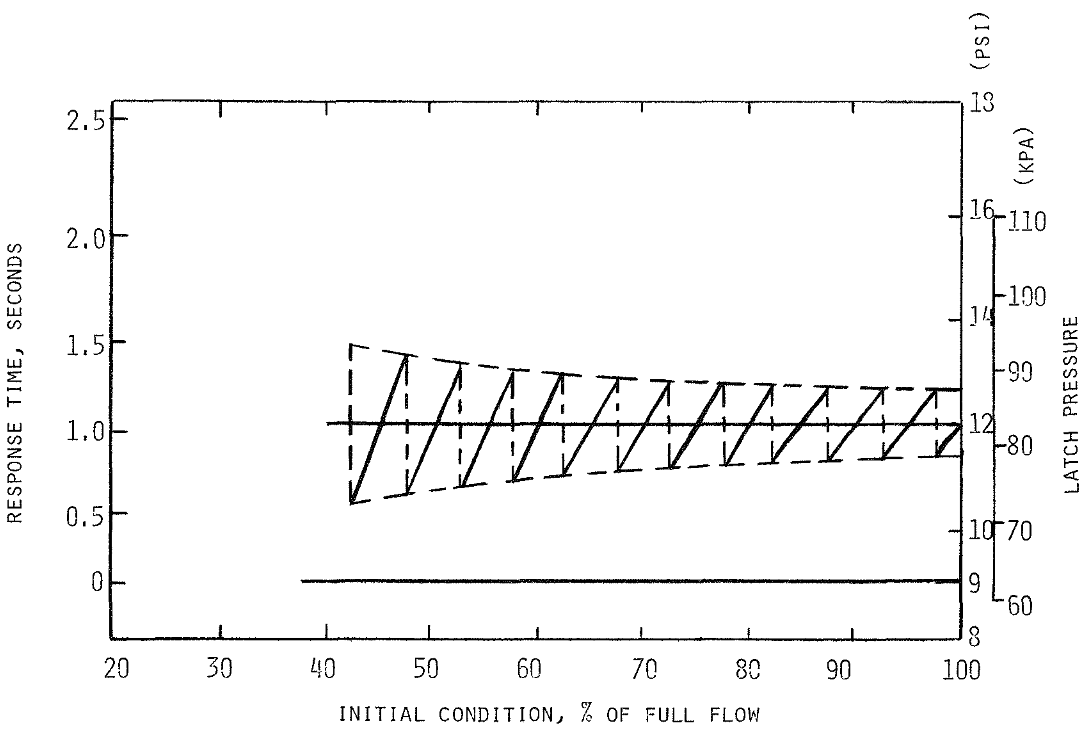


FIGURE 3-9 RESPONSE TIME OF VARIABLE ORIFICE (12 STEP) SYSTEM

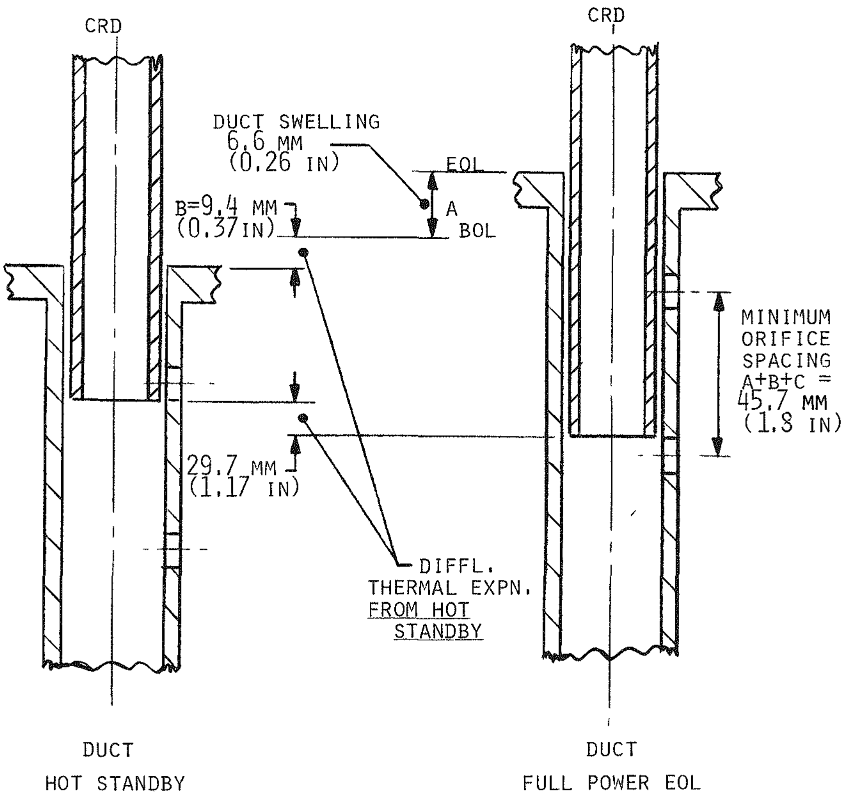


FIGURE 3-10 SYSTEM VO-VALVE SETTING PROBLEM WITH BASIC CONCEPT

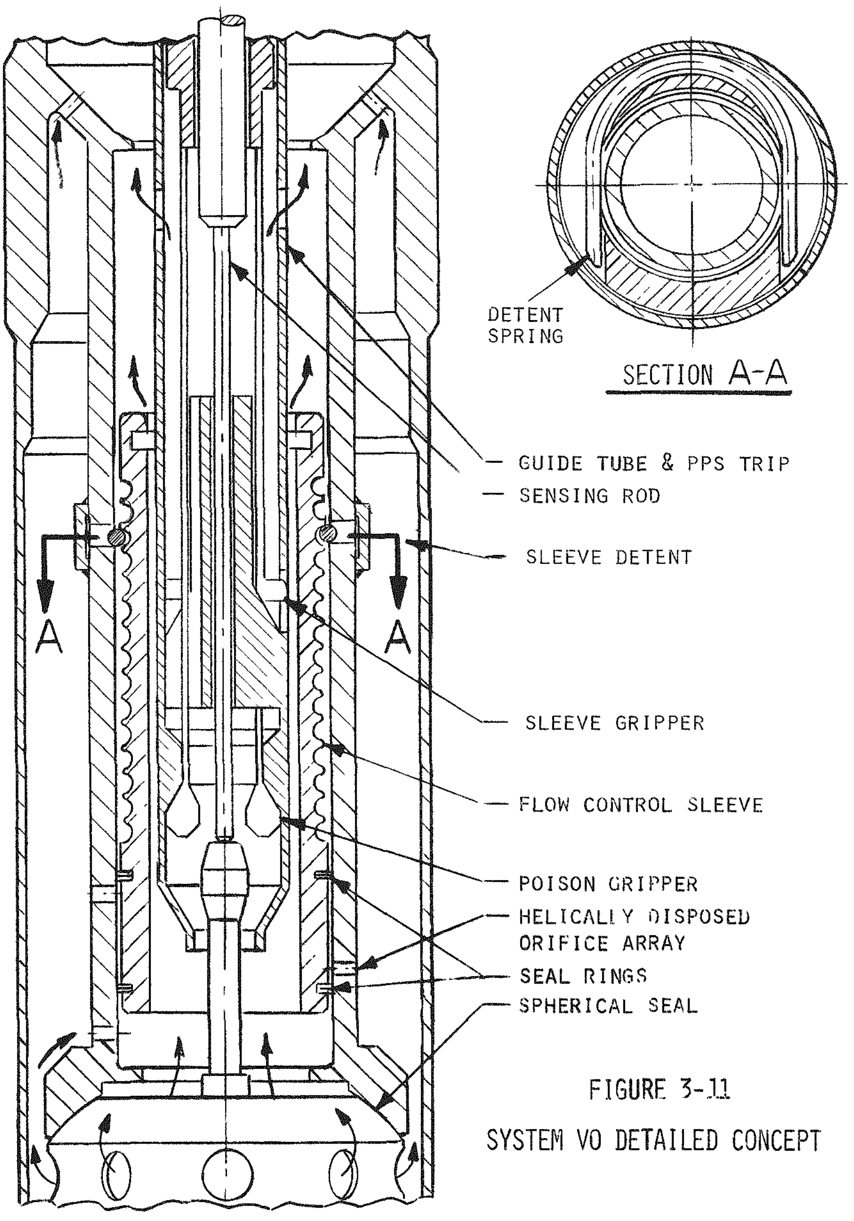


FIGURE 3-11

SYSTEM VO DETAILED CONCEPT

five fixed orifices in the seal provided for operation at 40% of full flow rate. The 12 orifices are opened at the rate of 1 orifice per 5% increment of full flow. Bypass flow orifices are provided at the top end of the annular space around the orificed cylinder to facilitate venting and to ensure adequate control rod cooling. The System VO control assembly arrangement is shown in Figure 3-12.

The flow control sleeve is an approximately 90 mm diameter cylinder which closely fits within the orifice bearing cylinder. The two sets of seal rings in the sleeve minimize the bypass flow and center the sleeve within the duct cylinder. The sleeve is spring loaded by means of a U-shaped Inconel X-750 detent spring and can only be moved axially with the CRD gripper. The lower seal ring is located so that when the sleeve moves up, the seal ring uncovers the required number of orifices. The spring detent is virtually unloaded during reactor operation at a given setting and, therefore, creep relaxation of the spring is negligible.

The CRD gripper tube shown in Figure 3-11 is approximately 50 mm in diameter and closely fits within the control sleeve. It is similar to that for the CRBRP secondary shutdown system except that the flow control sleeve gripper is incorporated into the design. The gripper rides on a cam formed with the innermost tube within the CRD guide tube. By relative motion of the gripper tube, with respect to the inner tube, the gripper fingers extend outward with the help of the cam surface and engage the control sleeve for adjustments. The gripper fingers are spring loaded so that when the cam surface is lowered with respect to the gripper tube, the gripper fingers disengage from the control sleeve thereby leaving the sleeve in a set position. Control rod release is determined by means of the sensing rod shown, which also aids location during retrieval of the control rod.

With the orifice control governed by operation of the CRDM, it is possible for the operating pressure across the hydraulic seal to be set erroneously at an unsafe value. If the pressure setting is too high, a longer coastdown delay results for SASS acutation. To prevent this occurrence, a dead weight relief valve, as illustrated in Figure 3-13, is connected across the support seal. The valve opens when the support seal pressure exceeds the operating pressure by a value higher than the margin for normal operational variations. The differential piston effect causes the valve to open wider after it rises from the seat, thereby, increasing the bypass flow and decreasing the seal differential pressure for rod release.

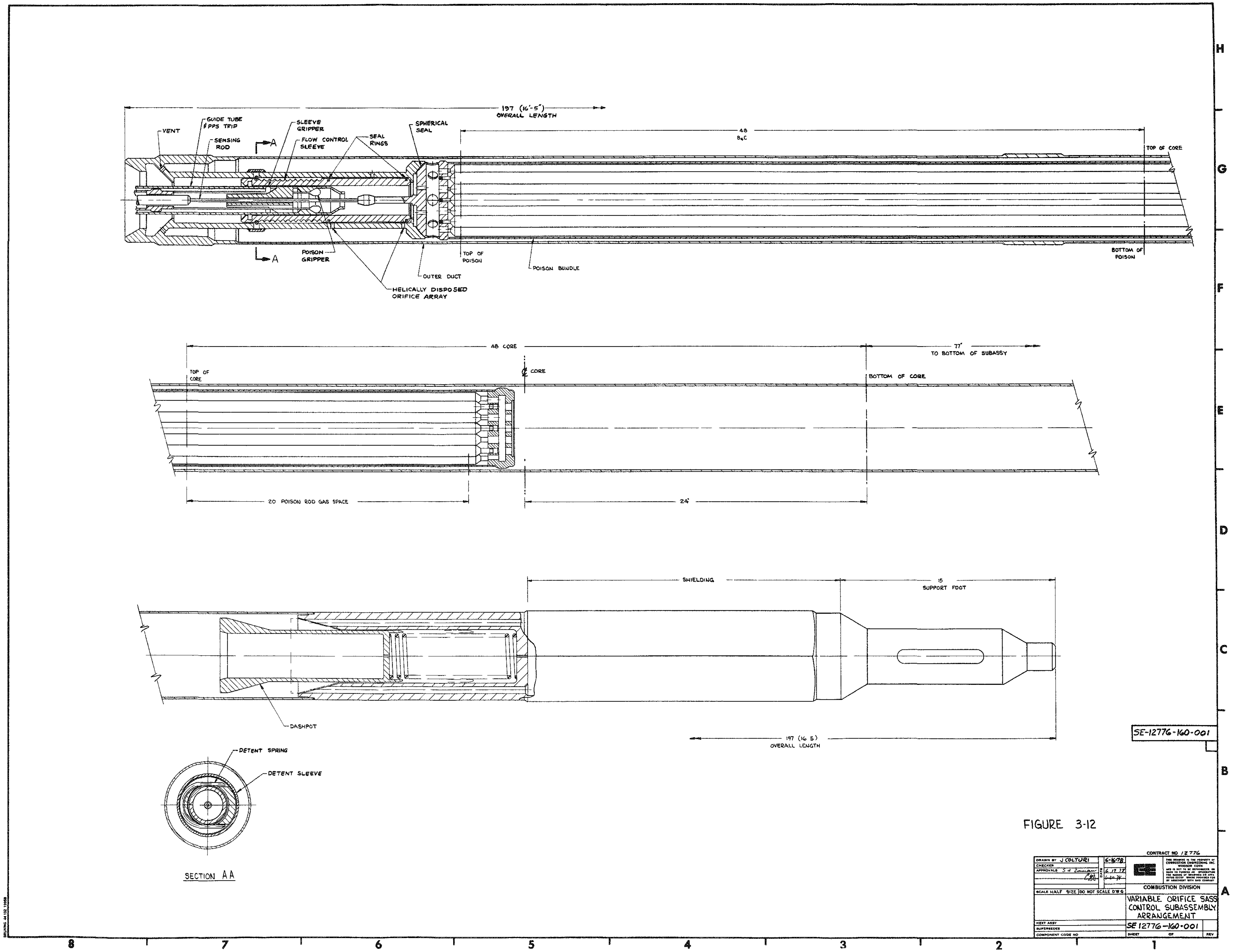

197 (16'-5") OVERALL LENGTH
VENT
GUIDE TUBE & PPS TRIP
SENSING ROD
SLEEVE GRIPPER
FLOW CONTROL SLEEVE
SEAL RINGS
SPHERICAL SEAL
48 B4C
TOP OF CORE
TOP OF POISON
POISON GRIPPER
OUTER DUCT
POISON BUNDLE
BOTTOM OF POISON
HELICALLY DISPOSED ORIFICE ARRAY
48 CORE
77" TO BOTTOM OF SUBASSY
TOP OF CORE
℄ CORE
BOTTOM OF CORE
20 POISON ROD GAS SPACE
24"
SHIELDING
15 SUPPORT FOOT
DASHPOT
197 (16 5) OVERALL LENGTH
DETENT SPRING
DETENT SLEEVE
SECTION AA
SE-12776-160-001
CONTRACT NO 12776
DRAWN BY J COLTURI
CHECKER
APPROVALS
COMBUSTION DIVISION
SCALE HALF SIZE
DO NOT SCALE DWG
VARIABLE ORIFICE SASS CONTROL SUBASSEMBLY ARRANGEMENT
SE 12776-160-001

FIGURE 3-12

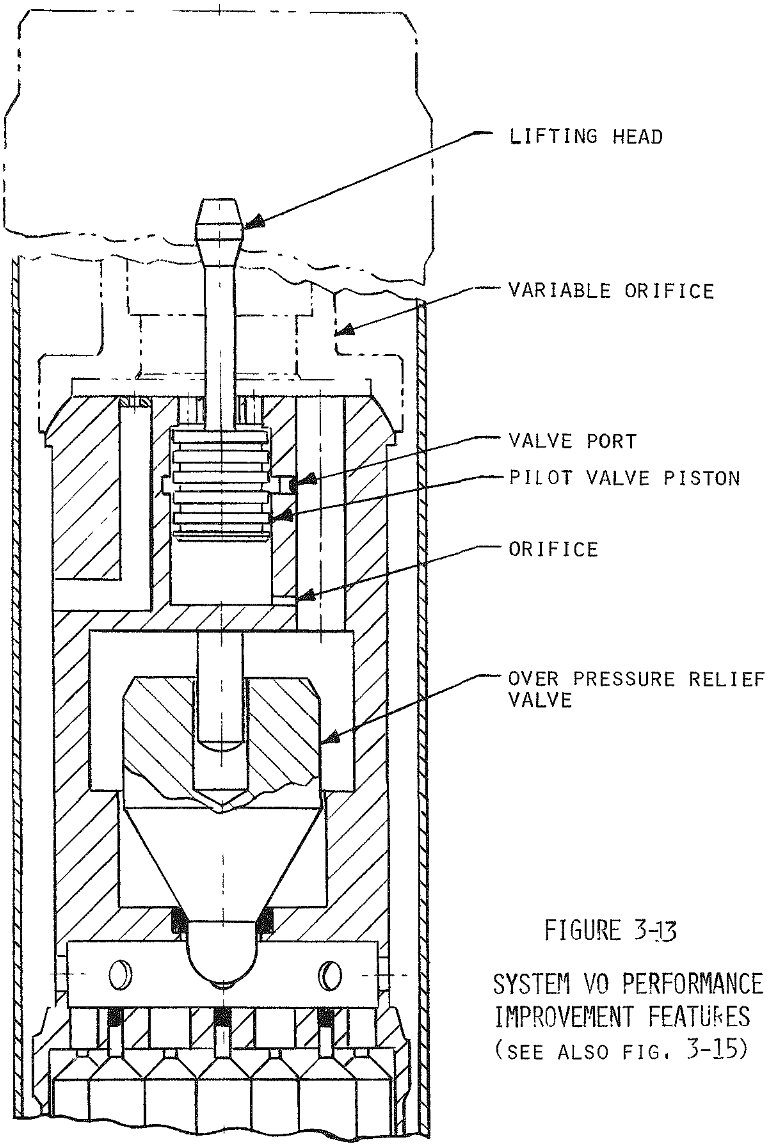


FIGURE 3-13

SYSTEM VO PERFORMANCE IMPROVEMENT FEATURES
(SEE ALSO FIG. 3-15)

In order to obtain a 0.5 second release time for the poison assembly, the operating pressure should be set approximately 1 psi above the trip pressure. This small differential pressure results in a very marginal resistance to an accidental rod drop due to flow induced vibrations, mechanical shocks and low intensity earthquakes. To overcome this problem, a pilot valve, as illustrated in Figure 3-13, has been incorporated in the design. This allows a relatively high differential pressure across the hydraulic seal which decreases the sensitivity to these vibration effects. The movement of the piston during these vibrations is limited so that the inlet port to the cylinder remains covered. Upon loss of flow, however, the piston moves down by gravity, thereby opening the cylinder inlet port and decreasing the seal differential pressure to release the piston assembly.

3.2.2 Modes of Operation

Self Actuating Mode

During the rise to power from hot standby conditions, it is proposed that the variable orifice actuators be adjusted by the operators, following the stepwise progression shown in the response time curve (Figure 3-9). The steps, corresponding to the 5% flow rate increments, are shown by a calibrated position indicator on each actuator. This procedure provides SASS protection during startup. The reverse procedure could be followed for shutdown, or, the opportunity could be taken for testing the SASS at power. Once set, the actuator equipment must be locked to prevent unauthorized interference during reactor operation.

Upon loss of flow, the pressure across the hydraulic seal is reduced due to the pressure decay associated with pump coastdown. The poison rod is automatically released and inserted into the core when the differential pressure is insufficient to support the poison assembly. The design ensures that this occurs independently of the PPS and without impedance from the PPS hardware.

PPS Mode

In addition to the self actuated trip of the poison assembly, PPS trip is also provided for the system. The CRD gripper nozzle is normally placed approximately 50 mm from the top of the poison assembly. A mechanical push by the CRD against the poison assembly is capable of breaking the hydraulic seal and releasing the control assembly. The force required to overcome the net upthrust due to the operating differential pressure across the hydraulic seal is moderate (less than 45 kg) but additional resilience may be required in the CRD to protect the system from the impact load.

Upon receipt of the trip signal, the CRD moves in the fast down drive mode to mechanically push down the poison assembly away from its seat, thereby releasing the assembly for insertion into the core under gravity drop. The CRD continues to move downward under fast down drive so that it will push the poison assembly if there is any interference to its movement. The time delay in the logic circuit is limited to 0.2 second, in order to ensure a response speed approximately equal to the primary shutdown system.

Calibration and Testing Mode

It is desirable to minimize the correction of the variable orifice positional readout at operating conditions, relative to calibration conditions. It is also important that calibration not require regularly scramming the reactor at power. The relationship between a hot standby calibration and that performed under operating conditions could, however, be determined very infrequently. These considerations lead to the selection of hot standby conditions, rather than refueling conditions, for performing calibrations. It is recommended that these be performed over the entire operational flow range to allow SASS protection during the progression to full power.

In addition to the CRD positional indication, the operator receives information from pressure transducers connected to the reactor inlet plenum, subcritical nuclear instrumentation, the poison gripper sensing rod, and from a load cell and an accelerometer (or acoustic sensor) situated in the upper drive line. The specification and design of such equipment is beyond the scope of this investigation. However, it is mentioned to assure the reader that means are available to allow the operator to follow what is taking place at the control rod support seal during calibration. Clearly, a display could be devised to simplify the interpretation of the instrument readings and, possibly, equipment could be provided to automate the whole procedure. As a minimum, the detent clicks should be detected acoustically and digitized, so that the readout shows the actual valve opening and not, simply, the vertical motion at the top of the CRD. In this way, the positional uncertainties, described above in connection with the basic System VO concept, together with the need for frequent calibration, are eliminated. If, in addition, the settings are related to the inlet plenum pressure transducer readings associated with power operation, rather than the flow rate as such, then correction of the hot standby calibration may be unnecessary.

A typical calibration sequence consists of raising the pump speed to 100% full flow with the coolant temperature maintained at the hot standby level. The variable orifice sleeve is engaged with the sleeve gripper, based upon acoustic or accelerometer feedback, and the VO opened to its fullest extent. The sleeve gripper is released, the poison gripper is engaged with the handling head (sensing rod feedback) and the poison assembly raised to the support seat. The poison gripper is released and the CRD is backed off until the sleeve gripper engages, leaving the sensing rod in contact with the poison handling head. The CRD positional readout is then adjusted to the value assigned to the fully open VO at the hot standby temperature. The VO is then actuated until release occurs, as detected by the sensing rod (also load cell, accelerometer). Insertion into the core region is detected by subcritical neutron detectors and/or acoustic sensors. Timers, linked to the detection circuits, could be used to monitor performance and detect any long term deterioration in either response time or insertion time. This procedure is repeated for successive reductions of 5% of full flow to provide a calibration over the entire operating range. The readings may then be translated into values applicable to normal operating conditions.

3.2.3 System Performance

The poison assembly, weighing approximately 91 kg (200 lb), requires a differential pressure of 62 kPa (9psi) across the 134 mm (5.3") diameter seal for suspension above the core. A decrease of hydraulic pressure below 62 kPa (9 psi), therefore, results in rod release. For reactor operation, a margin of 20.7 kPa (3 psi) over the trip value of 62 kPa (9 psi) is maintained for normal pressure fluctuations and acceptable operator errors. Thus an operating pressure of 82.7 kPa (12 psi) is required for the system, which leads to a nominal response time of 1 second.

The operating pressure of 82.7 kPa (12 psi) is maintained approximately constant, for all power levels in the operating range of 40% to 100%, by adjustment of the number of orifices opened for bypass flow, as illustrated in Figure 3-14. A minimum of five orifices is required to be open at 40% reactor flow, with a corresponding assembly flow rate of 1.07 kg/s (8500 lb/hr). The orifices are opened at the rate of one orifice per 5% increment in power level (flow rate), so that 17 orifices are open at 100% reactor flow rate.

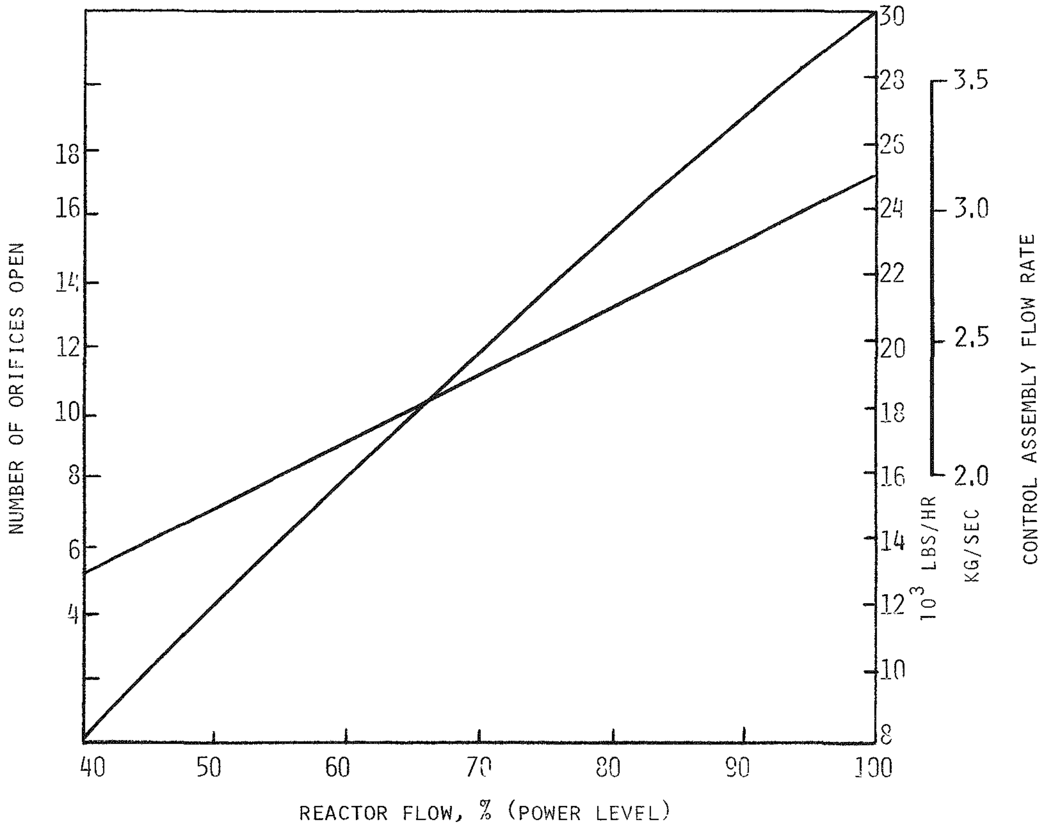


FIGURE 3-14 SYSTEM VO DESIGN CURVES

As illustrated in Figure 3-15, these orifices provide discrete settings at flow increments of 5%. The maximum pressure variation at any setting is $\pm$2.5%. Also an offset of one orifice corresponds to a maximum error of 10.3 kPa (1.5 psi). Therefore, an operating pressure of 82.7 kPa (12 psi) is adequate to cover the normal pressure variation plus an acceptable error of one orifice. The nominal response time is 1 second, but this may vary between 0.5 second to 2 seconds depending upon the normal variation of pressure and error in setting as noted above.

These operating parameters are initial estimates which could vary due to large uncertainties in predicting the pressure drop through the system. The correct operating parameters will be determined through in-situ testing and calibration.

As may be noted from Figure 3-15, the normal pressure variation should not exceed $\pm$20.7 kPa (3 psi) at any given setting and therefore, the maximum operating pressure is expected to be 103 kPa (15 psi). To overcome any gross discrepancy in the SASS setting, the over pressure relief valve is designed to lift at 110 kPa (16 psi).

At the lower end of the flow scale, the upthrust across the hydraulic seal is marginal so that the flow induced vibration or mechanical shocks could cause rod release. If a response time of 0.5 second were to be achieved, this margin would be reduced even further to limit acceptable vibrations to less than 0.05g as illustrated in Figure 3-16. However, it is desirable to maintain reactor operation up to OBE level. It is estimated that a local spectral acceleration of 0.5g could result due to an OBE. The pilot valve, incorporated in the SASS design, behaves analogously to a hydraulic support concept in that its spool valve geometry requires it to travel a given distance before opening. The pilot valve allows a high differential pressure to be maintained across the seal to resist seismic shocks but will cause insertion within the target time of 0.5 second. The pilot valve travel during a seismic event is govered by its housing, its inertia, and the dashpot effect, due to leakage around the piston and the lower orifice. These are sized so that the seismic vibrations less than the OBE will not result in rod release.

