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Design Requirement on KALIMER Control Rod Assembly Duct

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Submission Statement

To: The President of KAERI

This report is submitted as the report for the word of "Design Requirement on KALIMER Control Rod Assembly Duct."

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요약문

본 문서는 KALIMER 제어봉집합체덕트의 설계길잡이로써 설계하는데 필요한 제반 요건을 확립하였다. KALIMER 제어집합체는 흡수재가 배열된 내부 덕트와 이를 감싸고 있는 외부 덕트로 되어 있으므로 본 문서에는 흡수재의 기능 및 성능요건과 내부 및 외부 덕트의 설계한계 및 강도요건이 기술되어 있고 또한 그외 인접계통요건, 지진시요건, 구조적요건, 환경적요건, 신뢰도 안전요건, 표준요건, QA요건 및 기타요건 들이 기술되어 있다. 본 문서에서는 제어집합체계통의 구동장치, 구동선로를 제외한 KALIMER 제어집합체에 대한 설계요건을 다루고 있다.

Summary

This report establishes a design guideline which is needed for designing the control rod assembly duct of the KALIMER as a design document. It describes the design requirements on control rod assembly duct of the KALIMER that includes functional requirements, performance requirements, interfacing systems, design limits and strength requirements, seismic requirements, structural requirements, environmental requirements, reliability and safety requirements, standard and codes, QA programs, and other requirements. The control rod system consists of three parts, which are drive mechanism, driveline, and absorber bundle. This report deals with the absorber bundle and its outer duct only because the others are beyond the scope of fuel system design.

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1. General

Reactor power is controlled by changing the neutron flux. The options for the control are based on changing the neutron-leakage, production, or absorbing rates. This can be accomplished by moving either fuels or neutron-absorbing materials in or out of the core, or by moving reflector materials in such a way as to vary its effectiveness. The present method for reactivity control is the movement of neutron absorbing materials, sometimes coupling with movement of fuel, in and out of the core. This is wasteful of neutrons and decreases the breeding ratio.

The reactivity control and shutdown systems in the KALIMER (Korea Advanced LIquid MEtal Reactor) consists of six drive assemblies and SASS (Self Actuated Safe System) which are used for power control, burnup compensation and reactor shutdown in response to demands from the plant control or protection systems. It deploys in response to loss of electrical power signals from the reactor protection system or signal from the plant control system.

The control assembly consists of a movable inner absorber assembly (absorber material assembly) and outer assembly duct that remains in a fixed position in the core during normal reactor operation. These assemblies are similar in all currently conceived LMFBRs (Liquid Metal Fast Breeder Reactors).

The motion of the absorber assembly (inner assembly duct) starts and shuts down the reactor, makes adjustments in power level, and compensates for reactivity changes during operation. Absorber assemblies are also used in a safety function to shutdown the reactor rapidly. The absorber assembly consists of a cluster of absorber elements, supporting and spacing devices for elements, and lifting adapter by which connection is made to the drive line of the control drive mechanism.

The control assembly duct (outer duct assembly) is used primarily to isolate the movable absorber assembly from the stationary fuel assemblies. As such, it acts as one of the barriers between the driver fuel elements and the absorber elements.

The outer control assembly duct consists of an orifice assembly and a nosepiece, similar to that used in driver fuel assemblies, that acts as a neutron shield and contains an orifice to regular coolant flow through the entire control assembly; a hexagonal outer duct with the same outer dimensions as a driver fuel assembly duct; and handling socket at the top end, used for lifting and identifying the assembly.

The purpose of the control rod is to allow a shutdown reactivity margin and to compensate for the reactivity changes due to fuel burnup and fission product build-up during the fuel cycle. Moreover, the power shape can be controlled during the fuel cycle using effect of control rod insertion and optimum strategies can be devised to obtain an optimum power shape (i.e., flat) during the cycle.