3.3 SYSTEM MM

It was observed at the start of this investigation, that whereas the transient undercooling (TUC) protective devices proposed to date (e.g., levitated balls,

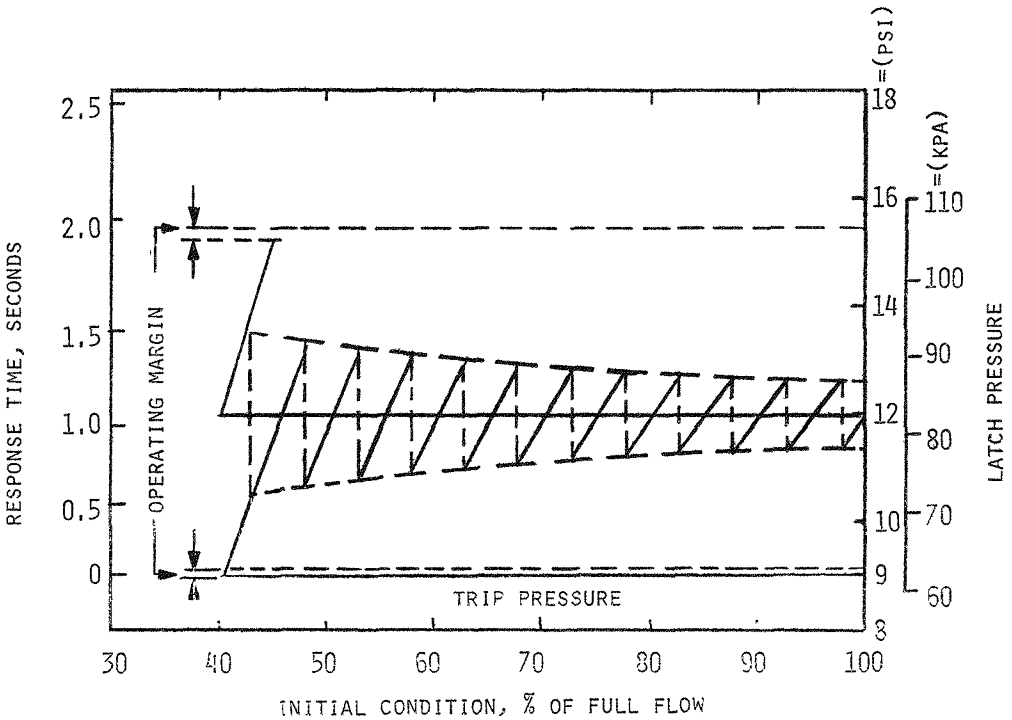


FIGURE 3-15 SYSTEM VO 12 STEP RESPONSE CHARACTERISTIC

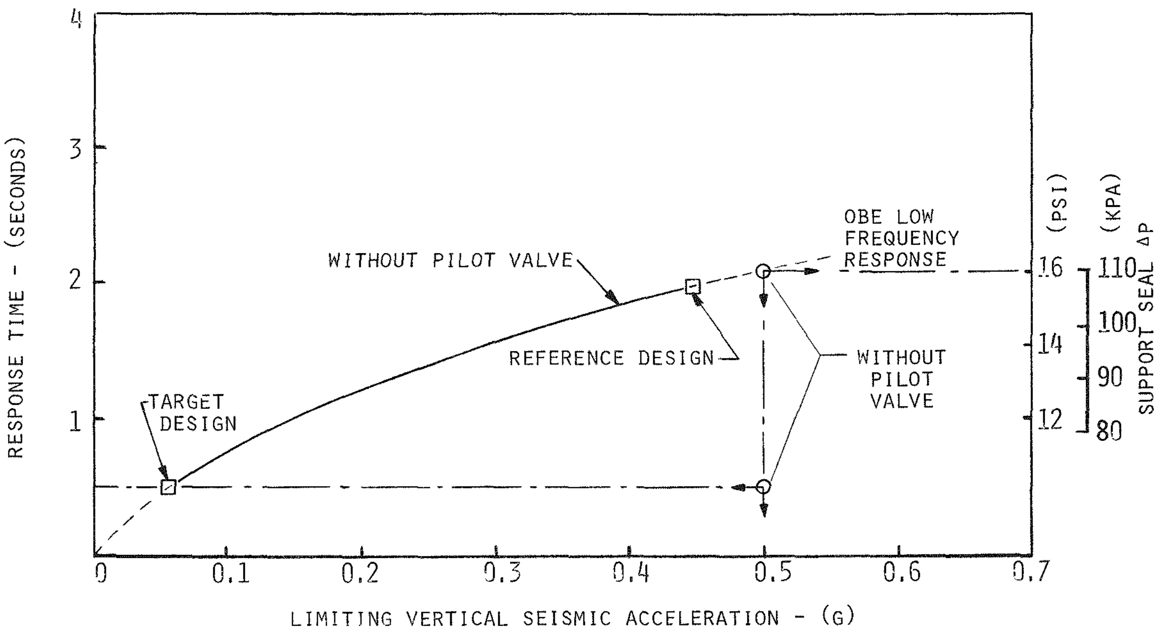


FIGURE 3-16 SYSTEM IMPROVED PERFORMANCE WITH PILOT VALVE

System M, etc.), responded inherently to a loss of flow, they also had an inherent failing. This involved the fact that power variations in LMFBR's are conventionally performed by correspondingly varying the flow rate and holding the reactor temperature rise fairly constant. Consequently, a TUC device, designed to release at, say, 40% power (or flow), would have an additional release delay equal to the coastdown time history used in this study. The penalty amounted to about 8 seconds, which was considerably in excess of the 0.5 second objective.

In response to this problem, Combustion Engineering offered a solution in the form of a device which would be triggered by the rapid rate of change of coolant flow associated with a pump coastdown condition. The device operates on the same principle as an aircraft rate of climb indicator by responding to the local rate of change of pressure (RCP). Typically, an LMFBR pump coastdown characteristic has a greater rate of change at the start so that the device has an inherently high speed of response. Also, a relatively fast response occurs at low flow levels, even though speed is less important at lower power.

3.3.1 System Description

The System MM hydraulic support seal is similar to that of System M except that an annular cavity is formed in it as illustrated in Figure 3-17. The hydraulic pressure in the annular region is vented to the low pressure side of the seal so that the differential pressure across the piston is adequate to maintain a hydraulic seal at all flow levels from 40% to 100%. During a flow coastdown the annular region is pressurized by the automatic opening of a valve, leading to a rapid decrease in differential pressure across the seals and rod release. This avoids long time delays in rod release, because the speed of response relies on the speed at which the valve is opened in conjunction with normal pressure decay due to flow coast down. The valve is actuated by the rate of change of pressure (RCP) which occurs at twice the rate of change of flow.

The operation of the RCP trip device, as illustrated in Figure 3-18, is based on partial release of potential energy from a gas accumulator bellows upon rapid loss of the coolant pressure.

The accumulator bellows is located in an enclosed sodium filled cylinder located in the lower section of the control assembly as illustrated in Figure 3-19. The cylinder is connected to the main coolant flow path through an orifice. The

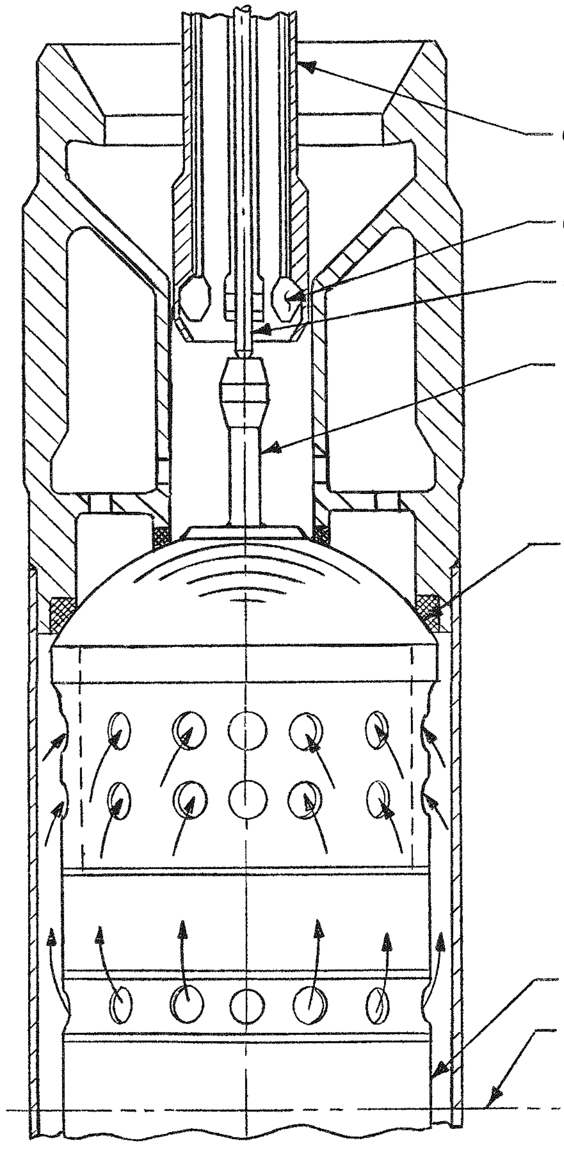


FIGURE 3-17 SYSTEM MM SUPPORT SEAL REGION

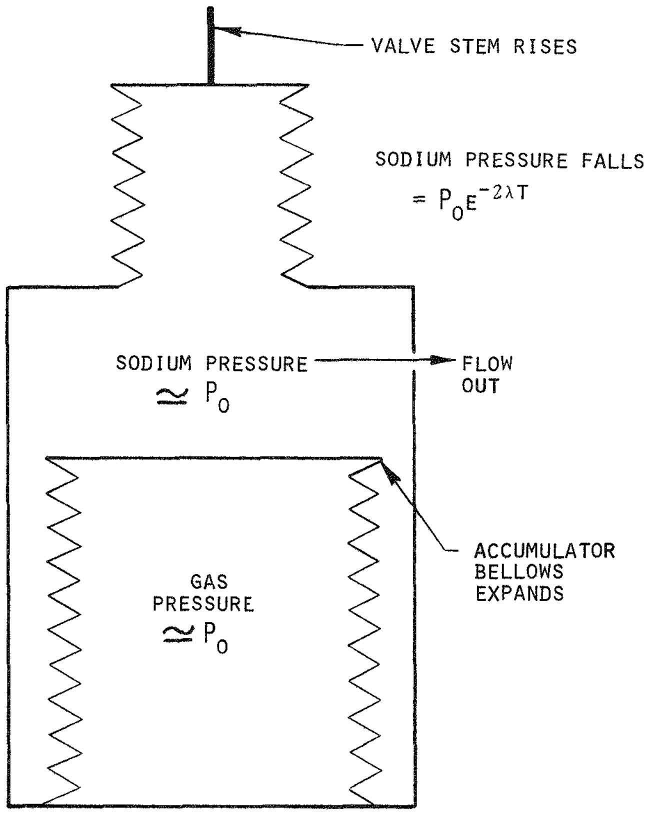


FIGURE 3-18 SYSTEM MM-OPERATING PRINCIPLE OF RCP DEVICE

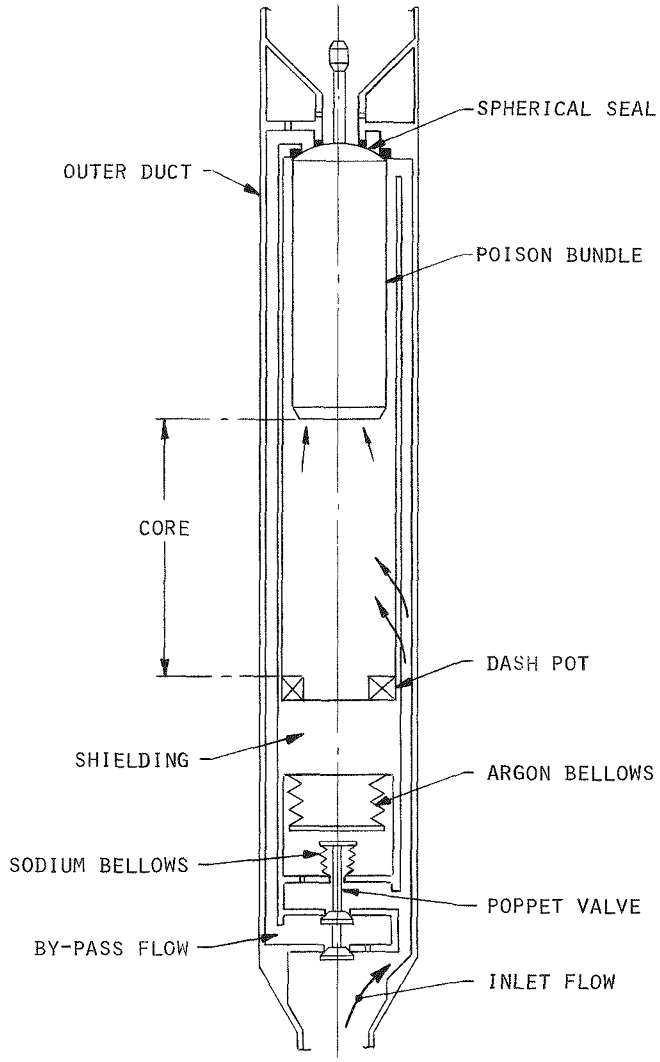


FIGURE 3-19 SYSTEM MM SCHEMATIC ARRANGEMENT

bellows is compressed due to the coolant pressure corresponding to reactor flow rate. As the coolant pressure varies, the bellows position and the residual fluid volume in the cylinder is adjusted by the flow through the orifice during normal reactor flow variation. This provides for an equilibrium of the accumulator bellows pressure with that of the coolant inside and outside the cylinder during reactor operation. During loss of flow, the coolant pressure falls rapidly as shown in Figure 3-20, whereas the fluid pressure within the cylinder decays slowly due to flow constriction in the orifice and replacement of lost fluid by the expansion of the bellows. The differential pressure thus created between inside and outside of the cylinder is applied to the other bellows (sodium bellows) to open the poppet valve. This valve opening leads to pressurization of the seal annulus, leading to a rapid decrease in the seal differential pressure for rod release.

Normal differential pressure across the hydraulic seal varies from 517 to 82.7 kPa (75 to 12 psi) for 100% to 40% reactor flow rate, whereas the trip pressure is set at 62 kPa (9 psi). The rate of change of pressure associated with normal flow coastdown is dependent on the initial conditions as illustrated in Figure 3-20, and it varies from 138 kPa/sec (20 psi/sec) to 20.7 kPa/sec (3 psi/sec) for 100% to 40% initial flow conditions, respectively. For these events, the RCP device releases the rod within 0.5 second upon loss of flow. The RCP device is, however, insensitive to normal (slow) variations of coolant flow, pressure and temperature, and therefore, spurious scrams are avoided.

The principal parts of System MM are described below:
The argon filled accumulator bellows shown in Figure 3-21 has a spring rate of 535 kg/m (30 lb/in.) and is made of Inconel 718. It is located within a sodium filled cylinder in the inlet region of the stationary control assembly duct beneath the lower axial shielding in a steady low temperature and low flux environment. The expected compression stroke of approximately 73 mm (2.8 in.) is less than 50% of the free length of the bellows, including a 7.6 mm (0.3 in.) allowance for stroke uncertainties, and 12.7 mm (0.5 in.) for the fail safe feature described below. The bellows parameters are given in Table 3-1.

The fail safe feature of the RCP device is obtained by making the spring rate of the accumulator bellows higher than that of the sodium bellows. Upon failure, this accumulator bellows expands to approximately its free length, thereby forcing the poppet valve to open. Under normal operations, the argon pressure within the

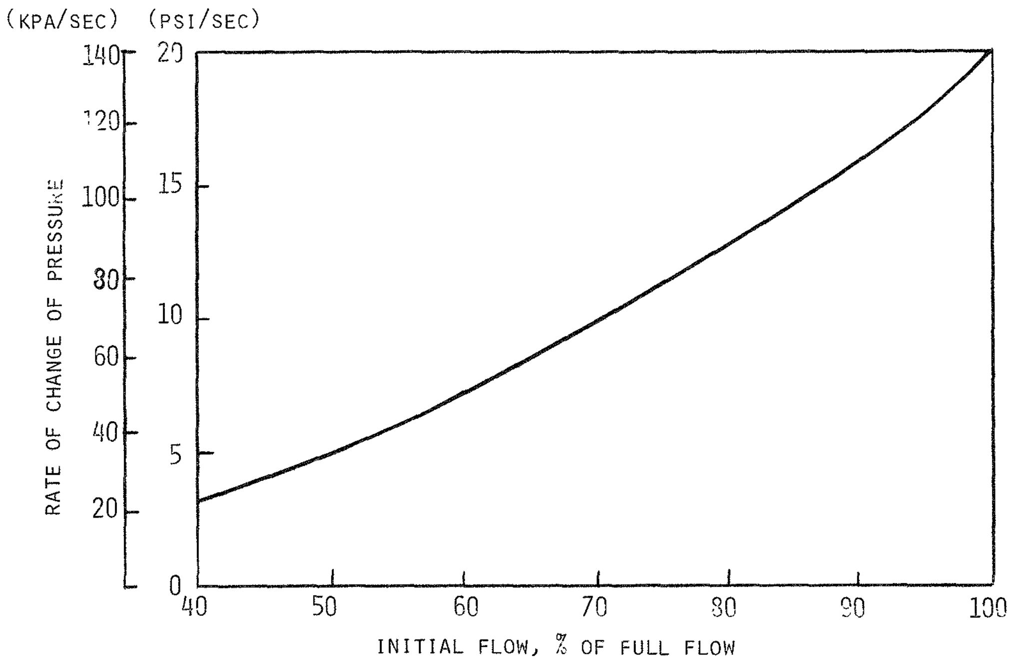


FIGURE 3-20 RATE OF CHANGE OF PRESSURE VARIATION WITH INITIAL FLOW RATES FOR FLOW COASTDOWN

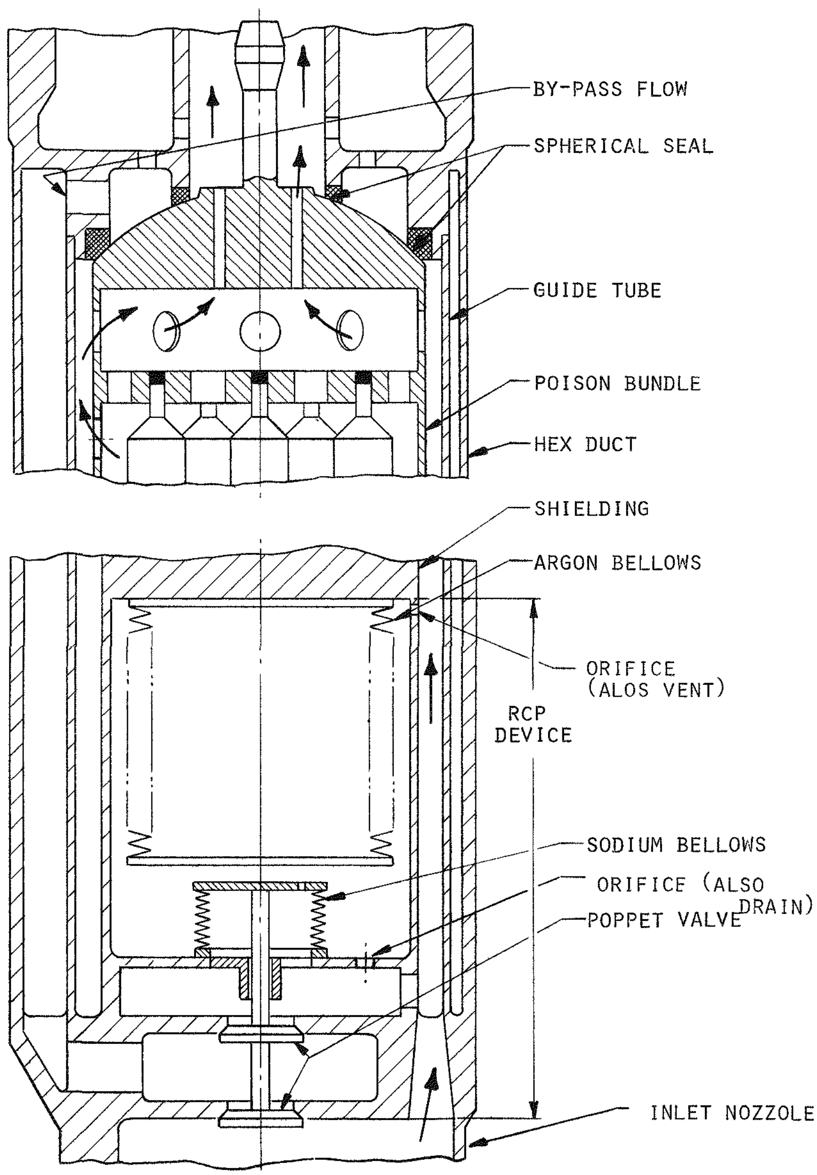


FIGURE 3-21 SYSTEM MM DESIGN DETAILS

bellows is in equilibrium with the coolant pressure within the cylinder and therefore the bellows experiences little differential pressure across its walls. During flow coastdown, the differential pressures generated across the bellows wall are also very low. The probability of the bellows failure is, therefore, very low.

The single ply, welded type sodium bellows, as shown in Figure 3-21, has a spring rate of 178 kg/m (10 lb/in) (see Table 3-1). This bellows is slightly compressed to provide a preset force for keeping the poppet valve closed during reactor operation. The overall stroke of this bellows of up of 7.6 mm (0.3 in.) is required during RCP actuation. Also the bellows has little differential pressure across its walls during reactor operation. Therefore, the failure probability of this bellows is also very low.

The spherical seal provides a low pressure annulus at the upper section of the assembly which is connected to the plenum of the poppet valve as illustrated in Figure 3-21. The outlet orifices in the annulus are sized to maintain a low pressure during steady state operation but act as flow limiting orifices when the annulus is opened to the inlet plenum upon opening of the poppet valve, thereby pressurizing the annulus. The seal is hardfaced to resist erosion, galling or self welding.

The poppet valve assembly is an hydraulically balanced double valve, as illustrated in Figure 3-21, connected by its stem to the sodium bellows. The valve discs are seated in two 25 mm (1 in.) diameter ports at the assembly inlet, and are hardfaced to resist erosion, galling or self welding. A small reset force is applied by means of the sodium bellows to keep the valve in the closed position. During flow coastdown, the small differential pressure generated across the sodium bellows is sufficient to overcome the preset force and open the poppet valve for rod release. The poppet remains open until rod release and automatically closes upon decrease in the differential pressure across the sodium bellows. A detailed arrangement for the System MM control assembly is shown in Figure 3-22.

Redesign of System MM Without Bellows

The System MM design study showed that the bellows could be designed with extremely conservative stresses and deflection. The reliability of these bellows should, therefore be very high (see Appendix C). However, it is recognized that a history

Table 3-1

PARAMETERS OF BELLOWS

	Argon bellows	Sodium bellows
Material	Inconel 718	Inconel 718
Type	Single ply - welded	Single ply - welded
OD	4.75"	2.25"
ID	4.25"	1.75"
Effective diameter	4.50"	2.0"
Mean effective area	15.9 in^2	3.1 in^2
Material thickness	.005"	.005"
Spring rate	30 #/in	10 #/in
Free length	5.5"	1.5"
Compression stroke	2.8"	0.5"

of unfavorable experiences with under-designed and poorly fabricated bellows may tend to overshadow rational appraisal of System MM reliability during licensing. For this reason, a further variation of the RCP equipment was devised, from which bellows were eliminated. This is shown in Figure 3-23. The accumulator bellows is replaced by an argon filled chamber and the sodium bellows is replaced by a spring loaded piston within a guide sleeve. A control orifice is provided at the bottom of the cylinder so that the probability of entrapped argon gas escaping from the cylinder is very low. Also the fluid in the cylinder is quiescent and not in the direct path of the flowing sodium. The probability of the trapped gas going into the solution with the flowing sodium is, therefore, very low, hence, little deterioration of the response time is expected in the RCP device. It is also possible to minimize the liquid/gas interface area in order to limit the gas diffusion into the liquid by means of a float or by forming a bottle neck to the gas pocket.

The piston and sleeve arrangement as shown in Figure 3-23, minimizes sodium leakage into or out of the argon chamber. The piston is connected to the poppet valve through a stem, so that a differential pressure across the cylinder, experienced during flow coastdown, is adequate to open the poppet valve. The valve closes under spring assist upon decrease of the differential pressure.

The factors governing the selection or rejection of bellows devices in System MM are complex. It does not follow that, by simply replacing a bellows with some alternative means, a more reliable design with result. The earlier version had five bellows (Appendix C.2), each with appreciable structural conservatism, and each capable of orthodox fabrication, under stringent QA, to result in an extremely low probability of failure. The replacement of the support seal bellows with a spherical seat, provided an alternative means of accomodating misalignment, but produces a seal which requires special fabrication accuracy and would part under a very small mechanical shock. The replacement of the poppet valve seal bellows with a balancing poppet valve introduced the need for greater machining accuracy, including simultaneous lapping of the two valve seats with the double poppet valve. Finally, the low-stressed accumulator bellows may be replaced with a gas pocket, thus raising the gas solubility question, and the actuator bellows by a piston, which may invite jamming, due to crud deposition. Despite these assertions, bellows concepts appear difficult to "sell" to potential users, which may portend difficulties during subsequent licensing proceedings.

3.3.2 Modes of Operation

SASS Mode

During normal reactor operation, the poison assembly is held out of the core by the differential pressure across the hydraulic seal. Upon loss of flow, the poppet valve opens and releases the control rod as shown in Figure 3-24.

As an ultimate feature should the RCP device fail, the decrease in the hydraulic pressure due to flow coastdown results in rod release in a time determined by the initial operating conditions.

PPS Trip Mode

In addition to the RCP trip, the SASS incorporates a PPS trip capability (Figure 3-25). The CRDM is normally stationed 51 mm (2 inches) (zero power) to 25 mm (1 inch) (full power) above the 6.5 mm (1/4 inch) orifices in the low pressure plenum. On a trip signal, the CRDM under fast down drive moves approximately 25 mm (1 inch) to block the orifice which results in equalization of pressures across the hydraulic latch and consequent release of the control assembly. The CRDM continues to move under fast down drive and another 25 mm (1 inch) travel results in the CRDM pushing the top of the control assembly.

Testing Mode

The testing of the RCP trip device is performed during reactor shutdown. The pumps are started and a flow of $\geq$ 35% flow is established to maintain sufficient hydraulic pressure to hold the poison assembly in the up position. The poison assembly is now reset. The pumps are tripped and the assembly release and insertion is monitored acoustically and by subcritical reactivity measurements. A feeler rod is also provided for monitoring the assembly position for latch and detach operations.

Reset Mode

Prior to reactor startup, the CRD is lowered to grapple the poison assembly head. The poison assembly is then raised until it contacts the upper seals. A pre-contact limit switch followed by a load cell switch in the CRDM, and a spring-loaded lost motion device in the CRD together should insure that no mechanical

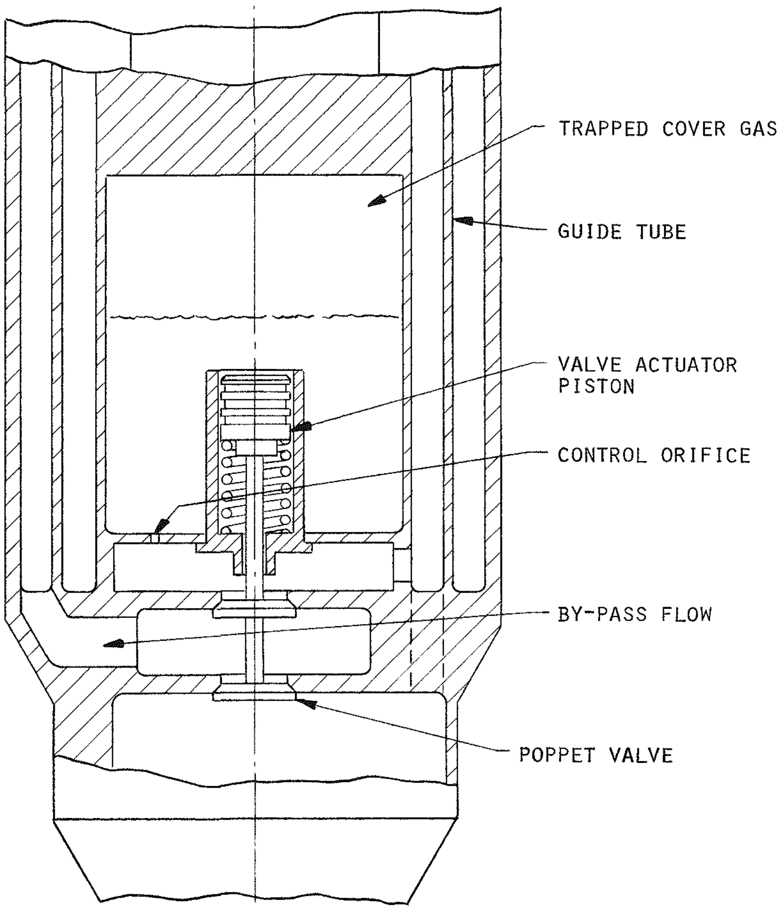


FIGURE 3-23 RCP DEVICE WITHOUT BELLOWS

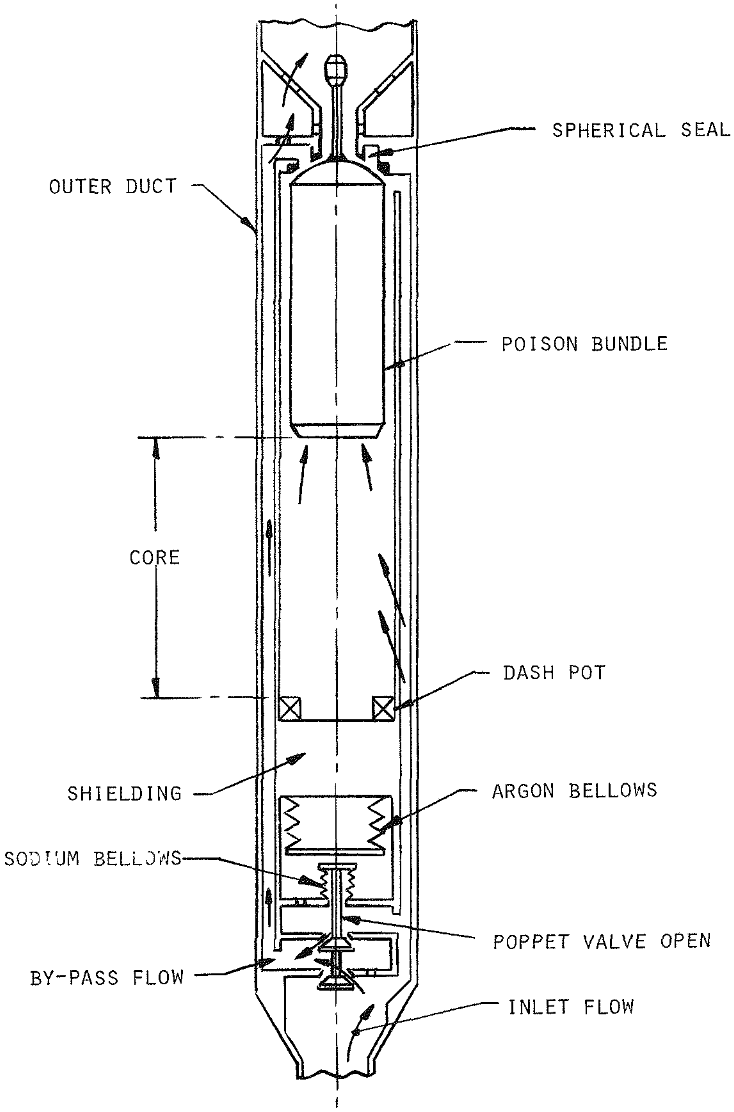


FIGURE 3-24 SYSTEM MM-SASS RELEASE MODE

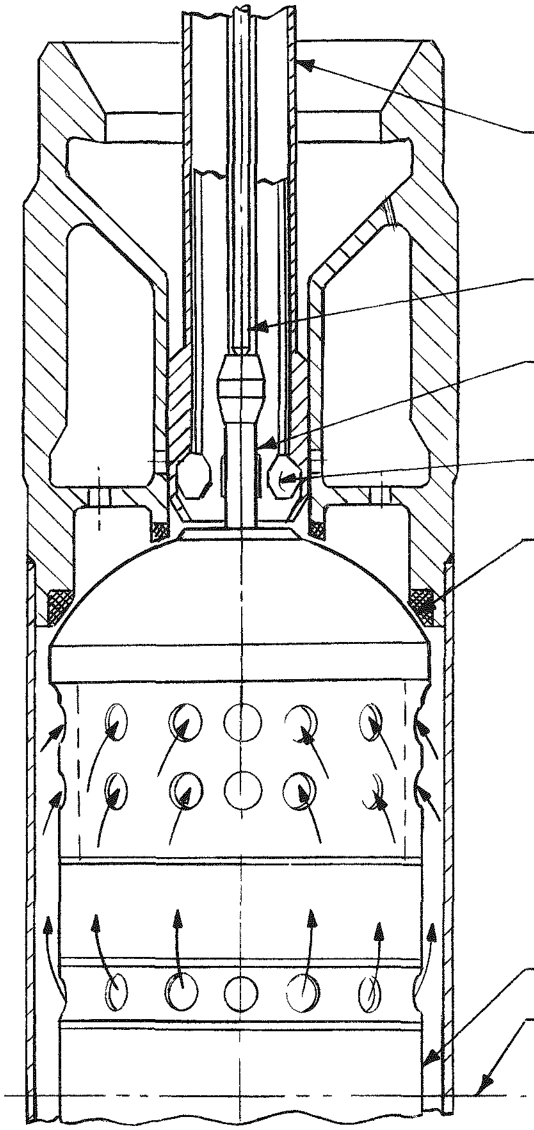


FIGURE 3-25 SYSTEM MM-PPS RELEASE MODE

overload occurs. When the reactor coolant flow rate reaches 40% of full power flow, the grapple is disconnected and withdrawn to its cocked position as described in the Section 3.3.2.