The calculation methods should be such that the reactivity of all the envisaged situations could be calculated and the associated uncertainties specified, to define the conservative reactivity value at each point of the procedure outlined above (including uncertainties).

In addition to the reactivity worth, more information related to the control subassembly performances is needed:

1) Helium production, in the case of boron carbide rods (helium production causes swelling and is a factor that determines the control rod life.)

2) Heating generation and, consequently, temperature in absorber pins or

control rod subassembly duct

3) Distorted power distribution in fuel subassemblies adjacent to control rods (the flux distortions cause displacement doses and dose gradient to vary during the cycle.)

Selection of a reference control absorber material and design shall take advantage of the LMFBR experience and recognize the difficulties associated with candidate materials, which presently include boron carbide, europium oxide, and tantalum. These difficulties include the gas release and swelling in boron carbide, the high decay heat rate in tantalum, and the low thermal conductivity in europium oxide; further, it shall be shown that the control absorber has an acceptable lifetime – with the minimum lifetime being equal to the refueling interval (normally one year).

Reactivity control and shutdown system of the KALIMER has two different types. One is active control and shutdown system (motor driven) and the other is passive reactor shutdown system (by gravity).

The active reactivity control and shutdown system consists of six drive assemblies which are used for power control, burnup compensation and reactor shutdown in response to demands from the plant control or protection systems. It deploys in response to loss of electrical power signals from the reactor protection system or signals from the plant control system.

For the passive reactor shutdown adopts a self-actuated shutdown system (SASS) as an ultimate shutdown system which comprises one ultimate shutdown assembly in the core which drop shut-off rod by gravity. The self-actuated shutdown system is a passive reactor shutdown system self-actuated by the natural physical phenomena without any external control signals and any actuating power in the emergency of the reactor.

Curie point electromagnet (CPEM) is to be used as a key component in the SASS, whose saturated magnetic flux density is remarkably reduced at the curie point of the temperature sensitive material used in the CPEM. When the temperature of the primary sodium goes up to the curie point, the CPEM loses its electromagnetic force to exert the shut-off rod. Then the shut-off rod with the CPEM drops into the core due to its deadweight. The shut-off rods are designed to be an articulated type for easy insertion into core even when the guide tubes are deformed due to the earthquake.

Design conditions for control assemblies are dependent upon the operating philosophy of the overall reactor control system. For example, in a control system having separate shim and safety drives, the absorber assemblies of the safety system are always fully withdrawn from the core when the reactor is operating.

The KALIMER control rod system consists of the drive mechanism, driveline, the absorber bundle, and absorber channel. However, the driver mechanism and driverline are beyond the scope of fuel system design. Hence, further details of control rod system are focus on absorber bundle, and inner/outer ducts.

1.1 Drive Mechanism

The drive mechanism is mounted on top of the reactor vessel closure and control axial motion of the absorber bundle in the core. It affects control rod insertion, withdrawal, and scram release.

1.2 Driveline

The driveline connects the drive mechanism to the absorber bundle. The driveline passed down through a shroud tube in the upper internal structure, which provides driveline alignment, support, and coolant flow from the reactor outlet.

1.3 Absorber Bundle

The absorber bundle is a closely packed array of tubes containing boron carbide pellets. The tubes, referred to as "pins," are each helical wrapped with wire and bundle into a triangle pitch, hexagonal pattern or bolt pitch pattern as like CANDU fuel bundle. The wire wrap maintains pin spacing so that coolant may flow freely through the absorber bundle. The bundles are contained in thin hexagonal ducts or round ducts (which is not determined) that channel coolant flow through them and protect the pins from damage as they are slid into and out of the core within outer fixed ducts. The outer duct is hexagonal, having dimensions identical to the adjacent fuel assemblies. The rigid bundle and inner duct transmit high insertion forces, if needed for powered scram drive-in. The control assembly is realized with two parts, the outer hexagonal shell and the absorber bundle. In the case of double hexagonal duct assembly, the external shape of the duct is similar to the driver fuel assembly one. The absorber rod itself is composed by the pin bundle, the inner shell, the upper guide tube, and lifting head connected to the mechanism. The bundle has several tens pins (TBD) and dozen dummy pins (TBD if applicable) on the periphery to improve the cooling. The pins are sodium bonded and the gap is determined to accommodate the B_4C swelling to avoid mechanical interaction at end of life and so the gap is a function of the expected residence time of the absorber.