Handling Mode

The poison assembly, contained in a hex duct, is replaced with a standard refueling machine at a frequency determined by the fuel management scheme. It is assumed that the normal frequency for replacement of control assemblies is about one life cycle of the core (approximately 3 years) as per design criteria described in Section 2.

3.2.3 System Performance

The performance of System MM has been determined by preliminary calculations. The results are described below for the two self-actuated modes and the PPS mode, and an assessment is made of the margin allowed to prevent trip by normal pressure variations and noted in Table 3-2.

Loss of Flow Trip

The poison assembly weighing approximately 91 kg (200 lbs) is hydraulically supported above the reactor core by a minimum differential pressure of 62 kPa (9 psi) across the hydraulic seal. This lower limit of the pressure drop corresponds to 34% ± 5% full flow, to ensure hydraulic support in the power range of 40% to 100%. The ±5% uncertainty is assumed in estimating the poison assembly weight and the pressure drops. Based on this lower limit, the full flow latch pressure drop is 517 kPa (75 psi). The poison assembly inlet and shield orificing provides for a 379 kPa (55 psi) pressure drop to limit the dynamic pressure to this value at full flow. As a result, the net upthrust on the seal varies from 121 to 667 kg (267 to 1467 lb.), providing a very adequate margin against tripping due to mechanical shock.

For the 40% to 100% flow (power) range of reactor operation, the control assembly is delatched on RCP actuation but below 40% flow, the delatch occurs at < 34% ± 5%, as noted above. The release time is then approximately 1 second.

Table 3-2

SELF ACTUATED SHUTDOWN SYSTEM

SYSTEM "MM"

TRIP LEVELS (POISON ASSEMBLY RELEASE

	Trip Level	Time Delay
Loss of Flow (Absolute Pressure)	34% ± 5%	Varies According to Initial Flow
Loss of Flow (low power) (Rate of Change of Press.)	40% - 50%	≤ 1.0 sec.
Loss of Flow (high power) (Rate of Change of Press.)	50% - 100%	0.5 sec. ± 0.1 sec.
Loss of Flow (one Pump Coastdown)	> 55%	< 3.0 sec.
PPS Trip (any signal)	0 - 100%	Approximately 1 sec.

Rate of Change of Pressure Trip

The RCP protection is provided in the flow range of 40% to 100% of full flow corresponding to the power range of 40% to 100%. Below 40% flow, the hydraulic pressure is fairly close to the trip pressure so that a scram is obtained at 30% flow level within 0.5 seconds. Below 30% flow rates the hydraulic pressure is too low to support the poison assembly.

The parameters of the RCP device, which impact the space, the response time and the overall arrangement, were optimized. Based on these parameters, the response time, as illustrated in Figure 3-26, was calculated and was found to be 0.5 sec ± 0.1 sec for the entire range of 40% to 100% of the full flow rate.

The rate of change of pressure varies from 245 kPa (35.6 psi/sec) at full flow coastdown, which leads to a faster projected response at increasing flow rates. But the margin of upthrust is lower at lower initial flow rates and, therefore, has a compensating effect on the response time characteristics. The resulting flat response time of 0.5 ± 0.1 second for the entire range of flow rates is desirable from the point of view of ease of calibration, limited testing requirements and predictability of performance.

The above discussion pertains to a loss of flow transient due to loss of flow from all pumps in a three loop plant. The RCP trip protection for reactor scram, however, is extended to a trip of one pump out of three with attendent adjustment of flow rates from the other two pumps due to changes in the reactor system hydraulic resistance. The rate of change of pressure due to tripping of one pump is subtantially smaller than that for a three pump trip and, therefore, the time response of the RCP device is much longer. It is estimated that at initial flow rates of ≥ 35% of full flow, the rate of change of pressure is adequate to actuate the RCP device in less than 3 seconds. A loss of one pump does not result in as severe an undercooling transient as for the three pumps' trip, and therefore, a longer time response may be acceptable.

Plant Protection System Trip

The poison assembly release can be actuated by the PPS as a backup to the self actuation of the assembly. Upon receipt of the scram signal, the CRDM moves under its fast down drive mode (approximately 3 m/min) and first blocks the

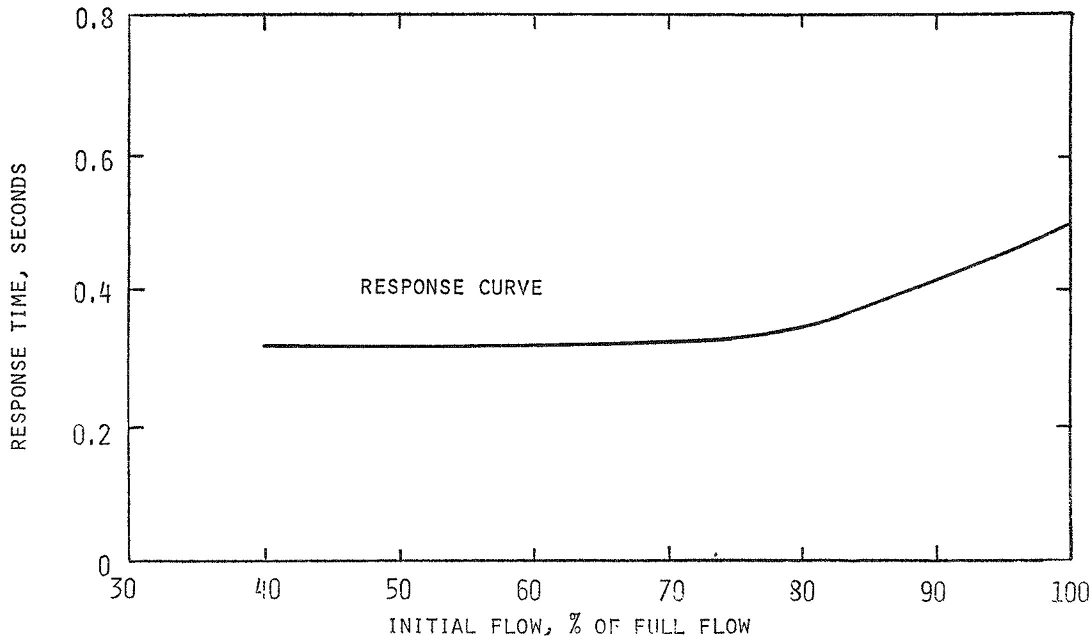


FIGURE 3-26 RESPONSE CHARACTERISTICS INLET RCP SYSTEM

coolant flow through the hydrualic latch. This reduces the differential pressure across the latch and push down the poison assembly head away from the bellows seal. The CRDM is stationed approximately 5 cm (2 inches) from the control assembly head during reactor operation and therefore, the poison assembly delatch is obtained in approximately 1 second under under CRDM fast down drive. Upon delatch, the poison assembly is inserted into the reactor core under gravity pull, being followed by the CRDM. In case of sticking or interference, the CRDM pushes the poison assembly into the core.

For reactor flow rates of less than 35% of full flow, the poison assembly is held up out of the reactor core by the CRBRP type CRDM pneumatic actuated gripper. Upon scram signal, the poison assembly is released by the pneumatic latch for insertion into the reactor core. This feature permits protected reactor operation at power levels of less than 35% required during startups and low power testing.

Spurious Trips

In order to ensure high reliability the RCP trip device parameters have been so selected to provide good discrimination against "spurious" pressure variations, as distinct from those associated with a TUC event.

It has been estimated that the pressure variation, due to, for example, pressure pulsations at the pump impeller, reactor vessel sodium level fluctuations, normal changes in the reactor flow rates and temperatures and sudden load changes at the turbine generators, will not exceed 14 kPa (2 psi) per second at the reactor inlet plenum. In Figure 3-27 the spurious pressure pulse is plotted with respect to the flow rates and compared with response characteristics of the RCP trip device. The response curve (valve full open) is a conservative estimate for the pressure pulse needed for poison assembly delatch. The poison assembly delatch occurs for pressure pulses larger than response curve (valve about to open) but less than response curve (valve fully open). These response curves being well above the spurious pulse curve, it follows that the RCP device is insensitive to spurious pressure variations.

The curve labeled "coastdown pulse" is the pressure drop rate corresponding to the rate of change of flow due to pump coastdown, and is provided as a representative TUC condition to which the device must respond.

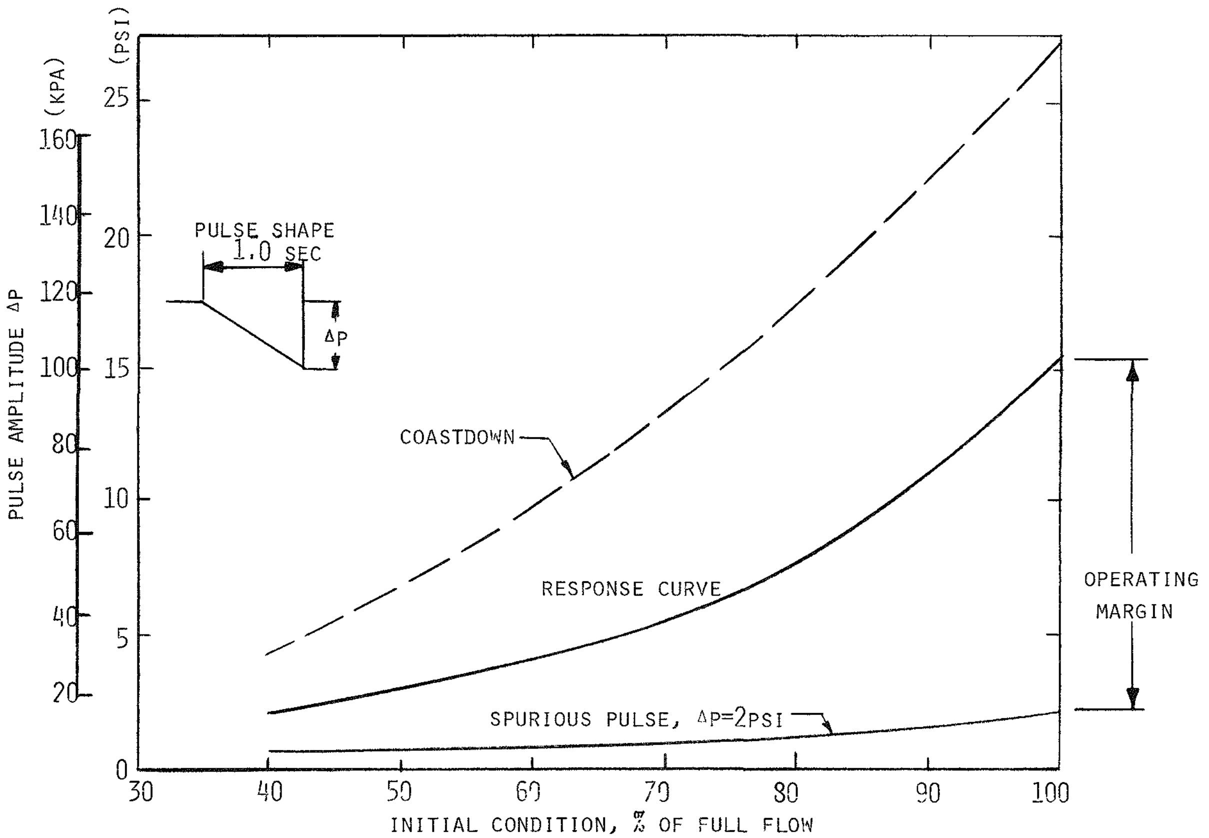


FIGURE 3-27 RESPONSE TO PRESSURE PULSES (REFERRED TO INLET PLENUM)

Figure 3-27, therefore, demonstrates that System MM can provide an adequate margin of operation to respond to TUC events and yet be insensitive to spurious (non-TUC) flow variations.

Section 4

SHUTDOWN SYSTEM PERFORMANCE

4.1 POISON ASSEMBLY

The poison bundle is contained within a round sleeve which provides support for the wire wrapped pins and forms an inner duct for the coolant flow. The sleeve has cylindrical bearing pads at each end which locally reduce the clearance between the poison assembly and the control assembly duct wall, which also has a circular cross-section. The bearing pad geometry, as illustrated in Figure 4-1. alows clearance for accomodation of duct curvature without excessive bypass flow around the poison assembly. A large (6.4 mm) radial clearance is provided between the poison bundle sleeve and the duct to ensure rod insertion with the maximum credible duct curvatures in the PLBR environment.

The stainless steel clad B_4C pins are arranged in a bolt circle arrangement as shown in Figure 4.2. This arrangement allows maximum poison loading, uniform flow distribution and cooling, and improved uniform clearance for increased bowing-limited lifetime. Alternatively, this arrangement affords more space for increase clad thickness for longer design life. The assembly parameters based on this arrangement are given in Table 4-1.

A comparison of the bolt circle arrangement with a triangular pitch arrangement is given in Appendix E. This appendix also contains alternative poison geometries to promote insertion into grossly deformed ducts.

4.2 REACTIVITY INSERTION

The insertion speed of the poison assembly, as shown in Figure 4-2, is affected by fluid drag, friction at the upper and lower bearing seals and the dashpot damping effect. The fluid drag forces are estimated to be small due to relatively small pressure drop along the assembly. There is little change in the fluid drag force during the assembly insertion because the poison assembly acceleration is

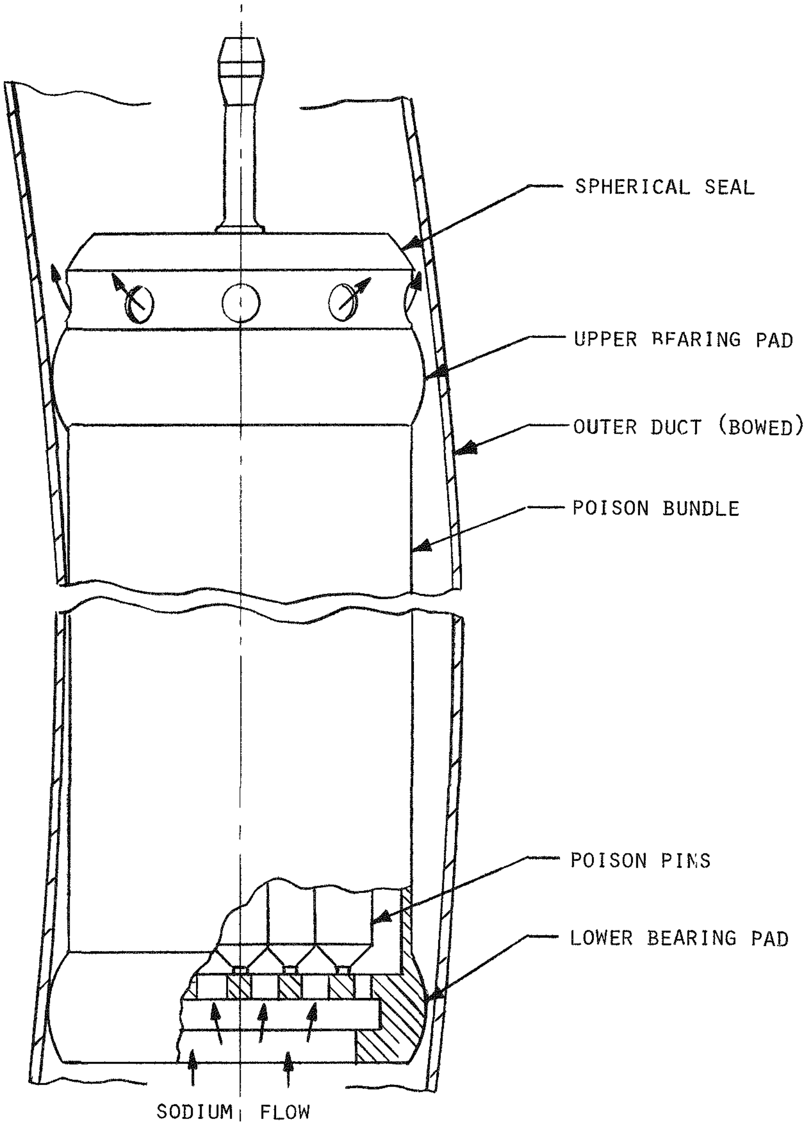


FIGURE 4-1 POISON ASSEMBLY-ACCOMMODATION OF DUCT BOWING

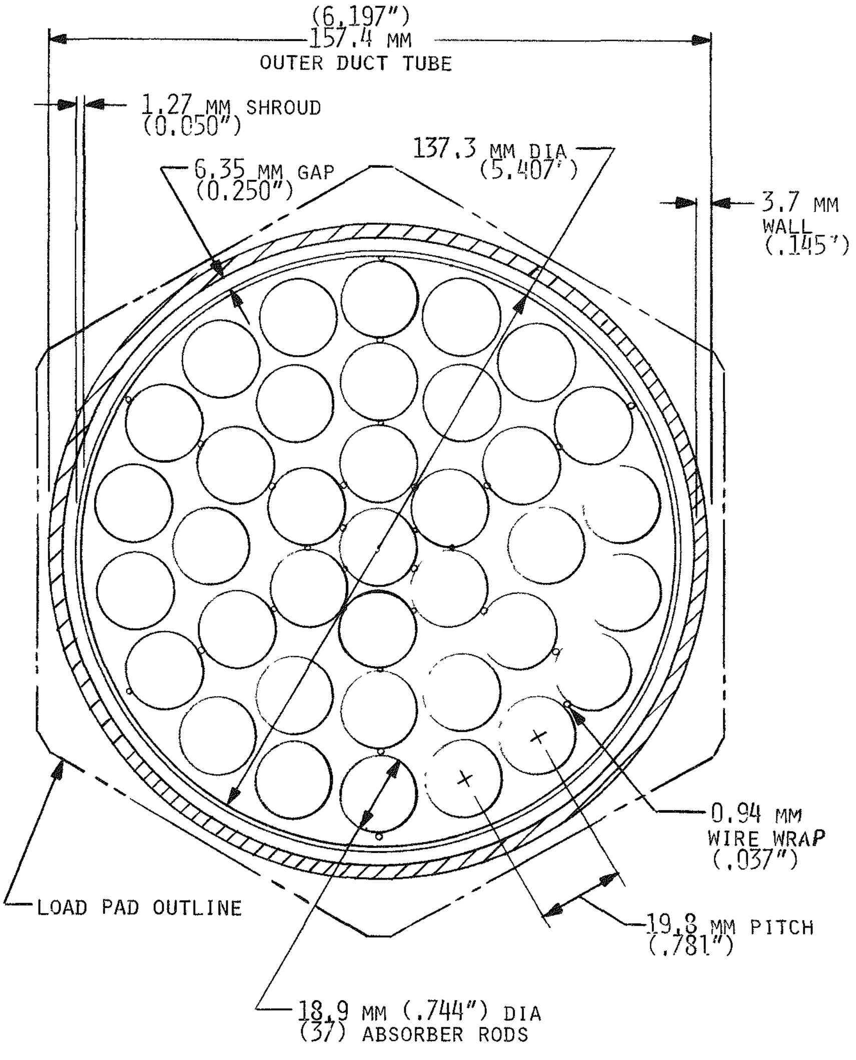


FIGURE 4-2 POISON ASSEMBLY PIN GEOMETRY

TABLE 4-1

B_4C PIN BUNDLE PARAMETERS

BOLT CIRCLE ARRANGEMENT

DUCT OD/THICKNESS (IN.)	6.197/.145
DUCT ID (IN.)	5.907
DUCT - GUIDE TUBE RADIAL GAP (IN.)	.250
GUIDE TUBE OD/THICKNESS (IN.)	5.407/.050
GUIDE TUBE ID (IN.)	5.307
PIN PITCH-TO-DIA. RATIO (IN.)	1.05
POISON BUNDLE DIA. (IN.)	5.257
BUNDLE-GUIDE TUBE DIAMETRAL CLEARANCE (IN.)	.050
NO. OF POISON PIN	37
ABSORBER (B_4C) LENGTH (IN.)	48
PIN OD/CLAD THICKNESS (IN.)	.744/.050
BORON DENSITY (LBS/IN^3)	.085
BORON MASS PER PIN DRY (LBS)	1.32
BORON MASS PER ASS'Y DRY (LBS)	49.2
GAS PLENUM (IN.)	20
10_β ENRICHMENT	92%

offset by flow coastdown. The friction resistance at the bearing pads, which are hardfaced to resist galling and erosion, is also estimated to be very low. It is, however, conservatively assumed that the effective acceleration for the assembly will be approximately 0.2g. This results in a rod drop time of about 1.0 seconds after its release for the first 1.06 m (42 in.) of its travel. The last 0.15 m (6 in.) of the rod travel is influenced by the dashpot force and is estimated to take about 0.5 second.

The normalized reactivity vs. distance relationship for a PLBR control rod (Reference 3) is shown in Figure 4-3. From a correlation of the Figures 4-3 and 4-4, a normalized reactivity vs. time relationship was derived and is shown in Figure 4-5.

From Figure 4-5, it may be noted that 90% of the reactivity is inserted in the first 1.0 second whereas the complete insertion takes place in 1.5 seconds. Allowing for approximately 0.5 second SASS release time, a total of 2.0 seconds is elapsed for 100% reactivity insertion which is within the stated criteria.

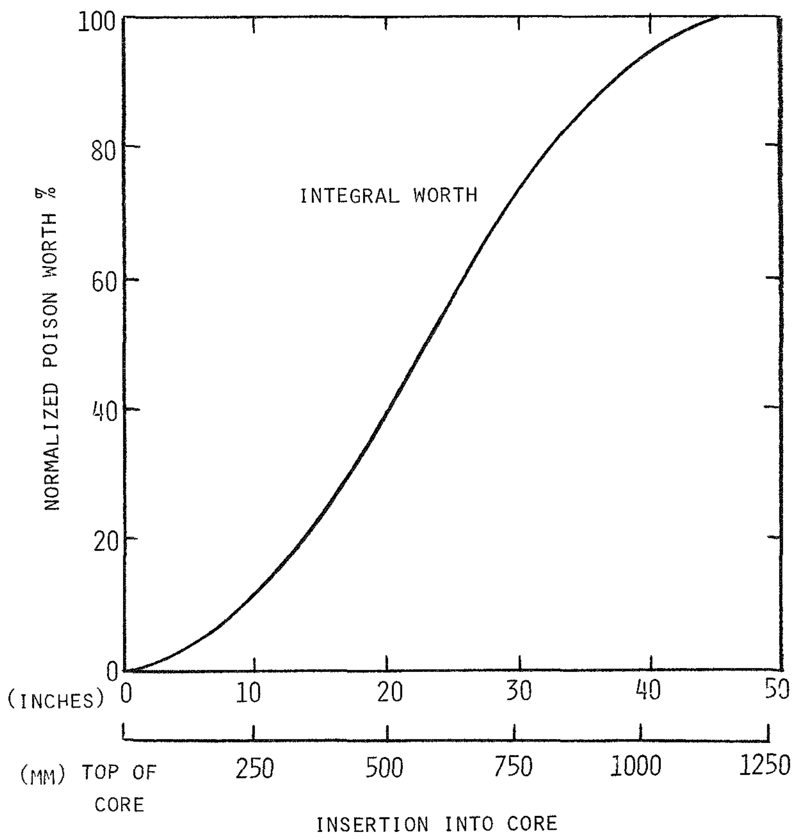


FIGURE 4-3 PLBR NORMALIZED CONTROL WORTH

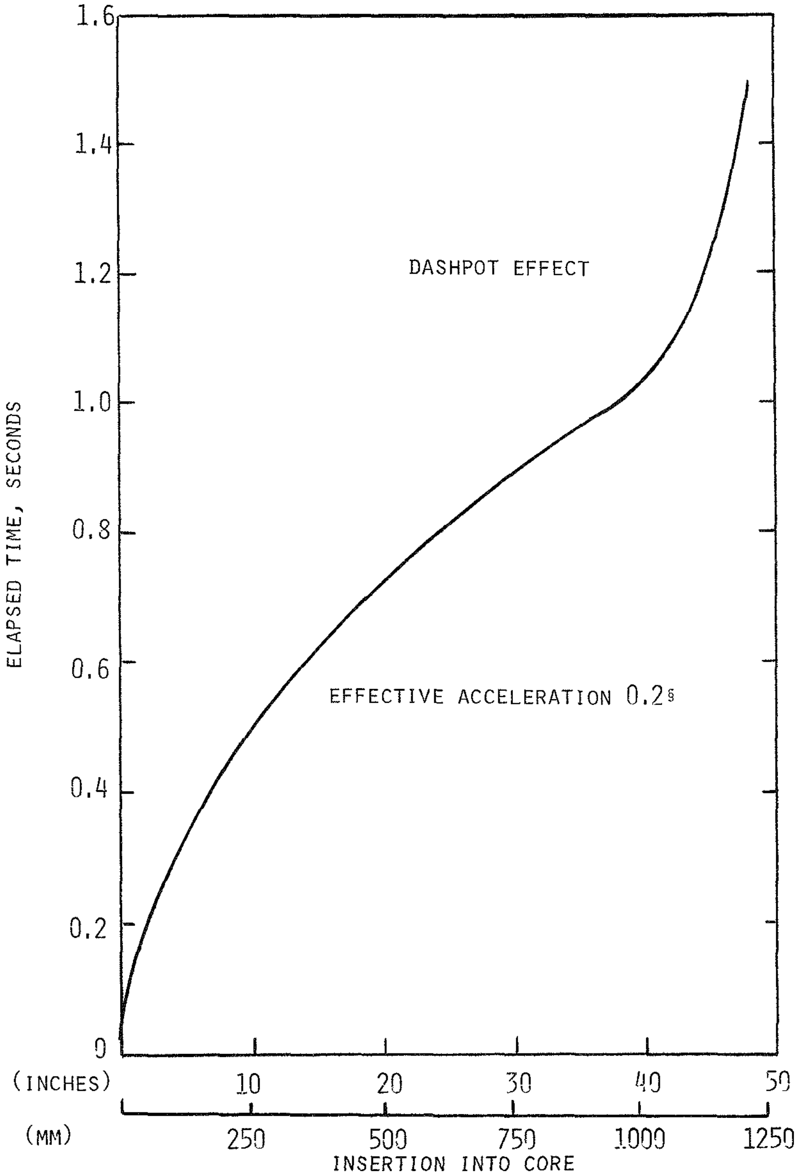


FIGURE 4-4 ROD DISTANCE VS. TIME

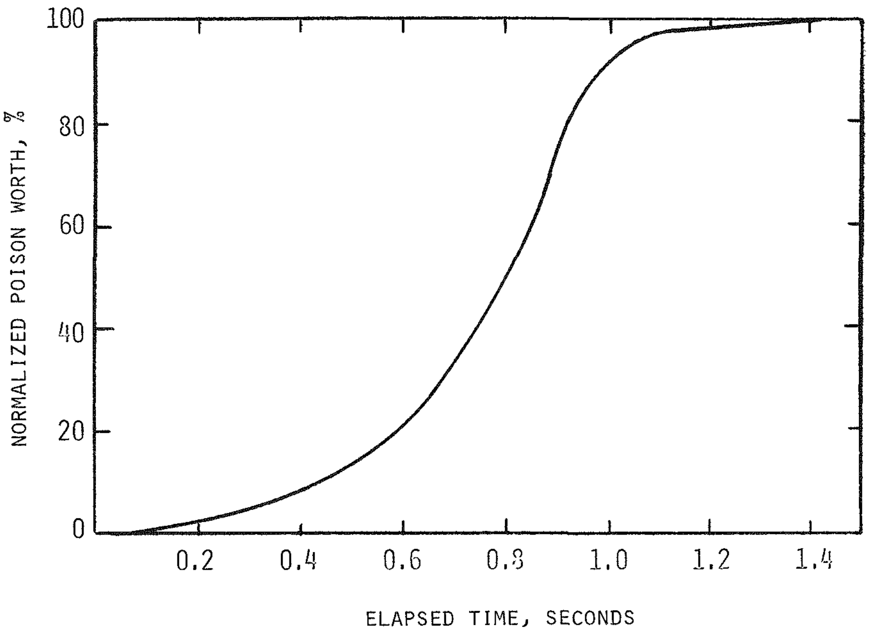


FIGURE 4-5 REACTIVITY VS. TIME

Section 5

DISCUSSION

The performance criteria which were assembled and pursued during this program reflect a conservative approach, conditioned by the work scope. This emphasized mechanical detail development of the candidate designs to permit an adequate feasibility assessment, rather than the refinement of the performance criteria for a particular large reactor design. The key element of conservatism in the criteria is the response time objective (0.5 second release, 2 seconds overall for complete insertion), which is based upon the CRBR specifications for the secondary shutdown system. It is acknowledged that opinion in the LMFBR design community as to the performance of a SASS required to achieve a significant licensing advantage covers a broad spectrum of response speeds. At the slow end of this spectrum, devices are proposed which only narrowly avert progression to a CDA following PPS failure, by rod insertion just prior to coolant boiling. The devices discussed in this report are aimed at obtaining an unquestionably adequate response time margin, with equipment which can become throughly developed, with demonstrated reliability, by the time of the large plant SAR submission. This approach should virtually eliminate the possibility that the detailed safety analysis of the final reactor design would disqualify the proposed SASS.

Notwithstanding these observations, it is appropriate to consider whether any of the designs have acquired significant additional complexity in the process of designing them to meet the conservative response requirements. Any better potential reliability of slower devices must be weighed against the risk of their becoming obsoleted by changes in reactor design and licensing requirements.

The following statements summarize the characteristics, advantages and limitations of the three TUC-responsive systems.

SYSTEM M

This is the simplest design and simplicity is a preferred feature for any safety device. The main drawback is that it leads to either reactor operation at one flow rate, or a slow response. An improvement in the response time is obtained by decreasing the hydraulic upthrust against the assembly seat, but this increases the probability of rod insertion due to flow induced vibrations and mechanical shocks, including minor earthquakes, resulting in inadvertent shutdown of the reactor. The piston arrangement, shown as an alternative to the spherical seal, improves its resistance to these vibrations but introduces a moving part which may reduce reliability.

SYSTEM VO

Once the variable orifice has been correctly set by the operator, this device assumes something of the simplicity of System M. However, without the presence of a reliable engineered or procedural safeguard, there is some risk that the variable orifice could be adjusted for too high a pressure drop, either inadvertently, or as a deliberate override action. This would result in a delayed release, the possibility of which could reduce the licensing credit assigned to the SASS to that of a System M shutdown system. Although redundancy of the SASS units may satisfy licensing requirements regarding accidental maladjustment, it is felt that the vulnerability of this system to temporary abuse, in the interest of operational expediency, may render it unacceptable. The simple dead weight over-pressure valve is one solution to this problem, but, as is generally true of failsafe features, it increased the probability of unnecessary shutdown.

Periodic testing of the SASS equipment is further complicated, and may be of increased frequency, due to the need for calibration of the variable orifice before any change in operating power level. The CRDM and CRD require additional components to perform the adjustments.

The problem of vibration sensitivity is the same as for System M. An alternative to the plug and socket seal is the pilot piston approach. Again complexity may be reduced at the expense of response time.

SYSTEM MM

This is the fastest of all three systems and is capable of maintaining a high response speed throughout the operating flow range of the reactor. The large upthrust margin prevents spurious tripping caused by flow induced vibrations, mechanical shocks and low level earthquakes. Also, the accumulator bellows, in conjunction with the flow limiting orifice, quickly discriminates between spurious pressure pulses and incipient coastdown.

However, there have been questions raised about the reliability of the bellows, in spite of the large margin of conservatism in their design. An attempt has been made to address these concerns, based upon sodium system experience with bellows (see Appendix C.2). The possibility that a bellows-less version of System MM might be devised, as suggested by Mr. E. Hutter of ANL, was pursued, with the result shown in Figure 3-23. This design may exchange the possibility of minor bellows leaks, which have little effect on performance, with that of piston jamming, due to particulate sodium impurities.

Another concern was that the system of orifices might involve some delicate tuning. A plexiglas working model was later built during this program, using pieces of flexible plastic hose and other scrap materials. This leaky assemblage, having fairly rough orifices and valves, performed very consistently, as witnessed by one design review meeting.

It should also be noted that, whereas the response time of Systems M and VO is, in common with the core coolant temperatures, closely tied to the primary coolant system coastdown curve, the System MM RCP feature provides considerable stretch capability from the nominal performance values used in this study. In this way, it would be possible to avoid a potential design trap with flow responsive devices, whereby the use of a slower coastdown rate to obtain lower transient temperatures is accompanied by a correspondingly slower SASS response.

A further benefit of System MM is that in-situ testing of the device can be performed at a fractional flow rate and thus the overall testing time shortened.

COMMON ADVANTAGES RELATIVE TO LEVITATED BALL CONCEPTS

Each device satisfies the requirement for inherent shutdown under loss of flow. The use of a high worth conventional poison geometry (rod bundle) simplifies the detection of incomplete insertion or withdrawal. Activation of the CRD and the use of a feeler rod at the gripper, locates the top of the poison element and thus the whole of it. Reactivity measurements provide further evidence of satisfactory operation.

In comparison with levitated ball concepts, the hydraulic release mechanisms described in the report are inherently superior in response time (Systems MM and VO are an order of magnitude faster), poison worth and poison accountability. Levitated balls tend to release progressively as the flow is reduced so that a significant time elapses between insertion of the first and last balls. The localized pressure drop in the rod bundle concepts produces a much lower excess pressure effect and thus a more sharply defined (shorter duration) release point. The higher drag force on the balls after release, relative to the rod bundle, can be used to aid insertion by a flow reversing mechanism, but such an elaboration can also be incorporated into a rod bundle system. The progressive release effect becomes worse with increased bed depth, which tends to reduce the total quantity of poison to some fraction of that possible with a conventional control assembly. Since the balls are not physically connected, there is no way of checking that every ball has been levitated, of comparable simplicity to the feeler rod approach. Other questions might be raised on the fabricability and durability (abrasion) of the ball system which could disperse neutron absorber, including long-lived radioactive species, into the coolant.

The main advantage of the levitated ball concepts is that, in the absence of significant upward drag forces, they obviously offer a greater probability of inserting poison through a grossly distorted control assembly duct. Less obvious is the manner in which such gross deformation could develop without events precursive to a CDA, the initiation of which the SASS is designed to prevent. The philosophy adopted in this study is that the decreased probability of fuel damage provided by a fast-acting SASS obviates the need to consider severe duct distortion. However, a conservative allowance for bowing and lateral dimensional changes due to the combined effects of irradiation swelling, creep, differential expansion, pressure and lateral restraint was made, based upon CRBR specifications, to ensure adequate clearance for unobstructed insertion. To cover the possibility that some larger deformation might be postulated in the future, a brief study was made of alternative rod bundle geometries. These are reviewed in Appendix E .

Section 6

CONCLUSIONS AND RECOMMENDATIONS

TOP/TUC Response vs. TUC Response, Only

It is recommended that flow responsive rather than temperature (power/flow) responsive SASS designs be pursued because:

- Addition of overpower protection capability to the SASS design by making it responsive to high temperature (as typified by System A) increases costs, increases complexity, reduces reactivity worth and reduces response time relative to flow responsive devices.
- SASS overpower protection is only marginally useful in improving licensing because the unprotected overpower transient leads to much less severe consequences than loss-of-flow and because severe overpower accidents are less probable than loss-of-flow accidents.

Fast Response vs. Slow Response

It is recommended that future SASS development be confined to fast-acting devices because:

- The order of magnitude faster release times ($\sim$1 second vs. $\sim$10 seconds) of System MM and System VO place them in a different class from System M and the levitated ball concepts.
- The slower devices are expected to have a substantially smaller impact on the excessive licensing conservatism described in the Introduction.
- These design studies have demonstrated that fast-acting devices can be designed with high reliability. It is, therefore, recommended that future SASS development be focussed upon short release time systems.

Selection of SASS Concept

In view of the foregoing and the following comparison of the two rapid release concepts considered in this study, it is recommended that System MM be selected for further development and that System VO be regarded as an acceptable backup concept:

- Both systems (MM and VO) can be developed to perform the desired safety functions with substantially equivalent performance and reliability. To achieve this high level of safety-function reliability, System VO requires the relief valve or an equivalent feature.
- System MM is substantially superior to System VO with respect to operational reliability and reactor availability. To achieve adequate functional performance and reliability, System VO must be relatively complex mechanically and requires a relatively complex procedure for calibration, functional testing and power changes.

Section 7

SUPPORT PROGRAM PLAN

Major uncertainties as to the feasibility and performance in the proposed designs remain which could be resolved through a limited testing program as described below. The scope and goals of this program is summarized below:

HYDRAULIC SUPPORT PERFORMANCE

The fabrication and testing of the spherical seal in a water loop should provide sufficient data to identify any problems in obtaining a low leakage seal, self alignment, rod support and release.

SYSTEM MM

The principle of the RCP actuation of the rod release will have to be demonstrated through a water test loop. The poppet valve assembly should also be testing to ensure proper seating and low leakage. The response time characteristics as a function of initial conditions should also be verified.

During the course of the present program, a working model of the RCP device was constructed and demonstrated at the design review meeting. Although, made from scrap materials, including odd pieces of plastic bellows, the model sucessfully demonstrated both the hydraulic support and RCP effect in releasing a mock poison assembly under a simulated flow coastdown.

TEST PROGRAM

The test program for the proof-of-principle of the selected SASS can be divided into four tasks. These consist of:

Task 1: Verification of performance of the control rod release device through water tests.

Task 2: Verification of rod drop time for simple and special design poison arrangements to accommodate design basis and hypothetical distortions of the duct through water tests.

Task 3: Interpretation and application of test results for reactor conditions.

Task 4: In-sodium testing of the assembly.

Task 1

This test is proposed for the verification of the performance of the control assembly release device. A full scale mock-up of the control assembly using an existing C-E water test loop (TF-3) is proposed for the test to limit the cost of the test as well as permit verification at an early date. The TF-3 test loop is a 400 GPM, 200 psi loop incorporating a 12 ft. vertical section of 6" diameter pipe. With minor modifications and necessary instrumentation, a full scale mockup of the poison assembly can be easily accommodated in the test loop.

Specifically, this test will consist of the following:

a. Proof-of-principle of SASS hardware
b. Simulation of loss of flow events
c. Verification of the speed of response of the rod release mechanism
d. Verification of the operating range of the mechanism, variation of response time with the initial operating conditions
e. Verification of misalignment accommodation
f. Verification of discrimination against reactor design variations of pressure and flow rate (spurious trip prevention)
g. Confirmation of size and orientation of key components
h. Verification of uncertainties in effective seat diameter, holding pressures, flow rates, trip points, and operating range.
i. Verification of hydrodynamic instability and its effect on rod support, trip point and operating parameters
j. Verification of pressure drop apportionment necessary for acceptable performance

Task 2

Task 2 of the test program consists of simulation of distorted ducts including the design basis deformation, based on extrapolation of CRBRP data, and hypothetical deformation of the duct and poison bundle. The test should consist of:

a. Verification of rod drop time for the simple rod assembly for four geometries of deformation of duct.
b. Verification of two special designs of poison assembly for the same four geometries of duct deformation. The special designs should reflect improvement in the insertion time.

Task 3

The test results and their application to reactor conditions will be evaluated. In particular, the test results will be correlated to the operating range of reactor condition, e.g., temperature, sodium environment, normal pressure and flow rates. Some feedback to the test procedures and hardware is expected from this activity; however, the principal benefit will be concrete improvements to the SASS design, to its predicted performance under reactor conditions, and to the certainty of such predictions.

Task 4

A full scale mock-up in high temperature (~538°C) flowing sodium is desirable to ascertain any potential problems in critical areas, e.g., the hydraulic seal, performance of special valves used, the bellows and sleeve piston arrangement. A 1000 to 2000 scrams over a period of 3 to 6 months testing should provide enough data to form the basis of improvements or modifications in the design and to simulate reactor conditions. This testing could be performed in the C-E sodium loop with capability of 593°C (1100°F) sodium.

Section 8

REFERENCES

1. Letter, B.R. Sehgal to V. Loiselle, RFP 4494, "A Self Actuated Shutdown System for a Commercial Size LMFBR," Patent Disclosure, June 30, 1976.

2. Letter, B.R. Sehgal to R.C. Noyes, RP 897-1, "Self Actuated Shutdown System for a Commercial Size LMFBR," Patent Disclosure, March 3, 1976.

3. Letter, C.D. Felten (AI) to C. Dupen (C-E), "Control Rod Worth," 77AT-6148, dated July 21, 1977.

Appendix A

SELF ACTUATED SHUTDOWN SYSTEM DESIGN CRITERIA

Design criteria for the mechanical bulb/bellows delatch (System A) Self Actuated Shutdown System (SASS) and the hydraulic (System MM) SASS development effort have been established. These criteria summarize the specifications presented in (a) EPRI RFP 4494, (b) C-E's proposal to EPRI dated June 15, 1976, (c) C-E/EPRI 9/31/76 meeting agreements and commitments (revised proposal mailed 9/2/76), and (d) EPRI's idea disclosure for a hydraulic SASS. Where criteria differ for each of the two SASS concepts under development, they are separately presented.

1a) Trip Signal (Bulb/Bellows Only)

The system shall trip on a temperature rise of 30 ±8°C (55 ±15°F) of coolant heated by sensor fuel pins with an enrichment which will result in a flat power history over a full cycle, thus being representative of the average core outlet temperature.

1b) Trip Signal (Hydraulic Only)

The system shall trip on a rate of change of pressure $(d(\frac{P}{Po})/dt)$ exceeding -2.6 psi/second and, as a backup, on absolute low flow at 35% flow point.

1c) Trip Signal (Both Systems)

Provision shall be made for an externally actuated trip through the Plant Protection System (PPS). Design provisions will be made for an actuating mechanism which will not impede self actuation subsequent to a lateral displacement of the core with respect to the head structure.

2a) Response Time (Bulb/Bellows Only)

The system response time shall not be more than 0.5 seconds for poison release and a further 1.5 seconds for full insertion after the trip signal limit is exceeded.

2b) Response Time (Hydraulic Only)

The system response time shall not exceed 0.5 seconds for poison release and a further 1.5 seconds for full negative reactivity insertion to occur from the time at which flow coastdown has begun. Assuming failure of the rate of change protection, the response time for the low absolute pressure trip will be approximately eight seconds from an initial 100% flow event for the coastdown specified in Table 1.

3) Reactivity Worth

Reactivity worth shall be maximized within practical limits by utilizing as much of the absorber assembly cross-sectional area as possible and use of B_4C rods enriched in B_{10}.

4) Common Mode Failure

Functioning of the SASS in a self actuating mode of operation shall not be affected by movement of the top head of the primary vessel relative to the core. The design of the PPS trip and reset mechanisms shall not compromise this requirement.

5) Environmental Conditions

Operation of the system shall not be affected by the thermal, hydraulic and irradiation environment specified in Table 1, up to the maximum specified peak damage fluence limit of 2.5×10^{23} nvt at the midcore position. The design shall minimize the possibility of spurious trips due to phenomena such as structural distortion or flow induced vibration.

TABLE A-1

Design Parameters

Parameter	GE	W	AI	Assume* for C-E SASS
Reactor M. Mean Outlet Temp. Operating $^oC(^oF)$	468(875)	498(928)	499(930)	499(930)
Design $^oC(^oF)$	482(900)	510(950)	510(950)	510(950)
Reactor ΔT $^oC(^oF)$	167(300)	154(278)	155(280)	155(280)
Reactor Inlet Temp. $^oC(^oF)$	302(575)	343(650)	343(650)	343(650)
Inlet Plenum Press. MPa(psi)	.91(132)	.896(130)	1.0(145)	.896(130)
Driver Region Length m(in.)	1.22(48)	1.22(48)	1.17(46)	1.22(48)
Upper Axial Blanket Length m(in.)	.35(14)	.35(14)	.35(14)	.35(14)
Lower Axial Blanket Length, m(in.)	.35(14)	.35(14)	.43(17)	.35(14)
Fission Gas Plenum Loc/Lgth, m(in.)	TOP/1.9(75)	T&B/?	T&B/?	T&B
Overall Assembly Height, m(in.)	5.71(225)	4.80(189)	5.18(204)	5.0(197)
Assy. O.D. Across Flats, cm(in.)	13.8(5.43)	16.1(6.36)	15.3(6.034)	(6.197)
Assy. I.D. Across Flats, cm(in.)	13.4(5.26)	15.2(6.00)	14.8(5.814)	15.0(5.907)
Assy. Duct Thickness, mm(in.)	2.16(.085)	4.6(.180)	2.8(.110)	3.7(.145)
Assy. Pitch cm(in.)	14.8(5.81)	17.1(6.72)	15.8(6.234)	16.45(6.447
Peak Damage Disch. Fluence E>.1 Mev, nvtx10^{-23} (for Burnup 98-110,000 Mwd/MT)	2.5	2.5	2.5	2.5
Fuel Pin O.D., mm(in.) (All Oxide)	6.5(.256)	-	∿7.6(∿.30)	8.12(.320)
Operating Flow Range, %				40-100
Hydraulic Rate of Change Trip KPa/sec (psi/sec)				≥10.3(1.5)
Range of Protection, %				40 -100
Absolute Pressure Trip, %				35
Flow Coastdown Time Constant, sec.				7.3
NaK Bulb Upper Trip Level, $^oC(^oF)$				535(995)
Tolerance ±$^oC(^oF)$				8.3(15)
NaK Bulb Lower Trip Level, $^oC(^oF)$				288(550)
Orifice Velocity Limit m/sec (ft/sec)				15(49.2)

6) Assembly Size

The system shall be sized so as to be compatible with the EPRI specified fuel assembly dimensions given in Table 1.

7) Instrumentation

The instrumentation required to determine the position of the control rod cluster during reactor operation, shutdown and performance verification testing shall be specified.

8a) Testability (Bulb/bellows only)

The system shall be testable by some means of heated sodium and by a reduction in the core outlet temperature following shutdown. The high and low trip settings are specified in Table 1 for System A.

The system shall also be testable in part through action of the Plant Protection System which will mechanically delatch the holding arms, initiating gravity insertion of the rod cluster. Interfacing equipment essental for conducting in-situ tests shall be defined.

8b) Testability (Hydraulic only)

The system shall be testable by a flow coastdown or by reduction of the reactor coolant flowrate to less than 35% of full flow. The system shall respond to the resulting rate of change of pressure (between 2.6-35 psi/sec) based upon the plenum pressure and coastdown parameters presented in Table 1 and agreed upon by EPRI.

The system shall also be testable in part through action of the Plant Protection System which will mechanically force the piston off its seat and initiate a gravity assisted scram. Interfacing equipment essential for conducting in-situ tests shall be defined.

9) Resettability

The system shall be resettable in place. Interfacing equipment essential for resetting the system shall be defined.

10) Reliability

The reliability of the system shall be demonstrated by the use of components proven to have shown satisfactory performance in the high temperature sodium and high flux environment. The environmental conditions are listed in Table 1. Where there is no previous experience available, a scale model test in water or sodium may be recommended to verify the principle and function of the device and to accumulate reliability data.

11) Compatibility

The system should not limit the capabilities of normal reactor operation, including startup, shutdown, partial power and normal load variation.

12) System Impact on the Reactor

The self actuated shutdown system shall have minimum impact on the thermal-hydraulic and nuclear performance of the reactor. Any impact on the breeding gain, flux map, temperature distribution, fissile inventory and burnup shall be kept to a minimum.

13) Replaceability

The system components shall be replaceable during reactor shutdown for fuel handling and/or for other outages. The replacement time required for the self actuated shutdown assembly shall not significantly increase the total downtime required for refueling.

14) Fail Safe

The system shall be designed in such a way as to maximize the fail safe probability. An FMEA* shall be performed to determine the potential modes of failure.

*Failure Mode and Effects Analysis

15) <u>Orifice Limitation</u>

Sodium velocity through orifices shall not exceen 15 m/sec (∿50 ft/sec).

16) <u>Anti-Jam Requirements</u>

Protection against the various potential modes of jamming such as duct bowing, rotation and jamming of inner hexagonal shroud, latch friction, etc., shall be provided by use of appropriate design clearance and friction factors.

Appendix B

B.1 Design Calculations

A trip pressure of 62 kPa (9psi) was established for the poison assembly weighing approximately 87.2 kg (200 lb.) and having a seat area of .0143 m (22.2 in.^{2}) at the hydraulic seal. A normal operating pressure of 82.7 kPa (12 psi), therefore, includes a flow rate change of 2.5% (∿20.3 kPa) and a possible offset of one orifice (∿10.3 kPa). The response time of the system is approximately 1.0 seconds. The response time can be reduced to approximately 0.5 second if the allowance for orifice offset is deleted.

The number of orifices required to be open for satisfactory incremental settings at differenct flow rates was determined for a constant seal differential pressure of 82.7 kPa (12 psi) by the following derivations.

Let:

- P = plenum pressure, kPa (psi)
- P_o = plenum pressure at full flow, kPa (psi)
- W = flow rate, kg/sec (lb/hr)
- X = fraction of full flow
- K_1 = assembly inlet flow resistance
- P_a = seal pressure drop, kPa (psi)
- D = diameter of orifices in sleave, mm (inch)
- n = number of orifices
- c = orifice flow, coefficient
- d = density of sodium, g/cm^3 (lb/ft^3)
- K_2 = orifice flow resistance

Since the seal pressure drop is to be kept constant, the assembly inlet pressure drop varies as follows:

$$(P - P_a) = K_1 W^2 \quad (1)$$

and $$P = X^2 P_o \quad (2)$$

Therefore, $$W = K_1^{-0.5} (P - P_a)^{0.5} \quad (3)$$

by substituting (2) in (3) we get,

$$W = k_1^{-0.5} \ (X^2 P_o - P_a)^{0.5} \quad (4)$$

The flow through the orifices can be represented by

$$W = k_2 \ C \ n \ (D)^2 \ (P)^{0.5} \ (P_a)^{0.5} \quad (5)$$

therefore,

$$n = \frac{W}{k_2 \ C \ D^2 \ d^{0.5} \ P_a^{0.5}} \quad (6)$$

Substituting the value of W from equation (4), equation (6) becomes

$$n = \frac{k_1^{-0.5} (X^2 P_0 - P_a)^{0.5}}{k_2 C \ D^2 \ d^{0.5} \ (P_a)^{0.5}} \quad (7)$$

By substituting the values of the known parameters, the number of orifices required to be open at each flow condition can be calculated. The number of orifices and the variation of the seal differential pressure are tabulated in Table B-1 for the flow range of 40% to 100%. The response characteristics of the system are plotted in Figure B-1.

Table B.1

FLOW RATE %	NUMBER OF ORIFICES-OPEN	INLET PLENUM PRESSURE kPa (psi)	SEAL DIFFERENTIAL PRESSURE VARIATIONS kPa (psi)
100	17	896 (130)	82.7 ± 4.2 (12 ± 0.61)
95	16	807 (117)	± 4.4 (.64)
90	15	724 (105)	± 4.6 (.67)
85	14	648 (94)	± 4.9 (.72)
80	13	572 (83)	± 5.2 (.76)
75	12	503 (73)	± 5.6 (.82)
70	11	441 (64)	± 6.0 (.87)
65	10	379 (55)	± 6.5 (.95)
60	9	324 (47)	± 7.0 (1.02)
55	8	267 (39)	± 7.7 (1.12)
50	7	221 (32)	± 8.5 (1.23)
45	6	179 (26)	± 9.5 (1.38)
40	5	145 (21)	± 10.6 (1.54)

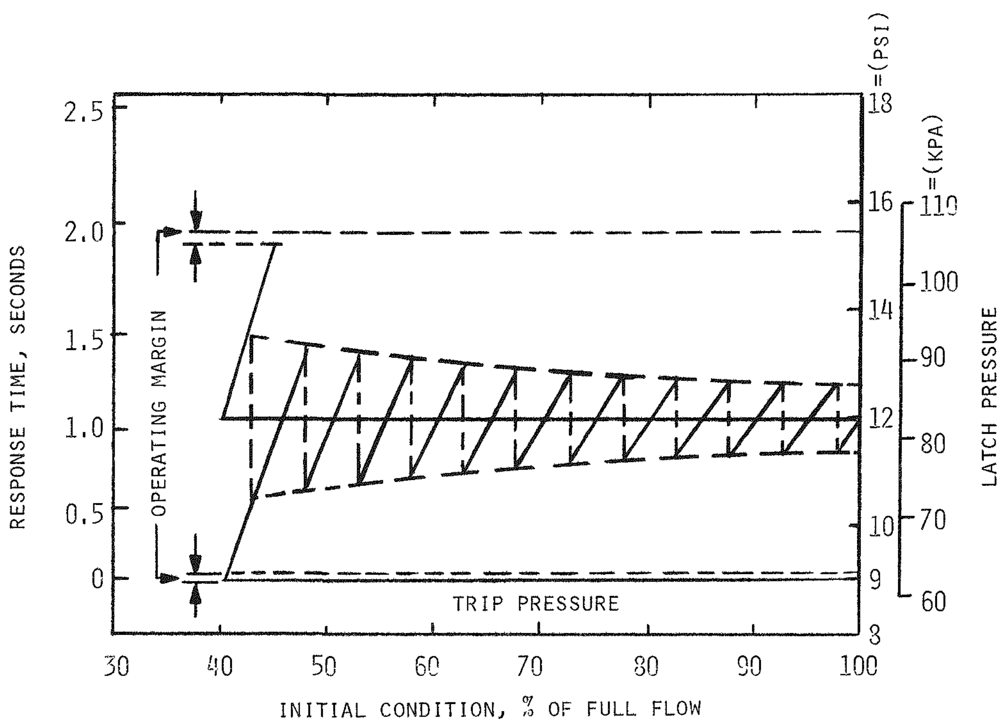


FIGURE B-1 SYSTEM VO 12 STEP RESPONSE CHARACTERISTIC

B.2 System VO Reliability

The reliability questions for System VO may be categorized as follows:

A) Reliability of equipment to release, if correctly adjusted

B) Reliability of equipment to avoid spurious trips

C) Reliability of either, operator and manual adjustment and operator's ability to notice any malfunction of it.

These questions have different answers depending upon which of the versions of System VO is under discussion. In fact, the successive modifications to the basic concept were introduced either for faster performance (reliability to avert a CDA), improved reliability to scram, or improved resistance to spurious trips. Due to the novelty of the equipment, no absolute assertions of reliability can be made without extensive testing. However, it may be useful to prepare a list of concerns for future investigation. These are as follows:

1. The piston features, incorporated for vertical mechanical shock resistance, may not produce the same breakaway reliability as the spherical seat design, due to solid impurities lodging in the piston clearance.

2. The deadweight pressure relief valve, introduced as an engineered safeguard against variable orifice setting error, may either be susceptible to leakage or jamming. Careful control of geometry and the use of hardfaced seals should cover these problems.

3. The variable orifice plug detent spring may fail. This could be made fail-safe by designing the plug to open upon spring failure and thus lower the pressure below the rod support valve.

4. Questions of the reliability of the orifice adjusting equipment to perform automatically or provide accurate feedback to the operator of the SASS behavior.

B.3 Alternate VO Flow Control Valve

As an alternate to the control sleeve arrangement, an arrangement based on the EBR-II INCOT shuttertype valve is used to control the flow and the pressure drop of the control assembly.

The valve consists of an upper valve face, an orifice cup assembly, a compression spring, a limit stop pin and a lower valve face. Each valve face has a 120° cutout; the upper face, which is piloted into the lower face, is rotated to regulate the sodium flow. The valve has Colmonoy-5 facing to avoid self welding. The stop pin entending from the upper half is positioned in a slot in the lower half to limit the rotation.

The orifice cups assembly contains orificing holes to allow a minimum flow with the valve fully closed. The flow control valve assembly is oriented and welded into the upper end of the control rod. The compression spring exerts a downward force on the upper section pressing the faces of the control valve together. The assembly is locked into position where it can be rotated 120° by the valve drive.

Since the CRDM normally actuates the mechanism in an axial or telescoping motion, a separate tube, with rotary motion, must be incorporated to oscillate the upper face of the valve withing a 120° span. The valve drive concept, as illustrated in Figure B-2 was developed based on the EBR-II INCOT drive.

A spanner tube is rotated through a bevel gear and pinion whose torque is induced by an outside drive through a nutating bellows and O-ring seals. The scaling system prevents the pressurized pressure gas from escaping into the atmosphere.

The upper portion of the spanner tube is provided with a splined section whereby the control rod drive (CRD) can telescope it upwards during refuelling or control rod replacement. A compression spring between the CRD and the spanner tube maintains pressure to ensure a constant engagement into the flow control sleeve.

The pinion and bevel gear drive located at the bottom of the cover head nozzle imposes a horizontal motion on the spanner tube through an internal sliding spline without affecting the axial motion of the mechanism. The pinion-bevel gear assembly is rotated by an hermetically sealed rotating drive whose torque is obtained from a separate drive introduced through the side of the cover head nozzle.

The spanner tube drive coupling is free to rotate within a sealed cover mounted at the end of the drive housing. The bellows welded at the bottom of the cover is also attached to a yoke, which imposes a radial force on the pinion eccentric plate. As the bellows maintain the sealing integrity, the yoke's rounded end slides within the eccentric; forcing the pinion and bevel gear to rotate in the desired direction.