The absorber bundle is contained fully within the control assembly at all times. Its movement in and out of the active core region regulates reactivity. Its stroke is about 100 cm (TBD) from full insertion to full withdrawal. During shutdown when the absorber bundle is disconnected, the control drive stroke is about 130 cm (TBD) so that the control rod driveline may withdraw from the control assembly and park far enough above the core to permit rotation of the closure plug from refueling. For recoupling after the absorber bundle is released from the driveline, the opening or nozzle at the top of the assembly aligns and guides the drivenline into re-engagement with the absorber bundle.

This document establishes technical design requirements for the design of safe, reliable, and economic KALIMER control rod system and their subcomponents including control rod assembly ducts. The design requirements in this document are intended to be used for the design of control rod system of KALIMER. The word "shall" or "must" are used to denote a requirement; the word "should" is used to denote a recommendation; and the word "may" is used to denote a permission, neither a requirement nor a recommendation.

2. Functional Requirements

2.1 Requirements of the Control System

For the KALIMER, the primary control rod system serves both reactor reactivity control and primary shutdown functions. The control rod system shall provide the following functions:

1) The control rod system shall provide to start-up of the reactor.

2) The control system shall provide the safety function by negative reactivity introduction to assure the reactor power decrease or shutdown when incidental or accidental situation occurs.

3) The control system shall be designed to scram the reactor on emergency conditions.

4) The control system shall provide to have compensation of reactivity effects due to thermal or power variations and to fuel burnup.

5) The control rod system should provide incremental rod motions small enough, when compared to the reactor controller dead band, to preclude controller limit cycling.

6) Rod motion steps on the order of 0.0635 cm (details are TBD) are desired to maintain adequate margin against limit cycling.

7) The control rod assembly duct must be designed to withstand axial compressive forces caused during loading or unloading of the duct.

2.2 Requirements of the Control Absorber Rod

1) The absorber pin (or rod) shall be designed to maintain their integrity during normal reactor operation.

2) The absorber rod with wire wrap shall be dimensionally compatible to accommodate absorber rod expansion due to irradiation

3) The absorber rod shall be designed to accommodate expected dimensional changes, such as element swelling, thermal expansion, creep, and its axial growth, during irradiation.

4) The absorber rod shall contain and confine within the cladding the solid and gaseous products that are generated by neutron absorption reaction.

5) The cladding shall provide structural integrity for the absorber pin and serve to separate the absorber material from direct contact with the coolant, thereby preventing the isotopes from entering the primary coolant.

6) The absorber rod shall be provided with wire wrap to maintain pin-to-pin and pin-to-duct space, and to mixup the coolant flow.

7) The sufficient plenum volume shall be provided to accommodate the released helium gas from absorber material, and to prevent cladding from over-pressurization by the buildup of gas pressure according to burnup increase.

8) The large sodium-filled gap between absorber pellet and cladding shall be provided to allow sufficient volume for absorber swelling, and to permit good heat transfer.

2.3 Requirements of the Control Rod Assembly

1) Each control rod assembly (bundle) shall have mechanical travel stops for

both directions of travel.

2) A loss of power to the control rod system shall results in the absorber bundle entering fully into the core.

3) The control bundle shall be provided with the outer duct for unobstructed motion over their entire length of travel.

4) Mechanical restraints acting directly on the absorber rods shall prevent their being accidentally disengaged from the outer duct.