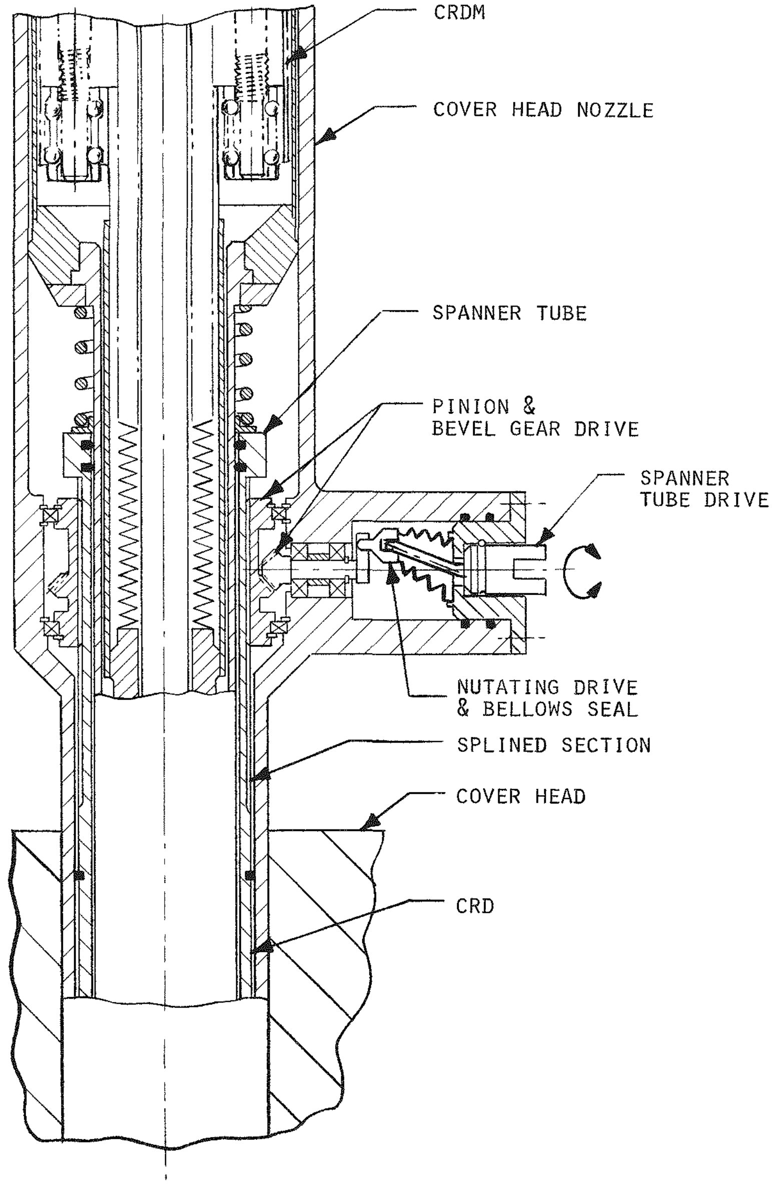


FIGURE B-2 CONTROL VALVE DRIVE

The drive coupling may be connected to various types of drivers capable of being monitored from the operating deck.

The objective of the independent SASS drive is to control the coolant flow rate through the self actuated control rod, in relation to the reactor power level during the reactor operation, without the imposition of any restriction or interference on the CRDM functioanl capabilities.

The separate system allows the operator to modulate the variable orifices for a fast response for the inherent protection against faulted conditions.

The parameters of the shutter valve were calculated to obtain the maximum variation of cycle of rotation vs. the projected power level range. The shutter valve has a 1/8" slot and is 3" long. A 110° to 15° angle change for the shutter valve opening corresponds to a power/flow change from 100% to 40%. The response characteristics of the shutter valve concept are shown in Figure B-3.

The uncertainties in the angular position of the valve result in an error band in the SASS response time as well as the pressure settings at each power level. These uncertainties which are due to distortion and gear slack, were evaluated and were found to be in the range 2° to 4°. A 4° error in angular displacement results in approximately 4% offset in the power level setting in the lower end of the reactor flow rate. At higher flow rate this spead is reduced, reaching approximately 2% at full flow.

With a 12 orifice step system, the uncertainty band results in a 5% offset in the setting. The improvement due to the introduction of the shutter valve is, therefore, marginal. Also the advantage of discrete steps to aid calibration and testing in the orifice step system must be sacrificed.

The alternate System VO which incorporates the shutter valve concept is shown in Figure B-4.

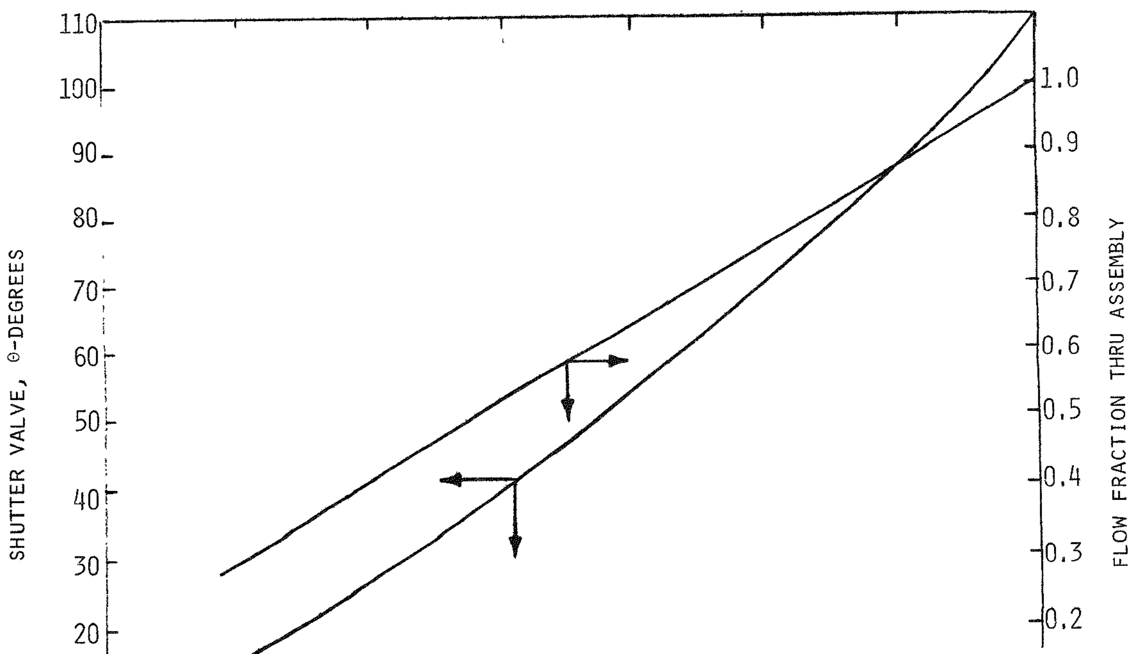
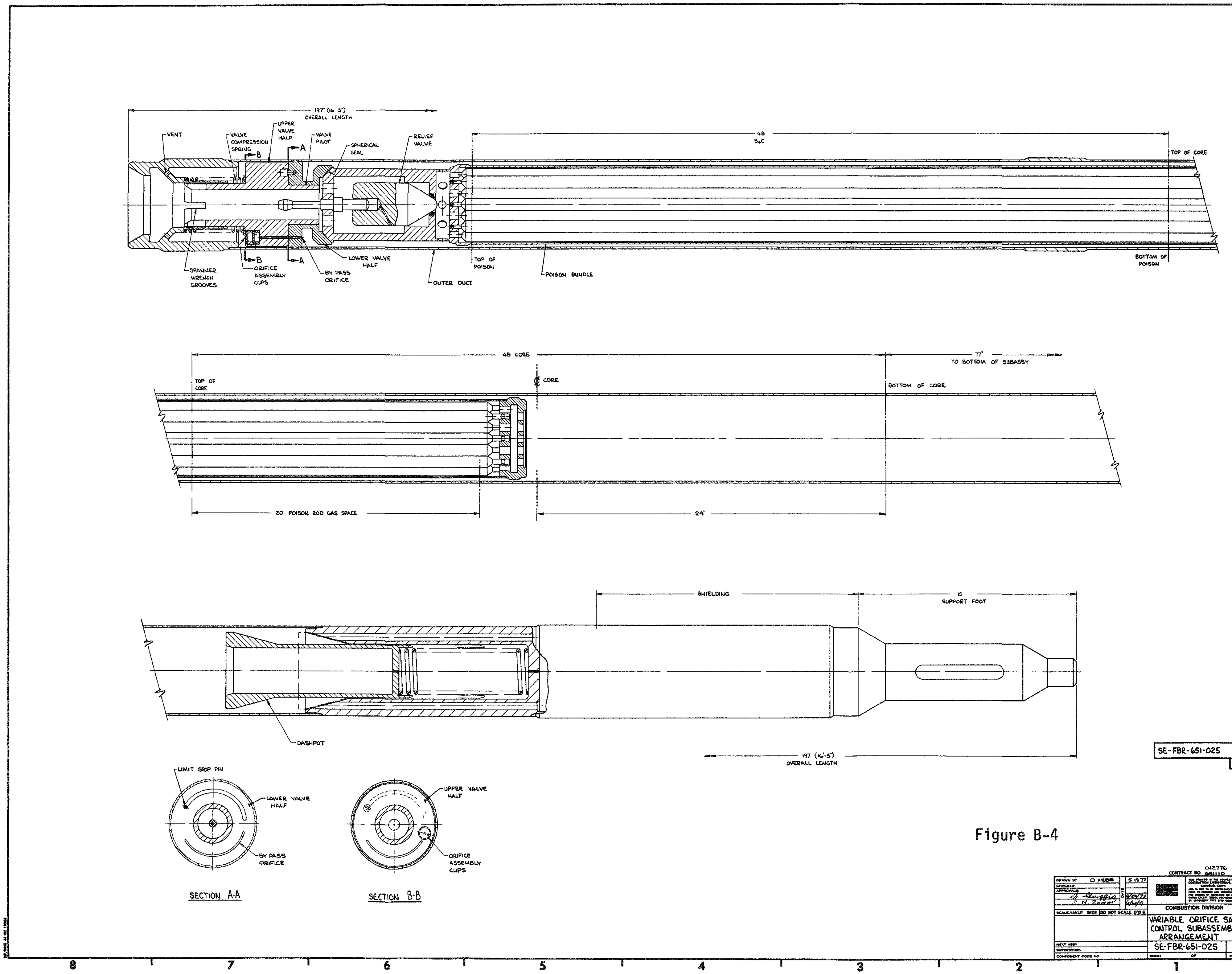
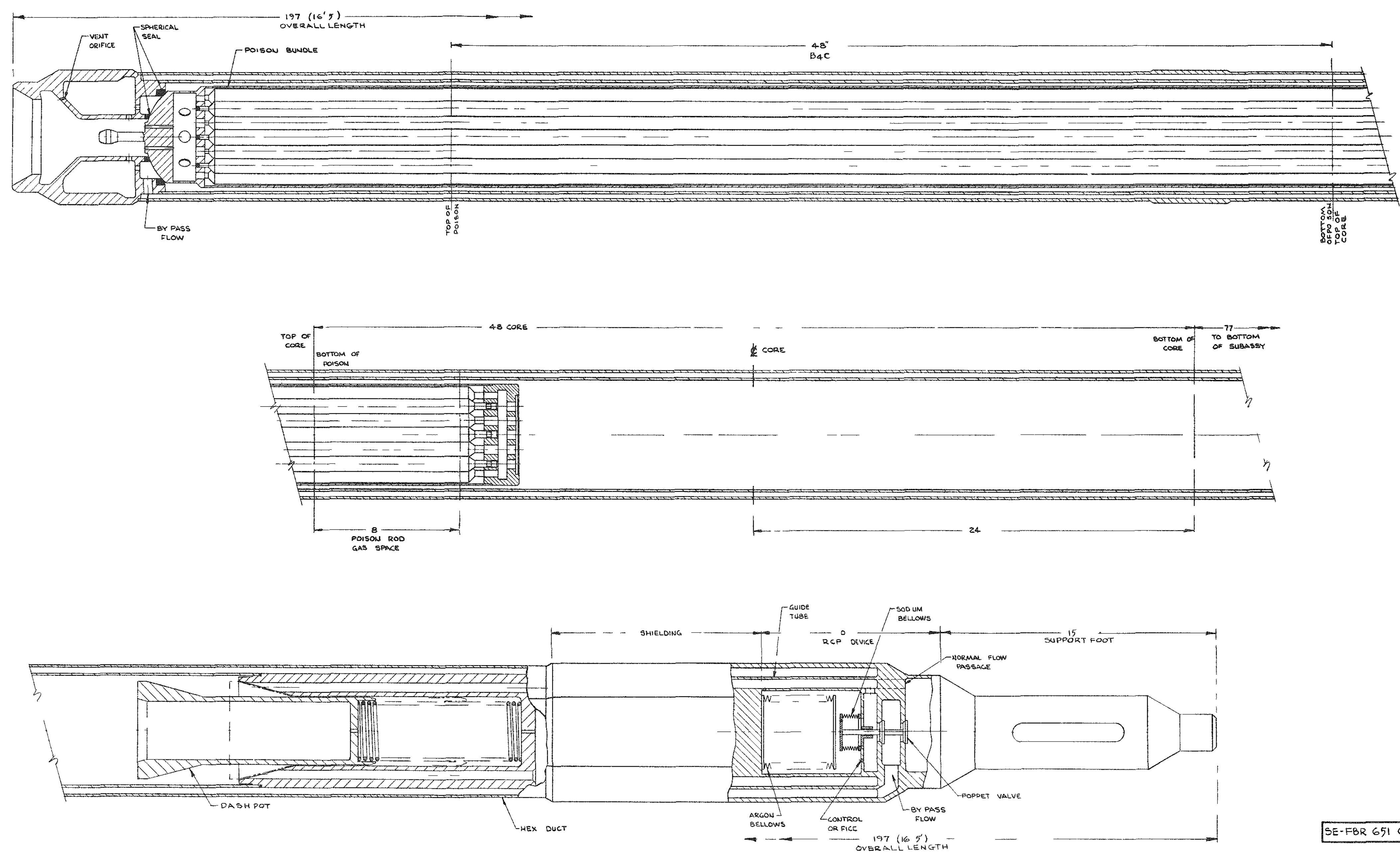


FIGURE B-5 VARIATION OF FLOW WITH VARIATION OF SHUTTER VALVE POSITION



197" (16'-5") OVERALL LENGTH
VENT
VALVE COMPRESSION SPRING
UPPER VALVE HALF
VALVE PILOT
SPHERICAL SEAL
RELIEF VALVE
48 B₄C
TOP OF CORE
SPANNER WRENCH GROOVES
ORIFICE ASSEMBLY CUPS
BY PASS ORIFICE
LOWER VALVE HALF
OUTER DUCT
TOP OF POISON
POISON BUNDLE
BOTTOM OF POISON
48 CORE
77" TO BOTTOM OF SUBASSY
TOP OF CORE
CORE
BOTTOM OF CORE
20 POISON ROD GAS SPACE
24"
SHIELDING
15 SUPPORT FOOT
DASHPOT
197 (16'-5") OVERALL LENGTH
SE-FBR-651-025
LIMIT STOP PIN
LOWER VALVE HALF
BY PASS ORIFICE
UPPER VALVE HALF
ORIFICE ASSEMBLY CUPS
SECTION A-A
SECTION B-B
CONTRACT NO. 651110
COMBUSTION DIVISION
VARIABLE ORIFICE SASS CONTROL SUBASSEMBLY ARRANGEMENT
SE-FBR-651-025

Figure B-4



SE-FBR 651 023

INLET RCP **(SYSTEM MM)**
LOSS OF FLOW
SELF ACTUATING SHUTDOWN SYSTEM

CONTRACT NO 651110 012776

REV	DESCRIPTION	S & DATE	CHK & DATE	ENG APPD	PRO APPD

DRAWN BY	D WEBB	4 25 77
CHECKER		
APPROVALS		
	S H ZAMAN	6/22/77
	[illegible]	6/22/77
SCALE HALF SIZE	DO NOT SCALE DWG.	
NEXT ASSY		
SUPERSEDES		
COMPONENT CODE NO		

COMBUSTION DIVISION

SASS
LOSS OF FLOW
CONTROL SUB ASSY
ARRANGEMENT

SE-FBR 651 023

SHEET OF REV

DNA

Appendix C

SYSTEM MM DESIGN

C.1 RCP Response Time Calculations

The response time of the rate of change of pressure (RCP) device is the time elapsed between the start of the TUC event and the delatch of the poison assembly. The assembly delatch occurs when the differential pressure across the hydraulic latch is reduced to a level that hydraulic differential pressure is insufficient to support the assembly. A poppet valve is used to activate a decrease in the hydraulic differential pressure.

The flow coastdown due to the pump trip can be represented by the following equation for the first few seconds (neglecting the effects of natural circulation)

$$W = \frac{W_o}{1 + \lambda t} \qquad (1)$$

W = flow rate at time t after the initiation of coast down

W_o = initial flow rate

λ = decay constant

t = time elapsed after the initiation of coast down

The sodium pressure variation with respect to the time can be derived from the following equation

$$P = KW^2 \quad , \quad P_o = KW_o^2$$

$$P = K\left(\frac{W_o}{1 + \lambda t}\right)^2$$

$$\simeq KW_o^2 \ (1 - 2\lambda t)$$

for $t \leq 1$ sec

Sodium pressure outside the sodium chamber can, therefore, be represented by

$$P = P_o(1 - 2\lambda t) \qquad (2)$$

The sodium pressure inside the sodium chamber is, therefore,

$$P_s = P + \frac{K_2\ \chi}{A} + \frac{F}{A}$$

or

$$P_s - P = \frac{K_2\ \chi}{A} + \frac{F}{A}$$

where K_2 = spring rate of sodium bellows,

χ = stroke of the poppet valve

F = preset on poppet valve

A = effective area of sodium bellows

The ΔP or $(P_s - P)$ is the ΔP which is normally applied against the sodium bellows to effect movement of poppet valve.

The sodium pressure within the sodium chamber is a function of the argon gas pressure and the spring constant of the argon bellows. The bellows are under compression during the entire operating range.

$$P_s = P_g + \frac{K_3\ T}{A_3} \qquad (4)$$

where

P_g = gas pressure

T = compression stroke of argon bellows

K_3 = spring rate argon bellows

A_3 = effective area of argon bellows

The time response of the rate of change of pressure device can be calculated from an equation based on mass balance.

i.e.

Volume change in the sodium chamber

= Volume expelled from the chamber

† volume increase due to movement of sodium bellows (4A)

The volume change in the sodium chamber could be ascribed to the expansion of argon bellows. According to Boyle's law

$$(P_{go} + P_a)V_o = (P_g + P_a)V$$

where $P_g + P_a$ = Gas pressure (absolute)

P_a = pressure due to sodium head and cover gas pressure

$$V - V_o = V_o\left(\frac{P_{go} + P_a}{P_g + P_a} - 1\right)$$

$$= V_o\left(\frac{P_{go} - P_g}{P_g + P_a}\right) \qquad (5)$$

From Equation 4

$$P_{go} = P_{so} - \frac{K_3 T}{A_3}$$

$$P_g = P_s - \frac{K_3\ T(t)}{A_3}$$

$$P_{go} - P_g = P_{so} - P_s - \frac{K_3}{A_3}\ (T - T(t))$$

and

$$P_g + P_a = P_s + P_a - \frac{K_3\ T(t)}{A_3}$$

for $t \to 0$

$T(t) \to T$

$$P_{go} - P_g = P_{so} - P_s \tag{6}$$

and

$$P_g + P_a = P_s + P_a - \frac{K_3 T}{A_2} \tag{7}$$

Substituting the equations 6 and 7 in 5, we get

$$V - V_o - V_o \left(\frac{(P_{so} - P_s)}{P_s + P_a - \frac{K_3 T}{A_3}} \right)$$

$$P_{so} = P_0$$

$$V - V_o = V_o \left(\frac{P_o - P_s}{P_s + P_a - \frac{K_3 T}{A_3}} \right) \tag{8}$$

The equation 8 represents the volume change due to the expansion of argon bellows

From equation 3

$$P_s = P + \frac{K_2 \chi + F}{A}$$

and from equation 2

$$P = P_o \ (1 - 2\lambda t)$$

$$V - V_o = V_o \frac{P_o - P_o(1 - 2\lambda t) - \frac{F + K_2 \chi}{A}}{P_o(1 - 2\lambda t) + \frac{F + K_2 \chi}{A} + P_a - \frac{K_3 T}{A_3}}$$

$$V - V_o = \frac{2\lambda t\, P_o V_o - \frac{F + K_2\chi}{A} V_o}{P_o + P_a - 2\lambda t P_o + \frac{F + K_2\chi}{A} - \frac{K_3 T}{A_3}} \tag{9}$$

The sodium expelled through the orifice in the chamber can be expressed by

$$\text{volume of sodium expelled} = K_1 \int_0^t (P_s - P)^{1/2} dt \tag{10}$$

where

$$P = P_o(1 - 2\lambda t)$$

$$P_s = P_o(1 - \alpha t)$$

$$P_s - P = P_o(2\lambda - \alpha)\ t \tag{11}$$

$$\text{volume of sodium expelled} = K_1 \int_0^t P_o^{1/2}(2\lambda - \alpha)^{1/2}\ t^{1/2}\ dt$$

$$= 2/3 K_1 P_o^{1/2} (2\lambda - \alpha)^{1/2}\ t^{3/2}$$

$$= 2/3 K_1 (P_o(2\lambda - \alpha)t)^{1/2}\ t \tag{12}$$

Using equation 11 for substitution of $P_s - P$

Volume of sodium expelled

$$= 2/3\ K_1\ (P_s - P)^{1/2} t \tag{13}$$

$$= 2/3\ K_1\ \left(\frac{K_2\chi + F}{A}\right)^{1/2} t \tag{14}$$

The above equation represents the volume change in sodium chamber due to loss of sodium from the sodium chamber under an applied time dependent ΔP of $P_s - P$.

The last term in equation 4A is the volume increase due to movement of sodium bellows which can be represented by

$$\text{volume increase} = A\chi \tag{15}$$

where A = effective area of sodium bellows

χ = movement of bellows

From equation 4A, 9, 14 and 15

$$\frac{2\lambda t\, P_o V_o - \frac{F + K_2\chi}{A} V_o}{P_o + P_a - 2\lambda t\, P_o + \frac{F + K_2\chi}{A} \quad \frac{K_3\, T}{A_3}} = 2/3\ K_1 \left(\frac{F + K_2\chi}{A}\right)^{1/2} t + A\chi$$

Therefore, the equation could be written as a quadratic equation of t,

$$4/3 K_1 \lambda P_o \left(\frac{F + K_2\chi}{A}\right)^{1/2} t^2$$

$$+ t[2\lambda P_o V_o + 2\lambda P_o A\chi - 2/3\ K_1 \left(\frac{F + K_2\chi}{A}\right)^{1/2} (P_o + P_a + \frac{F + K_2\chi}{A} - \frac{K_3 T}{A_3})$$

$$- A\chi\ (P_o + P_a + \frac{F + K_2\chi}{A} - \frac{K_3 T}{A_3}) - \frac{F + K_2\chi}{A} V_o = 0 \tag{16}$$

where

K_1 = orifice flow constant

d_o = orifice diameter, MM (inch)

ρ = density of sodium gms/cm^3 (lbs/ft^3)

C = flow coefficient for orifice

λ = flow coast down decay constant, t^{-1}

P_o = initial operating pressure (dynamic) in the vicinity of sodium chamber, kPa (psi)

K_2 = spring rate of sodium bellows and poppet valve bellows, kg/M (#/in)

χ = stroke length, MM (inch)

F = preset force, kg (lbs)

A = effective area of sodium bellows, MM^2 (in^2)

V_o = gas volume corresponding to initial condition, cm^3

K_3 = spring rate of argon bellows kg/M (lbs/in)

A_3 = effective area of the argon bellows, MM^2 (in^2)

T = compressed stroke of argon bellows corresponding to initial condition, MM (inch)

A computer program was written, based upon the above analysis, which eliminated the approximations. The effect of partial opening of the poppet valve was also incorporated in the calculation. The response times calculated with this program, are plotted in Figure C.1. It may be noted that the response time 0.5 $\pm$ 0.1 second is fairly constant for the entire flow range of 40% to 100%. The slight increase in response time at higher flow rates is due to the excess of the operating pressure drop over the minimum support value. This may be compensated by adjustment of RCP device parameters.

C.2 System MM Reliability Considerations

The reliability of the System MM design is projected to be very high due to the use of proven materials, minimum moving parts, and large margin of conservatism in the component and system design.

The critical components in the control assembly which are susceptible to failure, identified as the bellows and the orifices, affect the performance of the RCP device. However, the projected change in performance due to these failures is small, and is discussed in the following.

The diameters of orifices in the RCP assembly are large, $\geq$ 3 mm (1/8") and, therefore, the probability of plugging is very low. Moreover, by an appropriate provision of a screen or small diameter orifices at inlet, it can be ensured that no large diameter particles enter the assembly. A plugging of the RCP assembly produces little change in the RCP response time. In most cases, the control assembly is released upon orifice plugging and, therefore, a fail-safe feature is obtained for the shutdown system.

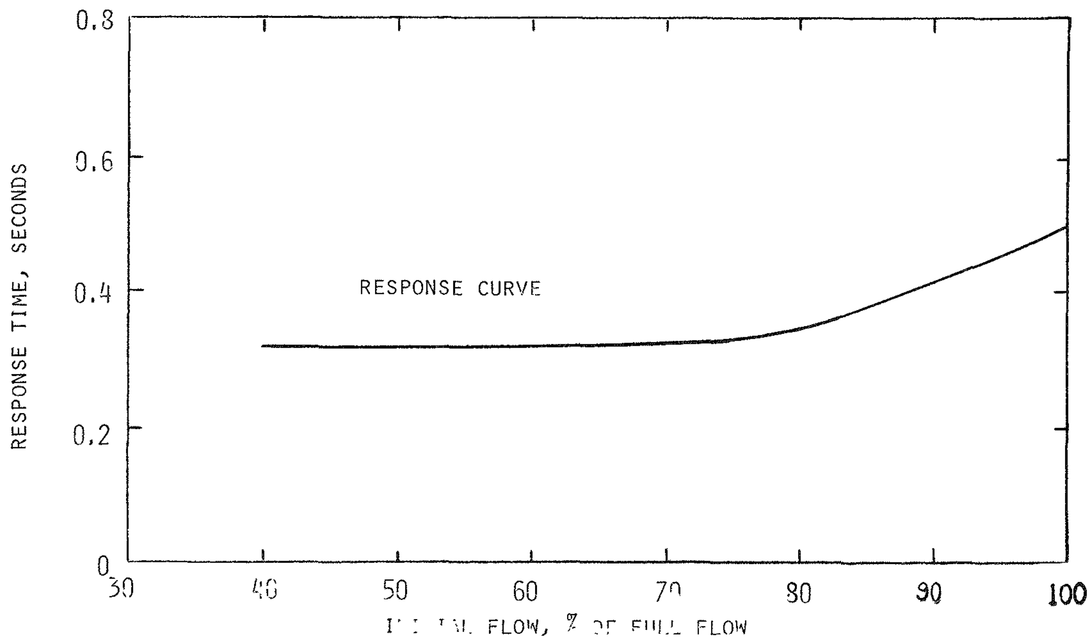


FIGURE C-1 RESPONSE CHARACTERISTICS INLET RCP SYSTEM

Due to local high sodium velocities, there may be some erosion in the orifices resulting in some increase in orifice diameter of the RCP assembly. The changes will have little effect on the response time of the RCP actuation and release of the control assembly.

The argon bellows, which is an essential component in the RCP actuator assembly, is a welded type Inconel 718 bellows. The normal sodium temperature is 600°F during full power operation. The bellows is located approximately 6 ft. below the reactor core and therefore is outside the high fluence damage region during reactor operation. The bellows is enclosed in a sodium chamber which is in communication with the flowing sodium through a flow limiting orifice. Therefore, the temperature transients imposed on the bellows due to reactor power variations or load changes are minimum. The compression stroke of the bellows is limited to less than 50% of the free length and approximately 60% of the allowable stroke to provide a large margin of safety. Physical stops are provided to ensure that stroke is less than 60% of the free length during the entire range of reactor operation.

The normal differential pressure across the bellows is less than 34 KPa (5 psi) during the entire flow range and does not exceed 138 KPa (20 psi) during abnormal conditions and, therefore, the stresses on the bellows due to differential pressure are kept to a minimum.

Due to a large margin between the allowable and imposed stresses due to thermal and pressure loadings and because of limiting the stroke length, the failure probability of the argon bellows is small. If, however, bellows fail and develop a small leak, the response time for the RCP device is increased due to a decrease in the potential energy stored in the bellows for the corresponding power levels. For a complete rupture, the bellows expands to its free length and pushes against the sodium bellows to open the poppet valve which leads to control assembly release. Therefore, a reactor scram is assured upon failure of the argon bellows.

The Inconel 718 welded type sodium bellows is normally under zero extension due to zero differential pressure across the bellows during the entire range of reactor operation. The differential pressure across the bellows during RCP actuation does not exceed 138KPa (20 psi) and, therefore, the induced stresses are kept to a minimum. The bellows are located outside the high fluence damage neutron flux at a normal sodium temperature of about 650°F. The temperature transients imposed due to reactor power variation or load changes are somewhat attenuated due to the bellows being located at more than 1.22m (4 ft) from the top of the core and away from direct flow path of the flowing sodium. The extension stroke during the RCP actuation is limited to less than 25% of the allowable stroke.

Due to low stresses and limited thermal and pressure cycling imposed on the bellows, the probability of failure is very low. If these bellows fail, the RCP device will not function to release the control assembly. However, upon a major failure of the sodium bellows, the sodium chamber will not be able to contain the high pressure sodium during loss of flow transient. Therefore, the argon bellows will expand to push the push rod, thereby opening the poppet valve. The response time, however, is much longer due to its dependence on loss of pressure.

It may, therefore, be stated that the bellows incorporated in the RCP device are in low neutron flux environment, experience attenuated temperature transients, normally are under low pressure loading, and experience substantially less than the allowable stroke. The failure probability of these bellows is, therefore, fairly low. The poison assembly is released under most failure events and, therefore, a fail-safe feature is inherent for the shutdown system.