5) The duct material shall have adequate strength and resistance to wear, erosion, corrosion and radiation damage or shall be encased in a sheath of suitable material, so as to maintain the absorber rod's shape and function for the design life of the reactor. In the event the absorber material is encapsulated, a void space shall be provided for any radiolytic gas generated.

2.4 Requirements of Inner and Outer Ducts

The inner (if applicable) and outer ducts to house a absorber bundle (or inner absorber duct) serve a number of functions in KALIMER, including the followings:

1) The outer ducts force the sodium to flow pass the control rods and not bypass the high-flow resistance path within the rod bundle or inner duct (if applicable).

2) The ducts provide structural support for the control rod bundle.

3) The ducts provide a mechanical means to load the rods into the core as a unit, with the assembly of ducts constrained by the core restraint system.

4) The core subsystems must be designed to withstand axial compressive forces caused during loading or unloading of the duct.

5) The inner and outer assembly duct must be designed to maintain its integrity during normal reactor operation.

6) The inner and outer assembly ducts must be designed to accommodate expected dimensional changes, such as element swelling, creep, and its axial growth, during irradiation.

7) The control rod assembly duct and core subsystems plugged-in receptacle on upper grid plate shall be designed to withstand the axial load caused by the hydraulic drag load of the primary cooling system.

8) The control rod assembly duct and core subsystems must be designed to withstand axial compressive forces caused during loading or unloading of the duct.

2.5 Service Conditions

The control rod system shall meet their functional requirements during and after all of the service conditions applicable to the reactivity mechanisms. These service conditions are:

1) Type 1 conditions

- Normal startup of the reactor
- Full power steady state operation of the reactor

- Setback (50% of full power) steady state operation of the reactor
- Normal shutdown
- Trip or scram shutdown
- Loss of primary cooling system cooling or circulation
- Loss of electrical power

2) Type 2 conditions

- Design Basis Earthquake

3. Performance Requirements

3.1 General

Design requirements for the absorber material and its assembly in the liquid metal reactors are derived mainly from the reactor system and control rod subsystem requirements. A primary function of the control rod system is to provide for safe and predictable operation of the reactor system. The absorber material selected must posses and retain reactivity worth sufficient to meet the functional requirements during its service lifetime. The absorber material must be compatible with absorber pin internals, maintain adequate physical integrity during its service life, and not produce daughter products that will limit the performance capability of any interfacing component such that the lifetime requirements are compromised. A general design criterion is that the length of the reactor cycle shall not be limited by inadequate absorber assembly performance.

The performance of the control rod system during normal operation, anticipated operational occurrences, and postulated accidents shall be considered to determine if all design bases are met. The control system components shall be considered not only as separate components but also as integral units such as control rods and control rod assembly ducts.

1) A reactivity worth-related characteristic which must be considered in evaluating absorber materials is burnout rate. A slow burnout rate is desirable, since rapid reactivity worth depletion could restrict the useful lifetime of an absorber assembly, and require early replacement.

2) Compatibility of the absorber material with surrounding components is mandatory. Significant chemical interaction between absorber pellets and their containment cladding shall be prevented.

3) The susceptibility of the absorber material to phenomena such as melting, phase change, or vaporization at operating temperature must be evaluated.

4) High thermal conductivity is a desirable characteristic in absorber materials, because such thermal problems are more likely to be avoided.

5) Consideration must also be given to compatibility of the absorber material with reactor coolant should a cladding breach occur. The rate and nature of absorber washout in the event of a cladding requires characterization.

6) The absorber material must retain adequate physical integrity with irradiation exposure to ensure that the absorber column remains intact and in its proper position within the pin.

7) Allowance must be provided in the absorber pin to accommodate irradiation-induced swelling of the absorber pellets. If the absorber swelling rate exceeds the cladding swelling rate by a significant degree, the large pellet-to-cladding gaps required to accommodate the diametric growth could results in such high pellet operating temperature that thermal problems such as those cited previously might be encountered.

8) Attention must be given to the reaction productions that result from neutron captures in the absorber material. If a gas is produced and released from the absorber, provisions must be made to accommodated or vent the evolved gas. Should the absorber become highly radioactive as a result of irradiation exposure, considerable after-heating may be incurred in the absorber assemblies. Such behavior could introduce problems related to cooling the absorber assemblies during shutdown period and following removal from service.

9) Material density is another property that should be considered in the selection of an absorber material. If the material possesses a vary high

density, the absorber assembly may become undesirably massive. This would increase demands on control rod drive mechanisms and scram arrest mechanism.

10) Commercial availability and fabricability, as well as cost of the absorber candidate must be evaluated. Considerable vendor development effort may be required before particular materials can be qualified for reactor service. Economics must be considered in all stages of the design process.

3.2 Design Criteria for Shutdown System

Broad guidelines for design of shutdown system are as follows:

1) At least two reliable, independent, automatic, fast actuating shutdown system shall be provided operating on diverse principles. At least one of the systems shall meet all functional requirements even in case of postulated core deformation. The reliability of each system shall be such that its non-availability is less than 10^{-3} per reactor year (TBD) and the overall non-availability of the two systems shall be less than 10^{-6} per reactor year (TBD).

2) The design shall provide sufficient redundancy so that failure of a single most effective absorber rod of a shutdown system shall not result in impairment of that system to an extent that it will not meet the minimum specified requirements of negative reactivity.

3) One of the shutdown systems could be used for reactivity control. However, while doing so, its functional capability to shutdown the reactor shall not be jeopardized.

4) The reactivity worth, speed of action and delay in actuation of each

shutdown system shall be such that during all operational states and postulated accident conditions of the reactor, including the most reactive state of the core,

- the reactor is rendered sufficiently sub-critical and maintained sub-critical under cold condition, taking into account uncertainties in the neutronics calculations/measurements,
- the specified fuel design limits are not exceeded,
- the reactor coolant system design limits are not exceeded.

5) The availability of safety support systems necessary for actuation of a shutdown system shall be commensurate with the availability requirements of the shutdown system.

6) All equipment shall be designed such that its probable failure modes will not result in an unsafe condition.

7) The design shall be such that all maintenance and availability testing which may be required during reactor operation can be carried out without a reduction in the effectiveness of each system below the minimum allowance requirements.

8) The design shall be such that each shutdown system can be actuated manually from the main and emergency control rooms.

9) The design shall be such that it is not readily possible for an operator to prevent a safe automatic action from taking place.

10) The control logic of the absorber rods and their drive mechanism shall be designed to prevent unintended movement in the directions which add reactivity.

11) Maximum reactivity worth of an absorber rod, together with its maximum possible withdrawal speed, shall be limited such that the fuel, coolant and cladding design limits are not exceeded in the event of uncontrolled withdrawal of the rod.

12) The control rod system is designed to tolerate a set of design-basis accidents with allowable consequences ranging from no significant degradation of expected control rod lifetime to maintenance of a coolable geometry.

3.3 Control Rod

The interaction between control rods in a bundle causes a varying temperature distribution around a rod, bowing, bundle compression due to cladding swelling, and cladding wear due to friction between rods. The control rod system shall be designed with appropriate margin to ensure that specified acceptable control rod design limits are not exceeded during any condition of normal operation, including the effects of anticipated operational occurrences.

The followings are the control rod performance and operational requirements

1) The thermal conductivity of control rod pellet shall be sufficiently high so that in-reactor maximum operating temperatures will be easily restricted to be lower than the melting temperature of control rod pellet.

2) The control rods must be designed to contain all gaseous gas and solid products during operation

3) The control rod pellet materials shall be stable thermo-chemically under irradiation, and shall corrode slowly in the events of a clad defect.

4) The control rod internal pressure shall be less than the critical pressure for plastic deformation of cladding. The maximum permissible diametric increase of rod shall be compatible with the thermal-hydaulic requirements, and in any event shall be less than 2 % (TBD).