Bellows Reliability

Inconel and stainless steel welded bellows have been used in LMFBR's for more than twenty years. Examples of such applications are EFFBR, EBR-II, FFTF, and foreign LMFBR's such as DFR, Rapsodie, Phenix and PFR. In the Fermi reactor, the bellows have been used as a pressure boundary between the pressurized He gas and the sodium vapor in the control rod drive extensions. The bellows have also been used in the EBR-II control rod drives to allow vertical stroke of the control rod drive while maintaining separation between the inert gas and the sodium vapor. The bellows have also been used in the FFTF control rod extensions. Extensive testing of bellows has been conducted by LMEC for the FFTF and CRBRP control rod drive development program. In general, the experience with bellows has been satisfactory. The failures of the bellows have been small and resulted in minute leakage.

Although no bellows testing in an irradiated environment has been performed irradiation is not expected to detrimentally affect the Inconel 718 bellows, since the flux level will be low. The environment of the bellows are less than 2.5×10^4 n/cm^2-sec total flux. The fluence for this condition after 30 years will be about 1.8×10^{14} n/cm^2.

No data is available for Inconel 718 irradiated at the low fluence service conditions. Data for substantially more severe irradiation exposures are given in Figure C-2. The very low levels of irradiation of the bellows would not be detrimental to bellows strength, ductility or performance.

The Inconel 718 welded bellows has also been tested at C-E, Windsor, during C-E shutdown assembly tests in a sodium loop. Of prime interest was the durability of welded Inconel 718 bellows under conditions of impulsive pressure, mechanical loadings, and thermal shock, especially in the presence of sodium at 593°C (1100°F). After nearly 2000 cycles of due scrams under their standard conditions of 593°C (1100°F) sodium and 960 KPa gas pressure, the assembly was dismantled, cleaned and inspected. The bellows was found to be sound and only slight polishing was evident in the rubbing parts.

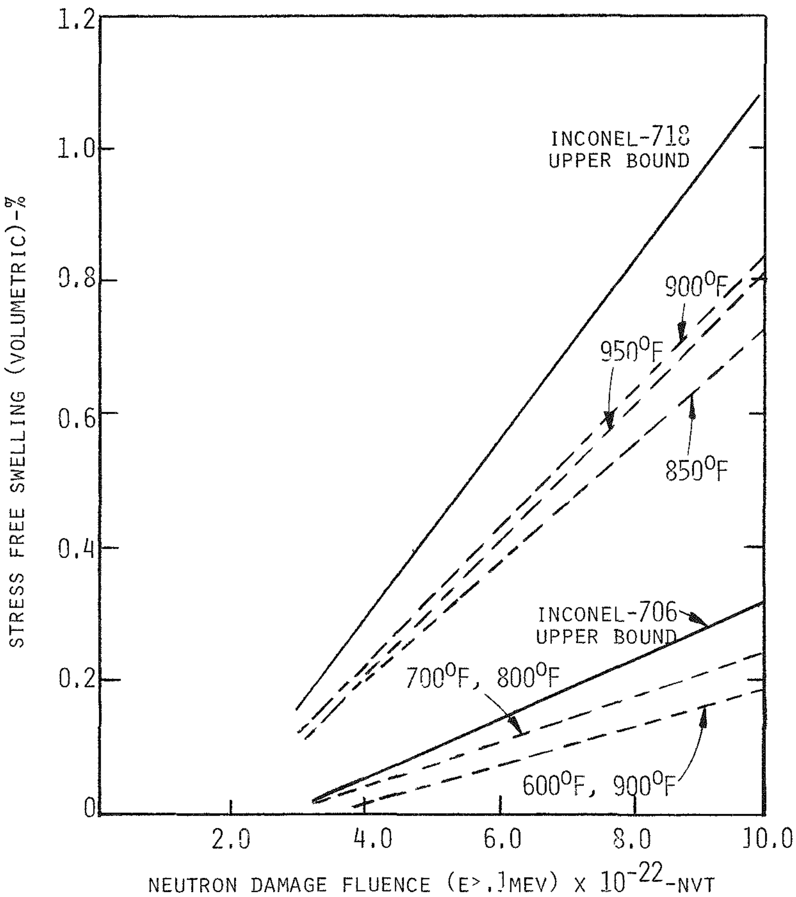


FIGURE C-2 IRRADIATION INDUCED SWELLING OF INCONEL-718 AND INCONEL 706

Appendix D

TRANSIENT OVERPOWER (TOP) SYSTEMS

As per CRBRP PSAR, Amendments, October 1975, the loss of flow events are more than an order of magnitude more energetic than even a 50¢/sec TOP event and result in significant work energy of the order of 100 MJ. Consequently, the current CRBRP analysis indicated that a self actuated device, which offers significant additional LOF protection, would provide the margin needed for licensing without untenable containment requirements. However, comparable analysis has not been completed for PLBR and therefore it is difficult to conclude that TOP events are far behind and that a TOP protection will not be required in PLBR.

Among the many concepts evolved during the development work, two concepts emerged as promising, which could provide effective protection against TOP events. Both of these concepts are fast acting and self actuate under a TOP transient to shut-down the reactor safety. These are as follows:

D.1 System A

D.2 System MM - TOP

D.1 System A Design Description

D.1.1 System Description

The operating principle of the System A self actuating shutdown device is illustrated by Figure D-1. A portion of the control assembly flow passes through a fixed central duct containing a bundle of seven fuel pins situated within the active core region. Immediately down stream of the fuel, the coolant temperature is sensed by the NaK-filled thermal bulb which is hydraulically connected to the bellows actuator. This bears on the spring loaded linear cam which holds the three latch arms in engagement with the poison assembly support ring.

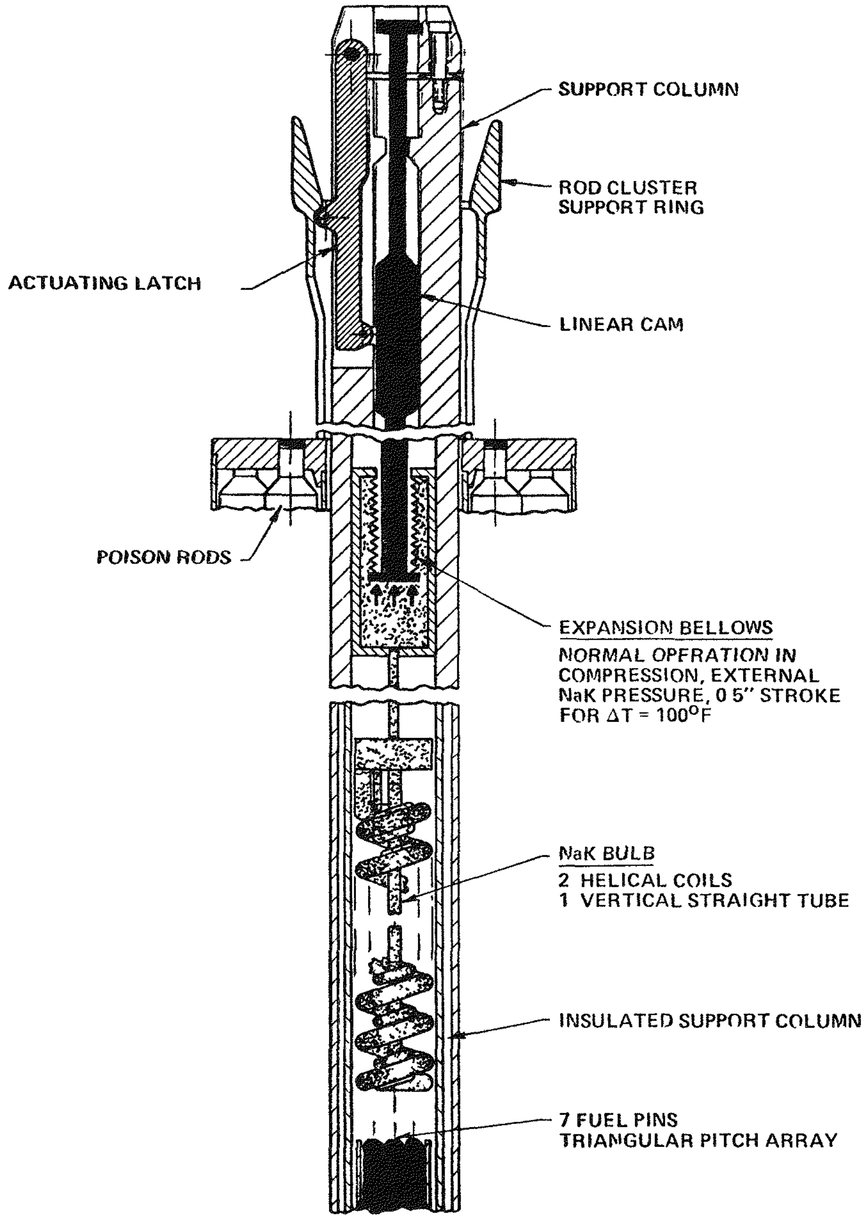


FIGURE D-1 SYSTEM A CONCEPT

Under TOP or TUC conditions the temperature rise of the coolant, exiting from the fuel pin cluster, is communicated to the NaK system and results in extension of the bellows actuator and retraction of the latch arms. The poison assembly then drops into the active core region and is brought to rest by a dashpot snubber.

The complete general arrangement of System A is shown in Figure D-2. The principal parts are the thermal actuator assembly, the mechanical latch, the PPS release mechanism, the poison assembly and the dashpot snubber.

Thermal Actuator Assembly

The thermal actuator assembly moves the mechanical latch linear cam and consists of the bundle of fuel pins, the insulated duct, the thermal bulb and the bellows actuator. These are all housed within the composite central column which also serves to support the mechanical latch.

The fuel pin bundle is shown in cross section within the hexagonal duct in Figure D-3. Seven wire wrapped fuel pins, 9 mm (0.32 in.) outer diameter, are arrayed in a triangular pitch having a pitch/diameter ratio of 1.12. The oxide fuel has a low enrichment relative to the core fuel to provide a flattened power history and the linear power rating is estimated to be an average 26 kW/m (8 kW/ft).

The central column is attached to the control assembly duct at the inlet end and is double walled with a gas or ceramic filled interspace to reduce heat loss from the fuel coolant to the poison coolant. The additional hexagonal duct may contain a shaped insert to minimize bundle bypass coolant flow.

The thermal bulb is designed for a high surface to volume ratio and consists of two concentrically coiled tubes and a central tube. In the interest of reducing the fluid transport time, the bulb is located close to the fuel region where the neutron damage fluence (over 0.1 mev) is about 4×10^{22} nvt over the 2-year design life. This introduces the problem of swelling which would reduce the bellows actuator movement for a given temperature rise. A low swelling material such as Inconel 706 has therefore been selected for the bulb.

The bellows actuator extends at a rate of 0.23 mm/°C (0.005 in./°F) and is expected to be resisted by a combined force of about 17 kg (37 lb) due to bellows, return spring and latch friction force. It is externally pressurized to remove the potential for bellows squirm.

Mechanical Latch

The mechanical latch is shown in Figure D.3 and consists of the central linear cam spindle and three latch arms which engage with another cam surface on the poison support ring. Each latch arm has two cam follower rollers which insure that the poison assembly will release and acceptable bellows forces would result even if the coefficient of friction were on the order of 2. It is determined from published friction and wear data that expected coefficients of friction would be less than 0.6 and negligible wear would result by the use of Stellite rubbing surfaces. The operation of the latch is described in Section D.1.2 below.

PPS Release Mechanism

The poison support ring is segmented (collect chuck principle) and mounted on cantilever springs inside a tapered outer sleeve so that axial movement of the sleeve causes the ring to spring apart and release the poison assembly independently of any mechanical latch movement. The mechanism is more fully described in Section D.2 in terms of its mode of operation, to avoid repetition.

Poison Assembly

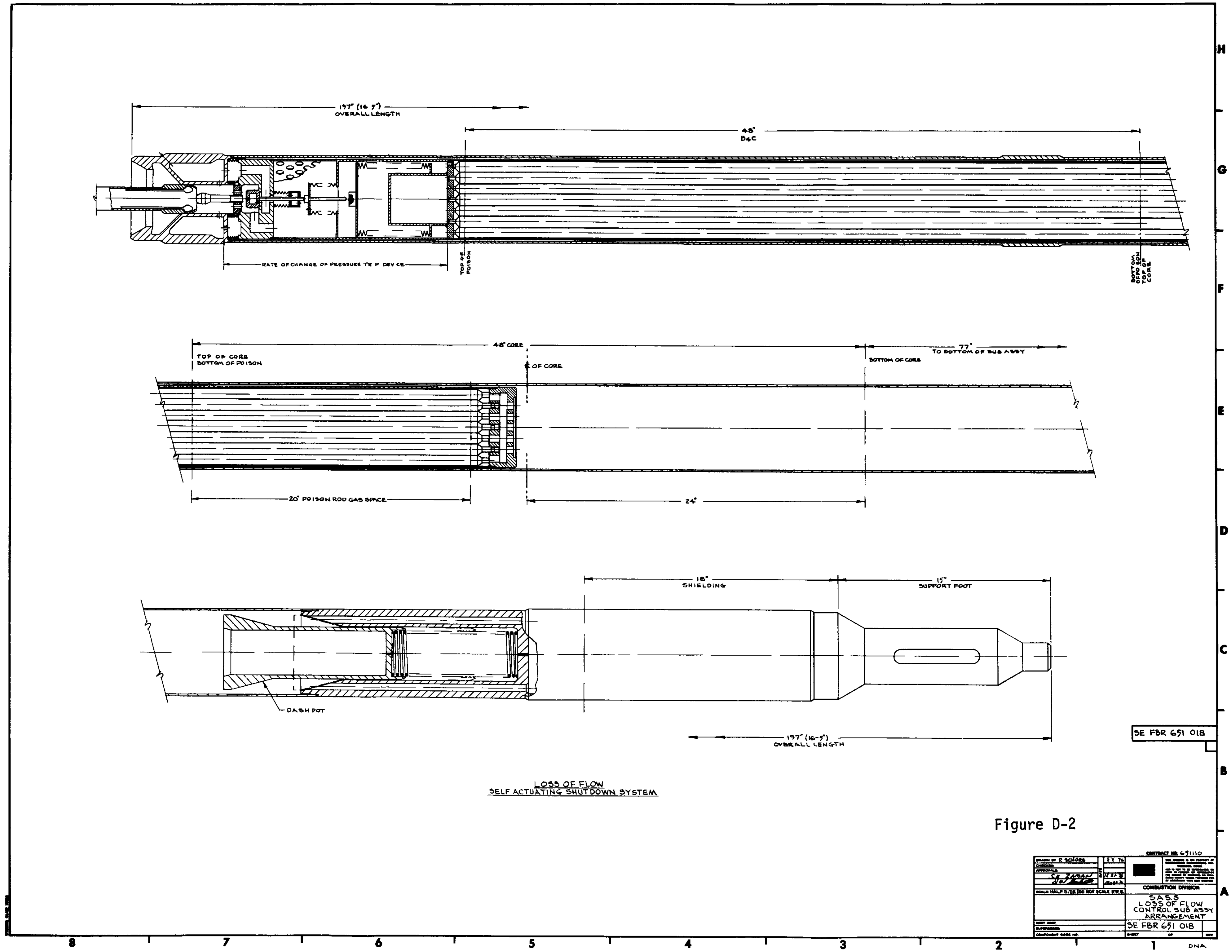
The array of 72 boron carbide pins having a clad outer diameter of 13.7 mm (0.539 in) is shown in Figure D.2. The pin size is chosen to maximize the quantity of poison which will fit in the hexagonal "annulus", and results in an estimated poison weight of 60 kg. (130 lb.). The clearance between the poison assembly and the shroud is based upon the latest CRBRP data.

D.1.2 Modes of Operation

The modes of operation of System A which are considered below include the tripping, reset, testing and handling operations required.

SASS Trip Mode

The device responds to a TOP or TUC event as shown in Figure D-4. The cam profile is designed so that, with the cam position as shown in the "operating mode", an increase in bulb temperature of 36 $\pm$ 8°C (65 $\pm$ 15°F) causes the latch to release the poison assembly as shown by "high temperature trip".



197" (16 5") OVERALL LENGTH
48" B4C
RATE OF CHANGE OF PRESSURE TRIP DEVICE
TOP OF POISON
BOTTOM OF B4C TOP OF CORE
48" CORE
TOP OF CORE
BOTTOM OF POISON
℄ OF CORE
BOTTOM OF CORE
77" TO BOTTOM OF SUB ASSY
20" POISON ROD GAS SPACE
24"
18" SHIELDING
15" SUPPORT FOOT
DASH POT
197" (16-5") OVERALL LENGTH
SE FBR 651 018
LOSS OF FLOW
SELF ACTUATING SHUTDOWN SYSTEM
CONTRACT NO. 651110
DRAWN BY R SCHORS
SCALE HALF SIZE
DO NOT SCALE DWG.
COMBUSTION DIVISION
SAS.5
LOSS OF FLOW
CONTROL SUB ASSY
ARRANGEMENT
SE FBR 651 018
DNA

Figure D-2

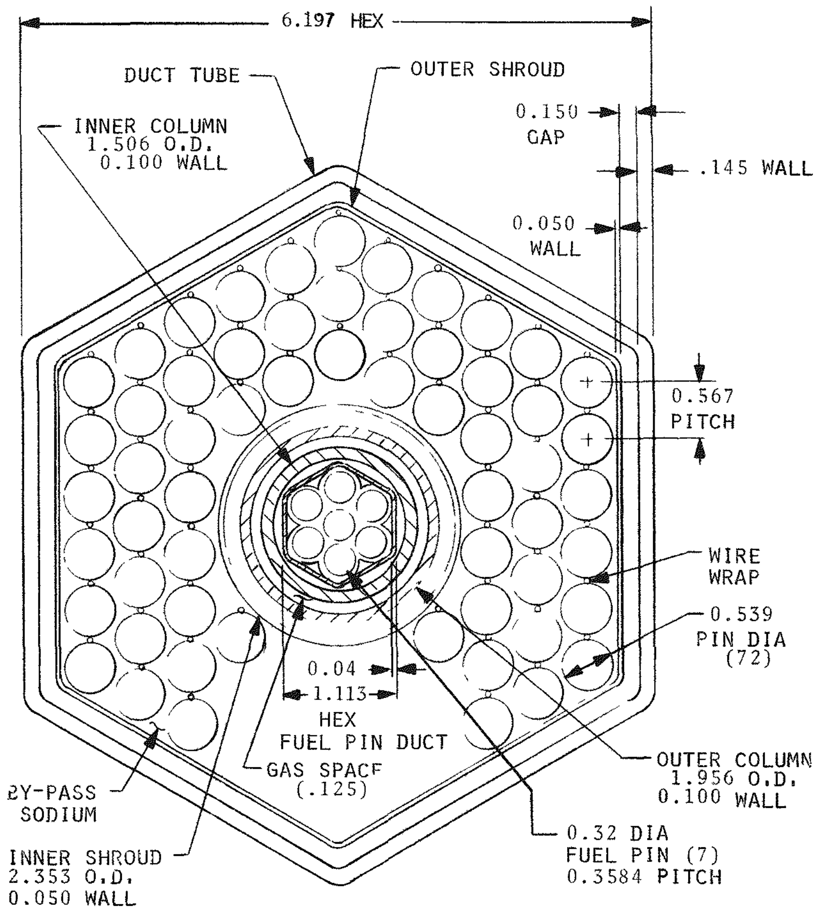


FIGURE D-3 SYSTEM A POISON BUNDLE CROSS SECTION

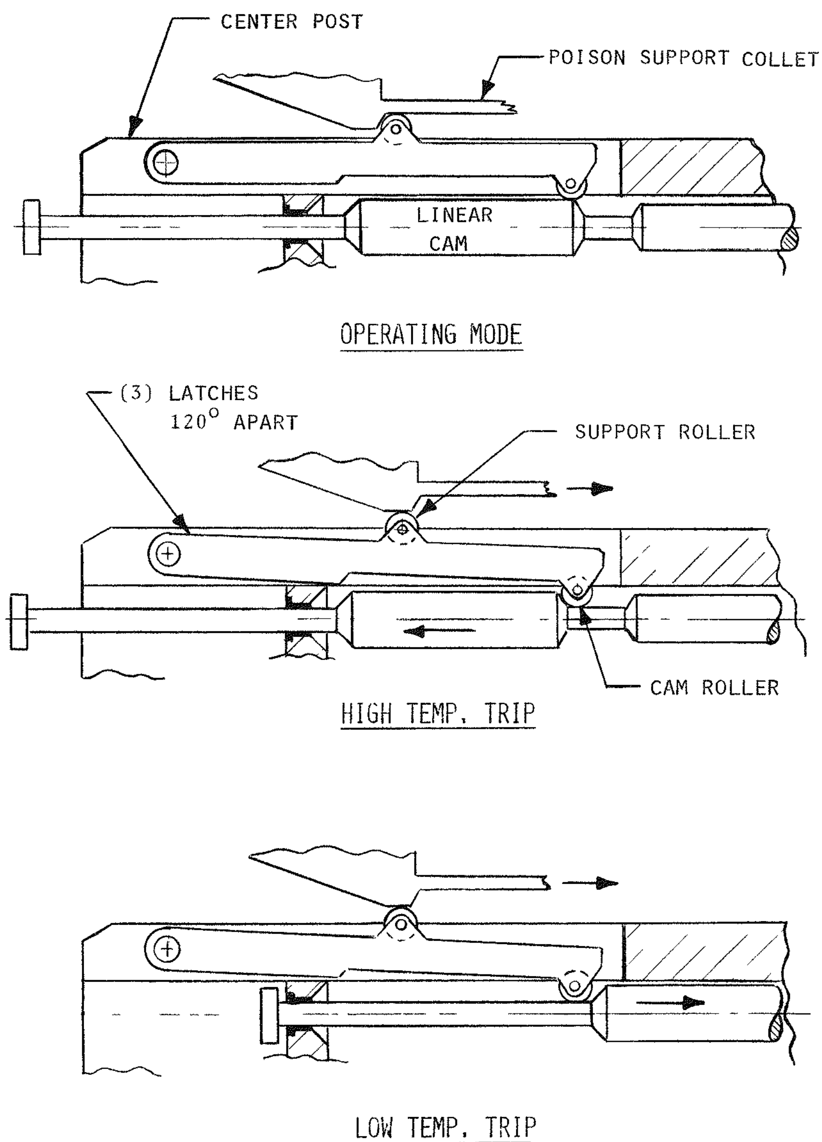


FIGURE D-4 SYSTEM A LATCH OPERATIONAL MODES

PPS Trip Mode

The device can be independently tripped by means of a conventional CRDM connected to the plant protection system. The drive line lower end detail is configured as shown in Figure D-5 ("reset mechanism"), so that during normal operation it is located just inside the control assembly duct and just above the upper extension to the poison assembly. The geometry is arranged to provide good alignment during normal operation yet permit poison insertion in the SASS mode under a hypothesized condition of extreme misalignment.

For PPS trip, the CRDM is operated in the fast down drive mode and the reset mechanism moves from the position shown in Figure D-5 to that shown in Figure D-6. In doing so, it depresses the PPS actuating sleeve against the spring force, which normally holds it in position, and allows the segmented poison support ring (collet) to expand radially. The ring then over-rides the protruding latch rollers and the poison assembly falls. A spreading feature is incorporated to force the collet open if it fails to spring apart due to friction or overstrain in the cantilever spring.

Testing Mode

If the reactor is voluntarily shut down and the PPS mode is not used, then the bellows actuator will retract and move the linear cam until, at the hot standby temperature of 288°C (550°F), it reaches the position shown at "low temperature trip" in Figure D-3. The latch arms then retract and release the poison assembly. Insertion of the poison assembly can be detected acoustically and confirmed by subcritical reactivity measurements.

This procedure exercises each active SASS component and release will not occur at this temperature if the bulb/bellows calibration has drifted appreciably (leakage, container swelling) or the mechanism is jammed (rubbing surface adhesion, distortion, yielded spring). Conversely, if release does occur at the specified low temperature then it may be argued that it should also occur at the specified over temperature. It is noted that the return spring has no effect on the high temperature trip and that adhesion, unlike friction, would be unaffected by the temperature. The latch was designed to operate with friction variations far in excess of reality (see Appendix A).

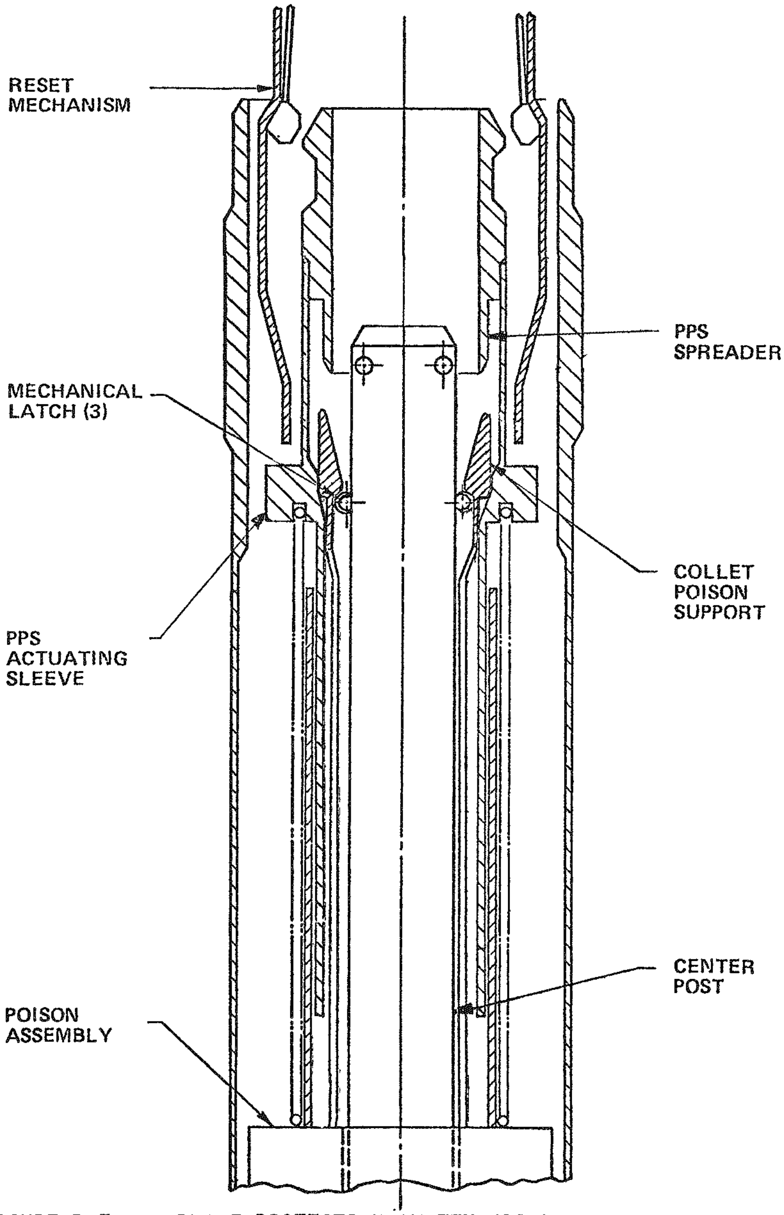


FIGURE D-5 PLANT PROTECTION SYSTEM (PPS) TRIP MODE - BEFORE RELEASE

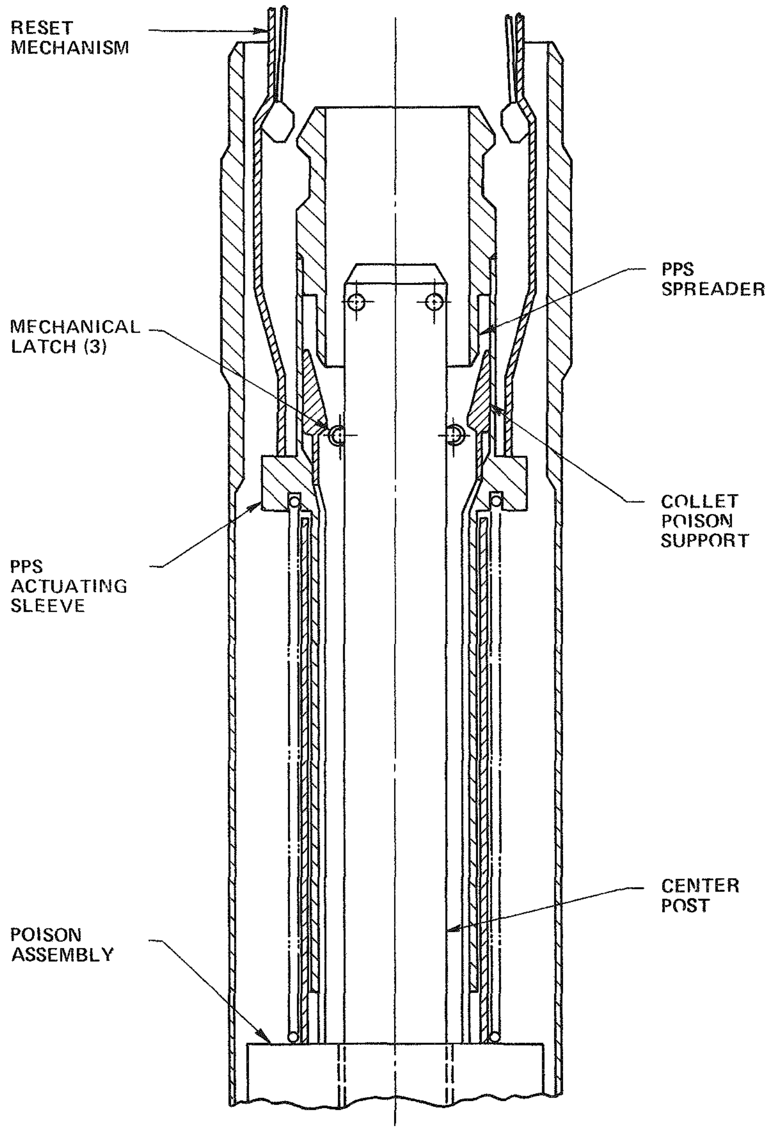


FIGURE D-6   PLANT PROTECTION SYSTEM (PPS) TRIP MODE

If this argument does not satisfy licensing requirements, then consideration should be given to simulating the over temperature condition. One method is to introduce hot sodium from a special supply. Another way, which would require considerable rearrangement of the SASS mechanism, is to insert an electrical heater through the head. The simplest way, if testing at partial power were permitted, would be to throttle the flow at the control assembly outlet. This might be done during the normal shutdown process provided that simultaneous actuation and monitoring of all SASS devices could be achieved.

Reset Mode

The reset mechanism is an adaptation of the CRBRP control rod disconnect. It is designed to grip the handling head of the poison assembly so that it can be returned to its cocked position during reactor startup and help there while the mechanical latch resets itself. This occurs when the temperature rises above the hot standby value and the latch cam returns to the cam dwell position form the low temperature position shown in Figure D-3.

Handling Mode and Summary

The upper end of the control assembly has a standard handling feature to allow removal of the assembly with standard fuel handling equipment.

D.1.3 System Preformance

C-E Design Criteria specify that the response time for SASS delatch and total insertion be 0.5 and 2.0 seconds, respectively, from the time at which trip levels are exceeded. Although these criteria appear to be unnecessarily stringent for SASS operation in a tertiary mode, it was judged that the licensing process would substantially benefit from a system whose response times to not substantially exceed those of CRBR.

Design techniques utilitzed to achieve a rapid response are the use of sensor fuel pins, the minimization of sodium transport delay time to the thermal trigger (bulb/bellows mechanism) and the maximization of the thermal bulb effective UA to obtain a short time constant.

TUC Event

A finite element transient analysis model was assembled and utilized to optimize the design of the "System A" bulb/bellows thermal trigger.

Improvements to the SASS design resulted in an extremely fast responding system. The reference case under study as a hypothetical transient undercooling (TUC) event presumably caused by loss of flow from 100% power with failure to scram. Using the CRBR coastdown, the driver region (and sensor fuel pin) outlet sodium temperature rises 44°C (80°F) at 2.55 seconds after pump trip, with primary flow at the 75% level. The "System A" response (Figure D-7) results were 0.95 seconds for delatch (3.5 seconds after pump trip) and 0.55 seconds more for full reactivity insertion at a 0.9g drop rate. Driver region peak pin inner clad temperatures rise 91°C (163°F) from an initial 628°C (1163°F) to 719°C (1326°F). Hot channel and radial peaking are accounted for by use of a 1.3 factor on average driver temperature rise. These mild results are very encouraging. However, a detailed pin thermal/hydraulic model is required to provide a more rigorous PLBR clad temperature prediction which accounts for differences in assumed fuel material, linear power, gap conductance, wire wrap and other effects.

TOP Event

Although results for transient overpower (TOP) were not obtained, the power/flow ratio rise of the first 2-4 seconds of the TUC event studied (using a CRBR coastdown) closely approximates that of a 10¢/sec TOP insertion ramp. A response time similar to the TUC event results would thus be expected, if not shorter, due to the reduced transport delay effects during a TOP if no coastdown is assumed.

PPS Trip

Trip signals transmitted to the PPS system will result in a fast down drive of the CRDM, normally parked above the PPS trip actuating sleeve withing the control assembly duct outlet. Acceleration to 3 m/min (118 in./min) and traversal of the 3.8 cm (1.5 in.) separation distance at operating temperature beginning of life conditions (greatest gap) and a further 1.9 cm (0.75 in.) stroke for collet support ring release will require approximately 1.3 seconds. Full insertion at 0.9g acceleration requires an additional 0.55 seconds, resulting in a total PPS insertion time of 1.85 seconds.

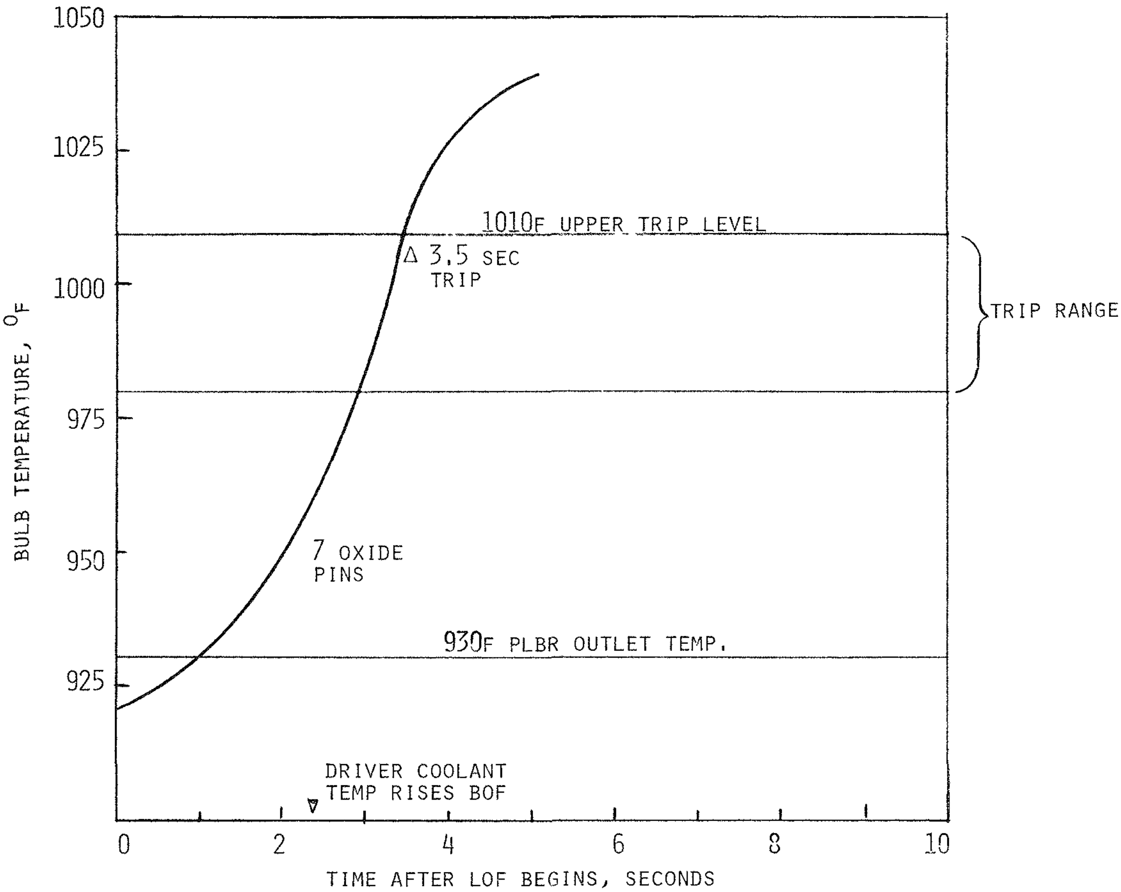


FIGURE D-7 THERMAL BULB TEMP. RESPONSE PLBR-UNPROTECTED LOF FROM 100% POWER

D.2 System MM - TOP

Subsequent to Task I, it was recommended that System MM be selected for further development to include the TOP protection. Consequently, several TOP-responsive devices were investigated, starting with modifications to System A and avoiding devices which would either adversely affect System MM or impede poison insertion through a distorted duct.

In view of the relative simplicity, inherent safety and speed of System MM, it was determined that modifications, which compromise those qualities, should not be pursued. Further, System A had been found to be a very efficient TOP device, following the design improvements of Task 1, so that modification of it to complement System MM should be regarded as prime candidates.

The following proposals were considered:

a) Integration of System A fuel/bulb/bellows with System MM poison assembly to open a parellel valve in the seal. The fuel is supported in the region and mechanically protected by the surrounding empty (lower gas space) tubes of the poison pins. The poison insertion is supplemented by displacement of the fuel from the core region during scram. Valve also opens at low temperature to provide in-situ testing independently of System MM.

b) Fuel inside bulb in lower blanket region and connected to bellows below dashpot snubber assmbly. Bellows actuates a needle valve which changes flow through control assembly. When reactor power increases at an unacceptable rate, it causes a rate of decrease of flow which trips System MM.

c) Similar to a) except that fuel inside the bellows to minimize loss of space for poison.

d) Similar to b) except that valve causes System MM to trip in low flow mode at overpower and, to provide a test of calibration, also at loss of flow.

e) Use of non-fuel heat source (e.g., Cs, Rb) withing gas bellows of System MM, so that the rate of temperature, due to an overpower transient, causes a rate of gas volume change sufficient to pressurize the sodium bellows and open the poppet valve.

The rate of change of power (or power/flow) devices are attractive because it may be possible to design them to be less sensitive to absolute power (or power/flow) and to allow axial placement of the heat source outside the core region. Another factor is that the question of special engineering for changes in specified normal and abnormal power (or power/flow), during and after construction, would be avoided.

A principal advantage of System A - type devices is that they respond quickly to power/flow mismatch and provide a simple calibration check by means of a low temperature trip. Proposals a) and c) are attractive because the fuel resides in the core region and so responds strongly and analogously with driver fuel to core power increases. Further, the fuel does not provide a stationary, potential impediment to poison insertion as in the original System A. It may, however, require a softer snubbing device.

A transient overpower (TOP) trip feature was incorporated in the MM design to fulfill the design requirement of over temperature trip for the self acturated shutdown system. This concept is based on integration of System A NaK bulb/ bellows concept with the System MM rate of changes of pressure trip concept.

In this concept, Figure D-8, the fuel is supported in the core region within a 1.5" diameter central tube, protected by the surrounding tubes of poison pins containing poison gas space. The NaK bulb is supported above the fuel within this central tube to facilitate NaK expansion or contraction in response to the coolant temperature. The NaK bulb is connected by a capillary tube to an actuator bellows which actuates a spool value to close or open a bypass passage across the hydraulic seal.

The bellows are sized so that the spool valve remains closed during normal reactor operation but opens during a temperature rise associated with a TOP. Upon the valve opening, the differential pressure across the hydraulic seal is rapidly reduced to effect a release of the poison assembly. The valve also opens upon decrease of temperature to a present value to permit testing and calibration during reactor shutdown.

The flow through the fuel/NaK bulb assembly is controlled by directing the flow through a pipe form the central tube to the low pressure side of the hydraulic seal. The pipe is sized to obtain the appropriate flow and temperature rise across the fuel bundle.

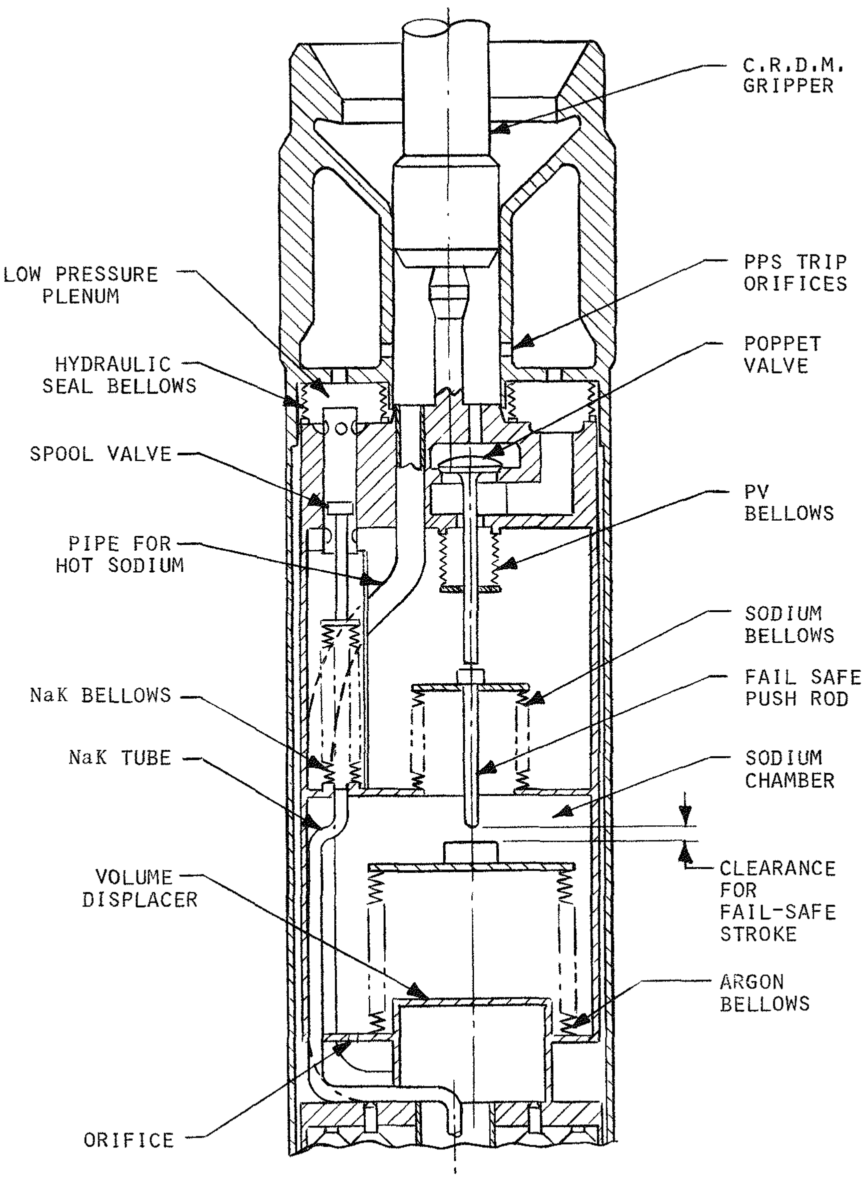


FIGURE D-8 SYSTEM MM - TOP FEATURE

The following are the significant merits of the proposed concepts:

1. Location of the fuel/NaK bulb assembly within the poison bundle structure avoids interference during insertion as might occur in System A.

2. The piped flow permits establishment of appropriate flow velocities and temperature rise across the fuel/NaK bulb assembly without effecting the low pressure drop requirement for the poison bundle.

3. The moving fuel concept results in an increase in the reactivity worth of the poison assembly.

4. The proposed concept has little impact on the present System MM design, and works independently of the rate of the change of pressure trip actuators.

5. This concept permits in situ testing and calibration during reactor shutdown.

6. Distinct boundaries between the fuel and the poison section in the assembly permit ease in assembly, disassembly and handling after irradiation.

The performance of this system is very similar to that of System A reported in the preceeding section. The modes of operating are similar to System MM described in Section 3.3.2.

D.3 Design Calculations

C-E Design Criteria specify that the response time for SASS delatch and total insertion be 0.5 and 2.0 seconds, respectively, from the time at which trip levels are exceeded. Although these criteria appear to be unnecessarily stringent for SASS operation in a tertiary mode, it was judged that the licensing process would substantially benefit from a system whose response times do not substantially exceed those of CRBR.

Design techniques utilized to achieve a rapid response are the use of sensor fuel pins, the minimization of sodium transport delay time to the thermal trigger (bulb/bellows mechanism) and the maximization of the thermal bulb effective UA to obtain a short time constant.

Summary of Effort

A finite element thermal transient model of the SASS control assembly was generated and inserted into an existing 1500 Mwe Target Plant Reactor model using the CEROS code. Through use of this tool, parameter studies were performed to determine the effect of the number os sensor fuel pins, fuel material, and thermal bulb configuration (surface-to-volume ratio) on SASS insertion time. Improvements to the SASS design resulted in an extremely fast responding system. The reference case under study as a hypothetical transient undercooling (TUC) event presumably caused by loss of flow from 100% power with failure to scram. Using the CRBR coastdown, the driver region (and sensor fuel pin) outlet sodium temperature rises 44°C (80°F) at 2.55 seconds after pump trip, with primary flow at the 74% level. The "System A" response results were 0.95 seconds for delatch (3.5 seconds after pump trip) and 0.55 seconds more for full reactivity insertion at a 0.9g drop rate. Peak pin inner clad temperatures rise 91°C (163°F) from an initial 628°C (1163°F) to 719°C (1326°F).

Although results for transient overpower (TOP) were not obtained, the power/flow ratio rise of the first 2-4 seconds of the TUC event studied (using a CRBR coastdown) closely approximates that of a 10¢/sec TOP insertion ramp. A similar response time would thus be expected, if not shorter, due to the reduced transport delay effects during a TOP if no coastdown is assumed.

SASS Model Description

In order to obtain a more rigorous comparison of the various options which affect the overall insertion time response, a detailed finite element thermal transient analysis model of System A was developed and inserted into and existing C-E Target Plant core model using the CEROS code. The model of the annular thermal bulb and sensor fuel pins is shown in Figure D-9 in comparison with the physical geometry proposed. Equations represented by the nodal model create a heat balance through conservation of energy at each time step. The problem becomes an initial value problem, with boundary conditions such as coolant flowrate and temperature rapidly varying at the thermal bulb location. Each node represents a specific thermal capicitance ρVC_p and conducts heat to an adjacent node with an effective interface conductance UA at its boundary. Transport delay effects are seen by modeling the sodium flow path as a series of incremental volumes. Optimum establishment of the time response is thus possible by parametrically varying each major parameter to determine response sensitivity to it.

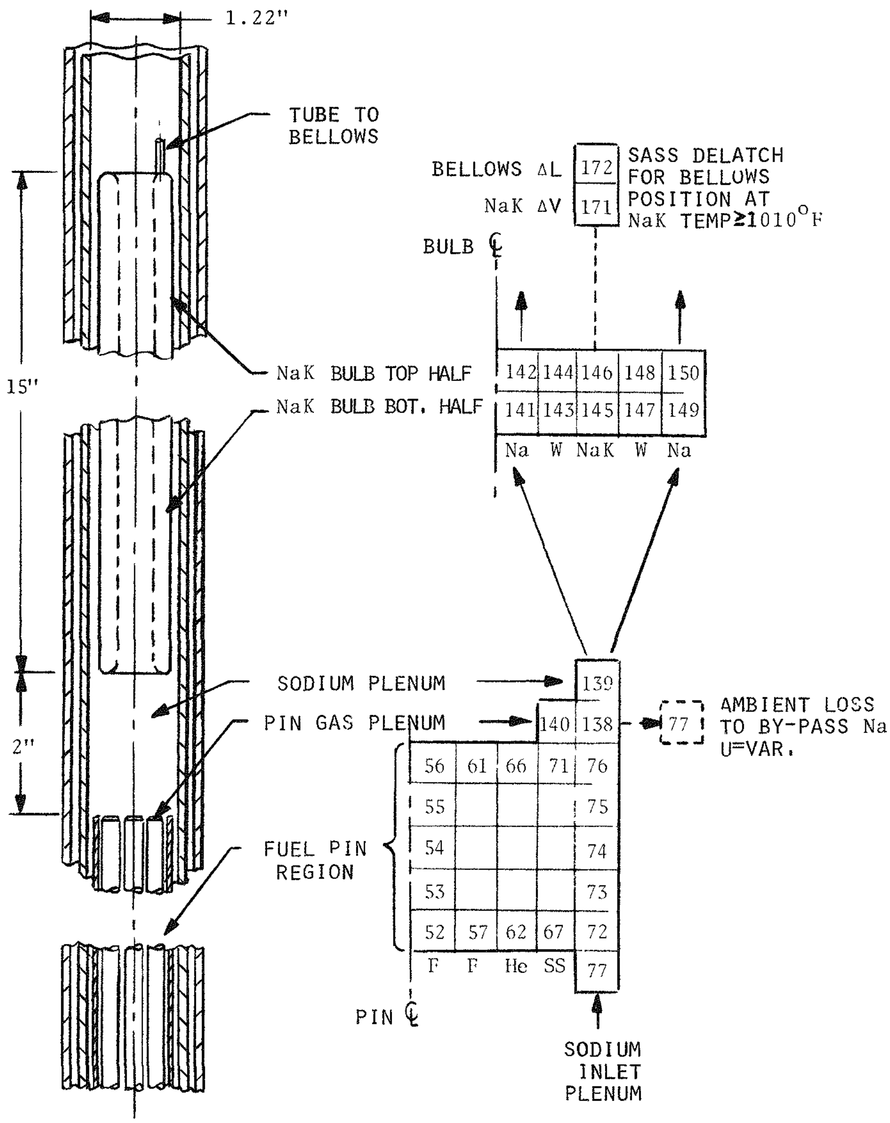


FIGURE D-9 SASS PORTION OF TRANSIENT ANALYSIS MODEL

The reactor model used is shown in Figure D-10. It includes the major core, blanket, reflector and bypass coolant flowpaths, the upper core structure, vessel outlet nozzle and piping connection. As anticipated, the rapid response of the system minimizes the TUC-generated thermal shock beyond the sensing device by upper plenum mixing, washing out any trace of an up-transient. The driver region is represented by an average fuel pin/assembly, from which hot channel and peak clad data may be obtained by superimposing the effect of the respective hot channel and peaking factors on the core temperature rise. Although a carbide core was used for the calculation, no effect on time response is created since reactivity feedback differences during the first few seconds of importance are nil. The SASS channel in the model, however, utilized oxided sensor fuel as per design criteria. Therefore, the number of pins, linear power, characteristic flow coastdown, sensor trigger position and set-point will thus determine the delatch time response of the system.

Results

The overall time response for System A delatch is given in Figure D-11. In this figure, the thermal bulb NaK temperature is plotted as a function of time for four SASS geometries, all for the unprotected TUC event starting from the 100% power/flow condition. Heat loss through the sensor pin column to the poison coolant flow (at inlet temperature) is constant for all four cases, with a U of 85 Btu/hr-ft^2 - °F based on an insulated column with a gas or ceramic filled gap. However, since the total sensor pin power varies between the four cases shwon, the initial outlet temperature (499°C (953°F) desired) varies for each case. Lower initial powers will generate lower inital temperatures since the column heat loss is constant and not diminishing as power is reduced. Calculations for an uninsulated column show that the initial outlet temperature depression of 5°C (9°F) increases by a factor of five for the 100% condition and ten for 50% power. The uninsulated column was immediately rejected.

Referring to Figure D-11, the curve on the right produces a 10.6 second maximum delatch time. This curve is based upon 3 oxide sensor fuel pins generating 8 kw/ft average pin power with a 1.22 m. (48 in.) fueled height, no upper axial blanket and an I-706 annular thermal bulb with dimensions given in Table D.1.

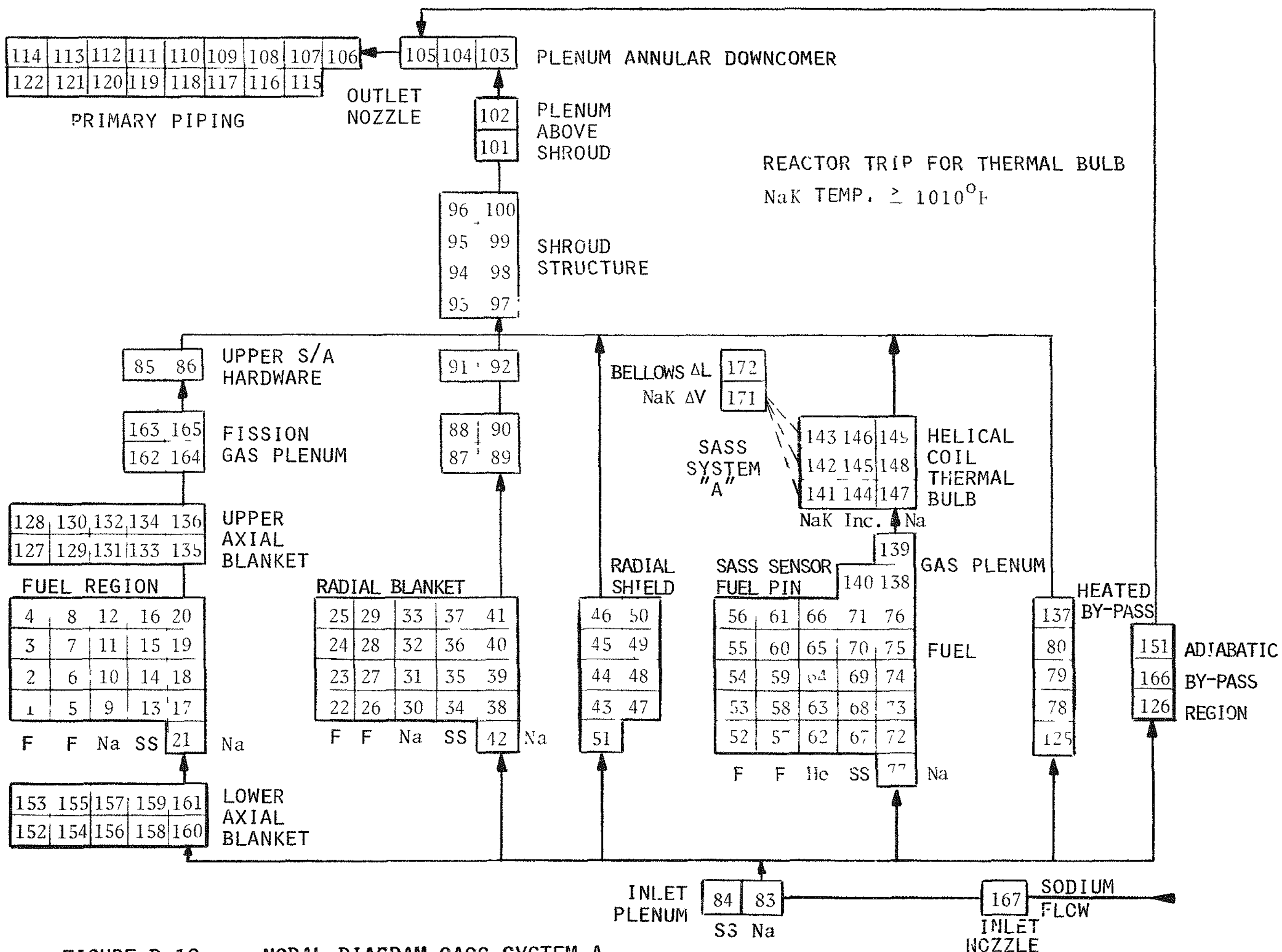


FIGURE D-10 NODAL DIAGRAM SASS SYSTEM A

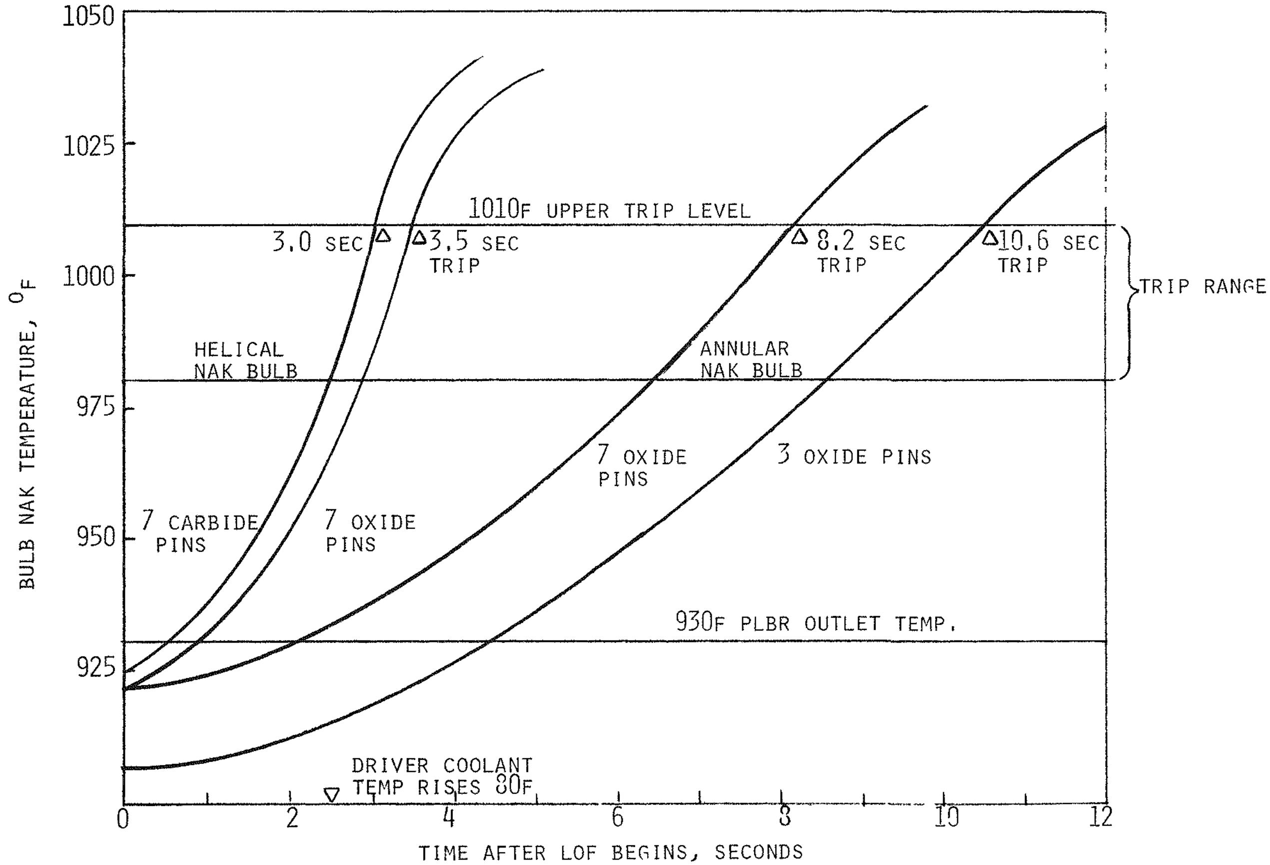


FIGURE D-11 THERMAL BULB TEMPERATURE RESPONSE PLBR-UNPROTECTED LOF FROM 100% POWER

Table D.1

ANNULAR BULB GEOMETRY

Outer Wall O.D.,	cm. 2.84	(1.120 in.)
Outer Wall Thickness,	cm. 0.127	(0.050 in.)
Inner Wall I.D.,	cm. 1.067	(0.420 in.)
Inner Wall Thickness,	cm. 0.127	(0.050 in.)
Length,	cm. 38.8	(15 in.)

Clad Temperature Response During TUC

Extremely mild clad temperatures are predicted due to the early TUC sensing and poison insertion. Assuming that the 122 cm (48 in.) rod cluster drop is resisted only by viscous sodium effects, a 0.9g insertion acceleration results in a 0.5 second total insertion time. The assumption that only one SASS assembly worth - $1.50 is fully inserted at t = 4 seconds produces a prompt power drop to 40% as shown in Figure D-12, and a gradual decay to 20% at t = 10 seconds. In comparison, sodium flowrate is shown in Figure D-13.

The resulting power/flow mismatch generates inner clad temperatures for the average driver pin that rise 90.5°C (160°F) from their initial temperature, as shown in Figure D-14. Accounting for radial peaking and hot channel factors using a 1.3 factor on average driver temperature rise produces a peak clad mid-wall temperature rise from 615°C (1140°F) to 708°C (1307°F). These mild results are very encouraging. However, a detailed pin thermal/hydraulic model is required to provide a more rigorous clad temperature prediction to account for difference in fuel material, linear power gap conductance, wire wrap and other effects.

Transient Overpower (TOP)

A neutron "prompt jump" kinetics analysis may be used to show that a 10¢/second reactivity insertion rate produces a power/flow ratio increase of approximately 10%/second during the first few seconds before the effects of delayed neutron population are felt. Neutron flux, thus power, immediately jumps following a reactivity introduction, ρ as shown below:

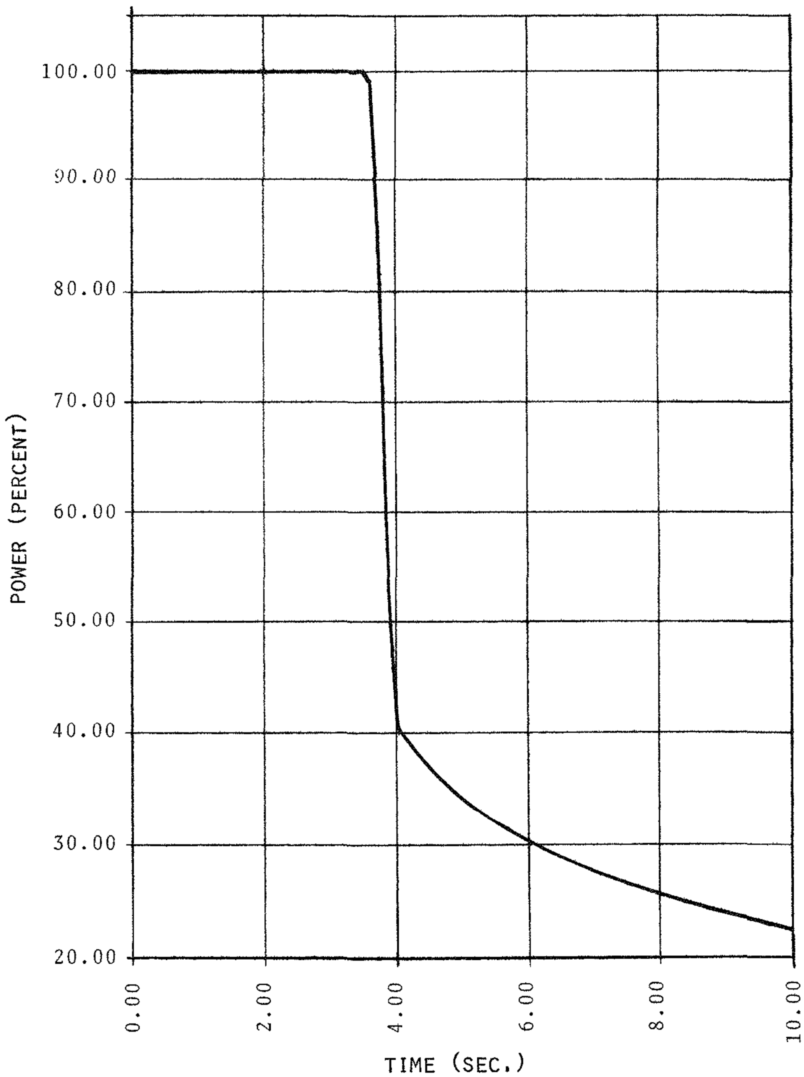


FIGURE D-12 REACTOR POWER DECAY

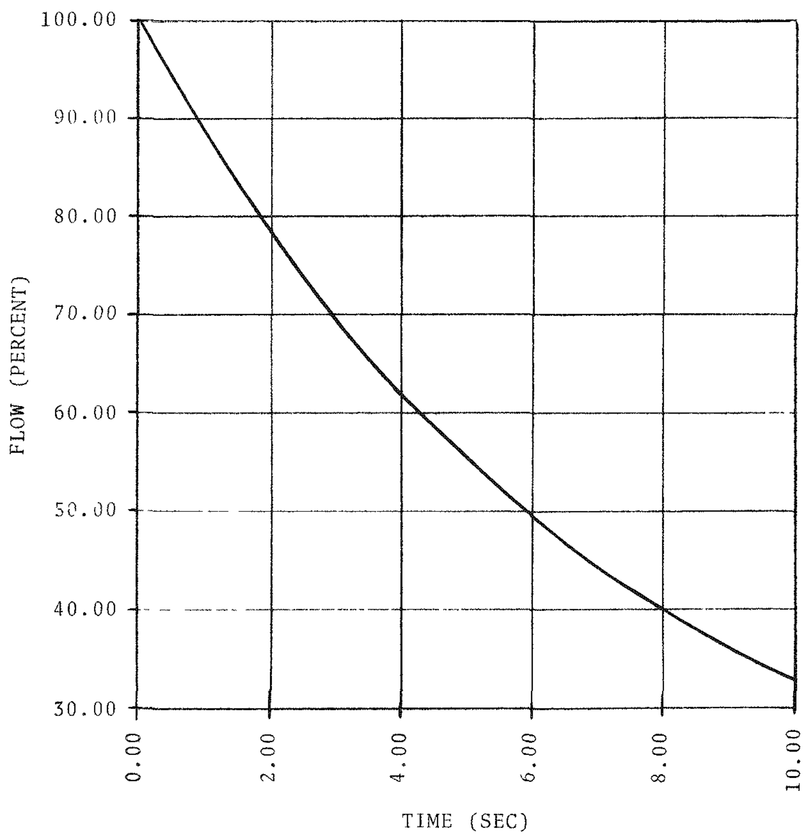


FIGURE D-13 FLOW COAST DOWN

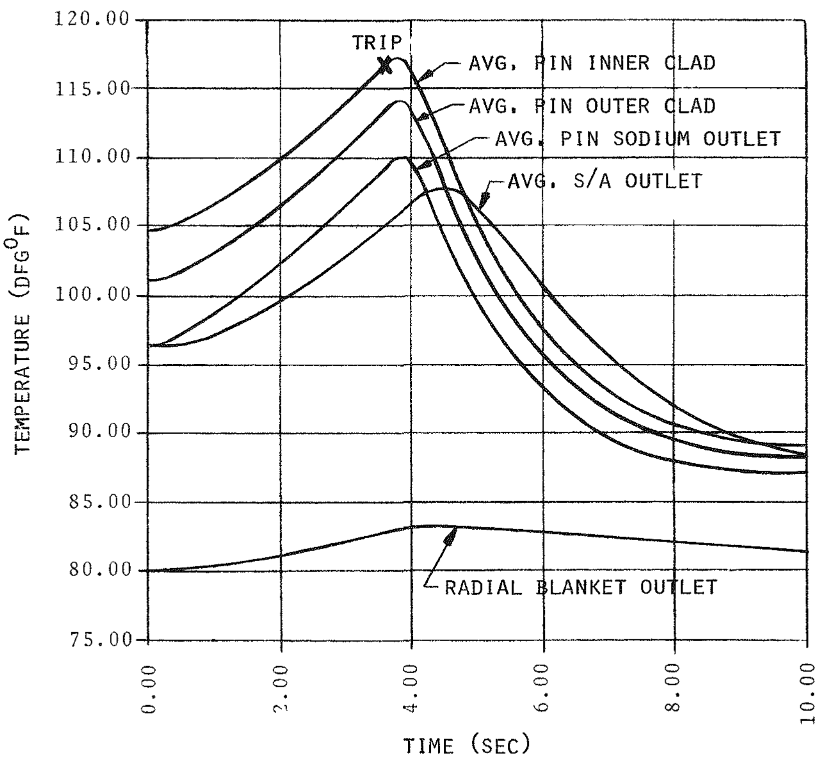


FIGURE D-14 AVERAGE FUEL CLAD AND SODIUM TEMPERATURES-TUC WITH SYSTEM A

$$\frac{n}{n_o} \approx \frac{1}{1-\rho} \qquad \text{for } \rho < 1 \text{ (in dollars)}$$

$$\frac{d\left(\frac{n}{n_0}\right)}{dt} \approx \frac{1}{(1-\rho)^2} \frac{dP}{dt}$$

at $t = o$, $\rho = o$

$$\frac{d\rho}{dt} = \$.10/\text{sec} \qquad \frac{d\left(\frac{n}{n_o}\right)}{dt} \approx .1/\text{sec}$$

A 10%/second power rate increase is thus expected immediately subsequent to the 10¢/second ramp introduction.

This power/flow ratio increase is identical to the ratio generated by the TUC case using the CRBR coastdown for the first three seconds. Comparable response times would thus be expected, although the SASS response to the 10¢/second TOP (without a coastdown) would be slightly sooner due to lower transport delay at full flow.

Appendix E

ALTERNATE POISON CONFIGURATIONS

A number of alternate poison assembly configurations were investigated which would offer highly reliable insertion, high reactivity worth and compact design. Specifically, the following features were incorporated in the assembly design:

- High reliability of insertion by accommodation of duct distortion.
- Maximum poison loading to minimize the number of rods required for shutdown.
- Round poison bundle within a cylindrical duct so as to withstand large laterel thrusts without distortion.
- Minimum weight-to-area ratio to minimize the differential pressure required for hydraulic support of the assembly.

Several alternate concepts were developed which would ensure rod insertion with gross distortion of the control assembly duct and are as follows:

(1) Flexible seal ring

(2) Hinged support

(3) Torsional-contracting support

(4) Telescopic-articulated assembly

The flexible seal ring concept, as shown in Figure E.1, incorporates rings of over-lapping flexible discs at each end of the assembly. These discs adapt to any radial or circumferential deformations in the duct to ensure assembly insertion under gravity drop. The rings also minimize bypass flow around the poison assembly. Flexible discs, however, may be susceptible to breakage during handling.

The hinged support concept, shown in Figure E.2, has been previously proposed by C-E (U.S.P. 3959.072). The poison assembly incorporates 18 pins mounted on hinged arms which retract upon meeting an obstruction to axial motion of the assembly. The assembly design is integrated to minimize the use of small parts

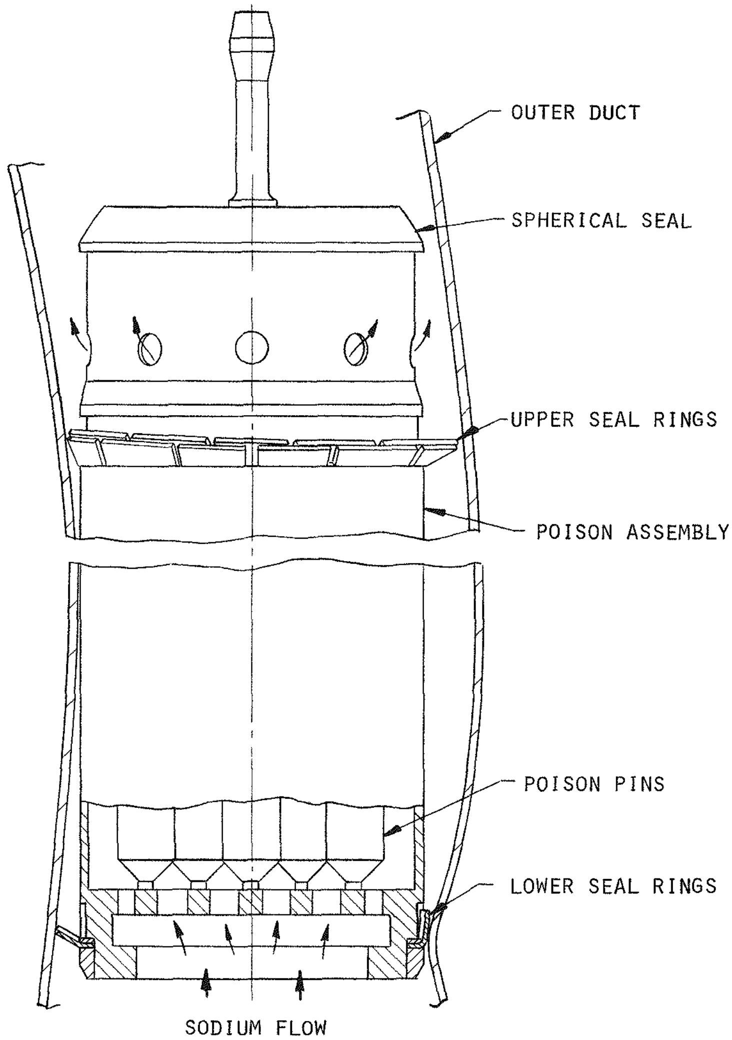


FIGURE E-1 FLEXIBLE SEAL RINGS CONCEPT

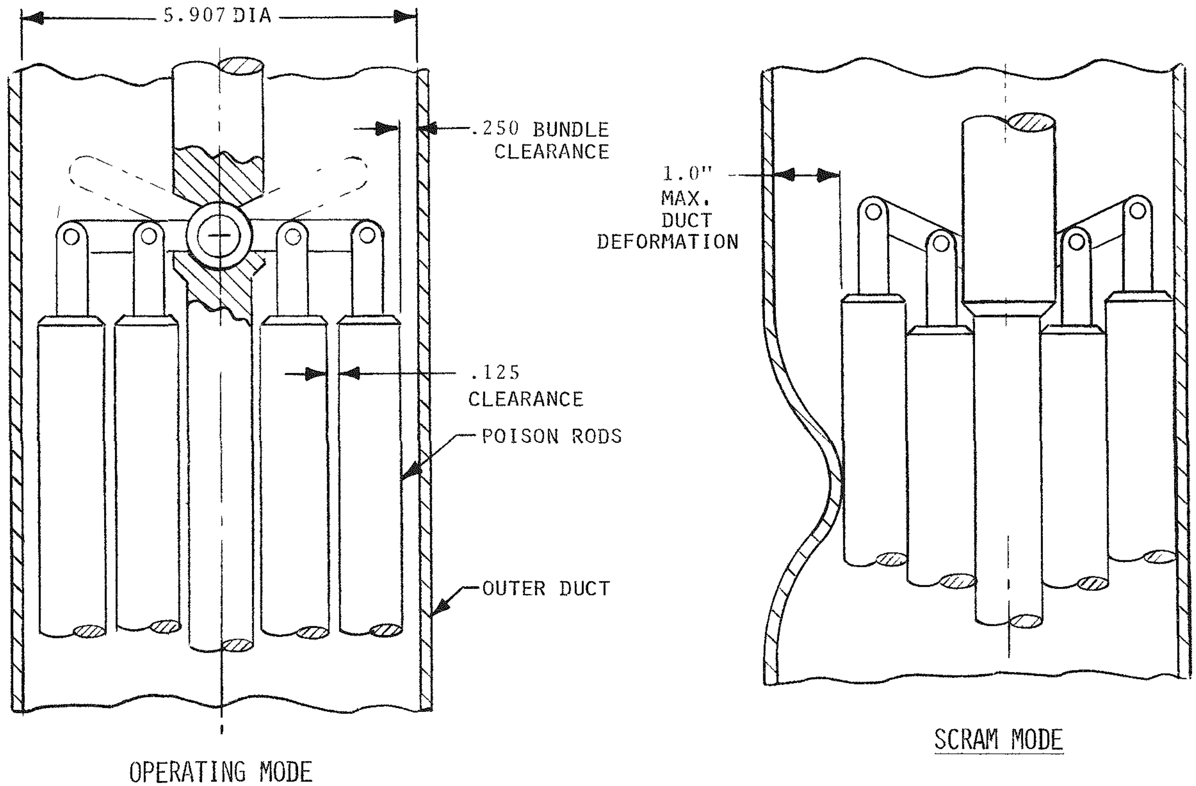


FIGURE E-2 HINGED POISON SUPPORT CONCEPT ELEVATION

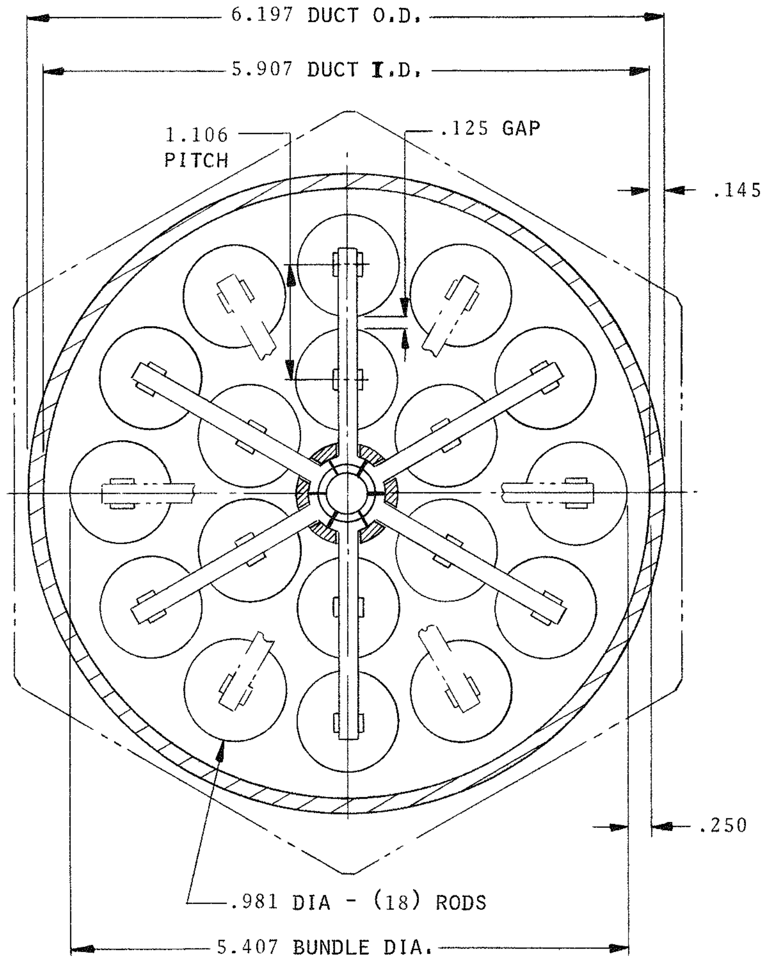


FIGURE E-2 HINGED SUPPORT CONCEPT PLAN

which may be released into the reactor system. This concept results in reduced poison loading due to the limited pin support system, but avoids the seal problem found with close-packed poison bundle concepts, since the rods are uniformly distributed across the entire flow duct.

The torsional contracting concept, shown in Figure E.3, consists of 18 absorber pins mounted in a circular pattern eccentrically to their tru axis, whereby each pin can rotate inward upon encountering an outer duct deformation. Each pin is oriented by a torsion spring to maintain the bundle symmetry and to absorb the shock during insertions. The main disadvantages of this concept are a reduced poison loading and relaxation of springs due to neutron radiation effects.

The telescopic articulated concept, as illustrated in Figure E.4, consists of an inner bundle containing poison pins and an outer cylinder containing B_4C. The outer cylinder is sized for adequate clearances both for the inner bundle as well as the duct/guide tube. In case of obstruction, the outer cylinder is held up and the inner bundle continues downward and thus contributes to total negative reactivity insertion. The main disadvantages of this concept are reduced poison loading and complex design of the bundle.

Within the cylindrical bundle envelope for the poison rods, two arrangements were considered, namely, a triangular pitch arrangement and a circular pitch arrangement. A comparative table illustrates the major parameters for the two arrangements. The triangular pitch arrangements contains slightly less poison because of non-circular voids at the boundary which must be filled with spacers for structural stability. The circular pitch arrangement, on the other hand, has low pressure drop characteristics and results in a fairly uniform distribution of poison pins within the cylindrical bundle.

The control assembly parameters were scaled up from the CRBRP secondary control rod parameters for PLBR.

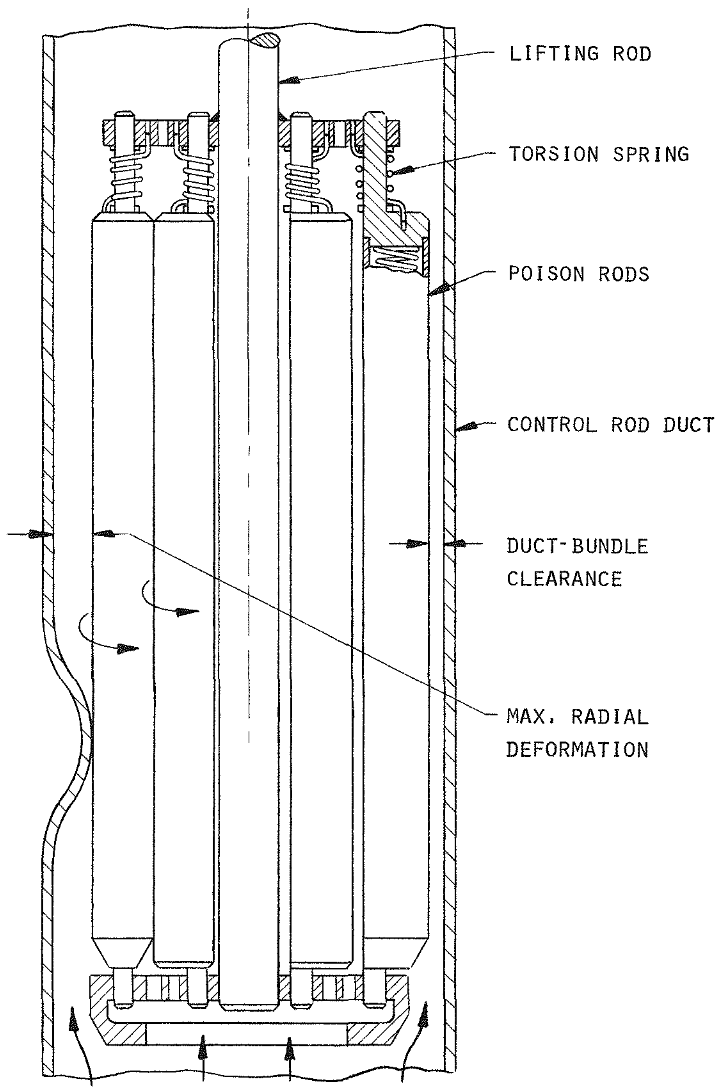


FIGURE E-3 TORSIONAL CONTRACTING CONCEPT ELEVATION

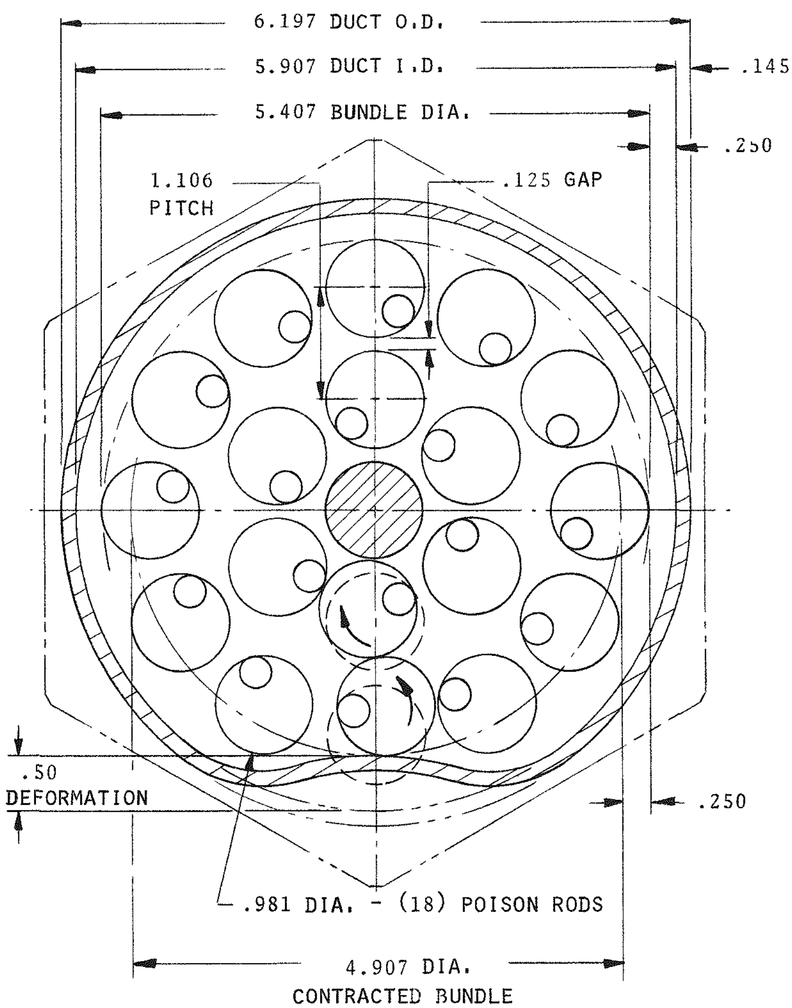


FIGURE E-3 TORSIONAL CONTRACTING CONCEPT PLAN

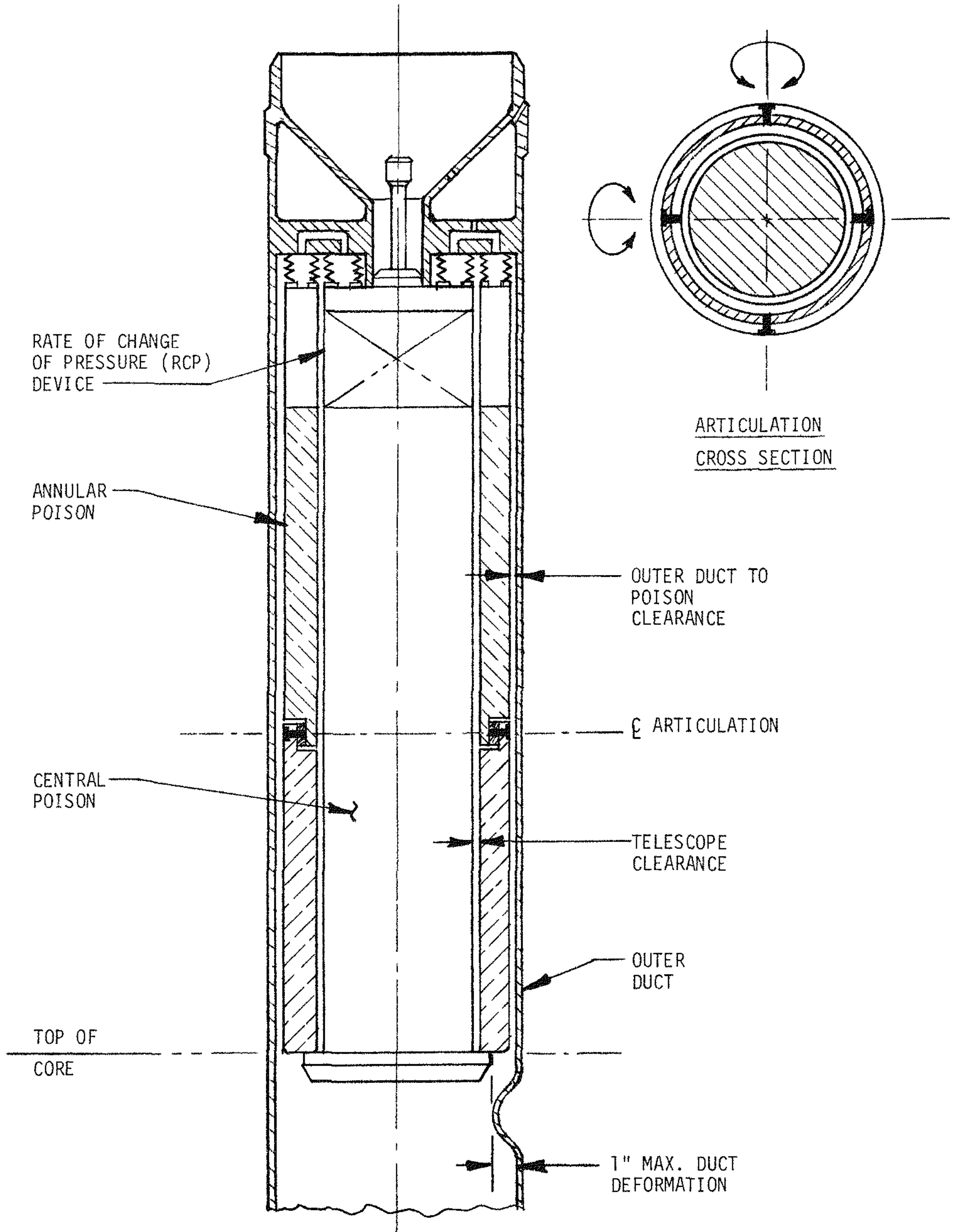


FIGURE E-4 TELESCOPIC - ARTICULATED POISON ASS'Y

COMPARISON

B_4C PIN BUNDLE PARAMETERS

	Circular Array	Triangular Array
Duct OD/Thickness (in.)	6.197/.145	6.197/.145
Duct ID (in.)	5.907	5.907
Duct - Guide Tube Radial Gap (in.)	.250	.250
Guide Tube OD/Thickness (in.)	5.407/.050	5.407/0.50
Guide Tube ID (in.)	5.307	5.307
Pin Pitch-To-Dia. Ratio (in.)	1.05	1.06
Poison Bundle Dia. (in.)	5.257	5.257
Bunndle-Guide Tube Diametral Clearance (in.)	.050	.050
No. of Poison Pin	37	37
Absorber (B_4C) Length (in.)	48	48
Pin OD/Clad Thickness (in.)	.744/.050	.781/.050
Boron Density (lbs/in^3)	.085	.085
Boron Mass Per Pin Dry (lbs)	1.32	1.39
Boron Mass Per Ass'y Dry (lbs)	49.2	43.0
Gas Plenum (in.)	20	20