5) Operation through normal and anticipated duty-cycle events which include load following and beyond cladding breach operation, shall not cause more than 0.01% (TBD) of the pins in the equilibrium core to fail per cycle.

6) The number of control rod failures shall be not underestimated for postulated accidents.

7) The control rod should be designed to maintain its structural integrity during its lifetime under NOC. CDF (cumulative damage fraction) shall not be greater than the following criteria ;

   - Steady state operation: < 0.001 (TBD)

   - Transient operation: < 0.2 (TBD).

8) The coolant flow past the control rods may cause pin vibration. The motions of the pins must be sufficiently small that the absorber assemblies are not damaged internally.

9) The absorber pin should be designed to meet requirements on stress levels at power and during refueling.

10) Cladding wastage including the internal attack shall be limited to be less than 10% (TBD) of the cladding wall thickness, so that cladding strength

degradation.

3.4 Control Rod Assembly Duct

The performance and operational requirements on the design of the control rod assembly duct should be prepared considering an important aspect of the control rod assembly duct in the presence of dilation and bowing due to thermal and irradiation effects. The bowing and dilation affect the movement of the control assembly, the operations primary heat transfer and fuel handling systems. The performance and operational requirements for the control rod assembly duct are the same as that of the driver fuel assembly duct.

3.5 Shutdown Performance Requirements

• Absorber life	To be determined later
• Travel length	To be determined later
• Insertion time over a length of travel of 85 cm (TBD)	To be determined later
• Insertion time over a length of travel of 100 cm (TBD) (i.e., fully inserted)	To be determined later
• Withdrawal time over 100cm (TBD)	Greater than 28 sec (TBD)
• Absorber rod diameter - outer	To be determined later
• Absorber rod diameter - inner	To be determined later

3.6 Control Absorber Performance Requirements

• Absorber life	To be determined later
• Travel length	To be determined later
• Insertion time over a length of travel of 85cm (TBD)	To be determined later
• Insertion time over a length of travel of 100cm (TBD) (i.e., fully inserted)	To be determined later
• Withdrawal time over 100cm (TBD)	Greater than 28 sec (TBD)
• Absorber rod diameter – outer	To be determined later
• Absorber rod diameter – inner	To be determined later

4. Interfacing Systems

For the control rod system, B_4C is chosen as absorber material because of its relatively high neutron cross section, commercial availability, ease of fabrication, low cost and good operating experience in fast reactors. B-10 enrichment is kept in the range of 20~70% (TBD) so as to have a margin for extra reactivity requirements in future without changing number of rods.

4.1 Control Rod Drive Mechanism

Detailed design features of the control rod drive mechanism are forced by specific operating requirements, interfaces and environments. The requirements typically include stroke length, velocity, system weights, scram and safety requirements. Environmental considerations include steady state and transient thermal duty cycle, atmosphere and seismic loading. The integration of the specific set of requirements for the KALIMER mechanism, and the resulting design configuration will be determined in future revisions.

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

The fundamental requirement is that the system provide incremental rod motions small enough, when compared to the reactor controller dead band, to preclude controller limit cycling. Rod motion steps on the order of 0.635mm (TBD) are desired to maintain adequate margin against limit cycling. A second concept limit factor is the desire to provide positive drive-in capability for the control rod which leads to a requirement to provide a 453.6kg (TBD) minimum drive-in force to free a stuck rod.

Other factor which did not necessarily fix the choice of systems but certainly influenced the choice were:

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

4.2 Reactivity Worth

Reactivity worth of absorber rods must be adequate to saticfy the following criteria:

- Adequacy of shutdown margin (SDM) to handle postulated incidents like LOF, TOP due to uncontrolled full withdrawal of the most reactive absorber rod or due to any reason, fuel melting and slumping in a few sub-assemblies, sodium boiling and voiding in a few sub-assemblies etc.
- Adequacy of reactivity worth in each individual shutdown system to bring the reactor to cold shutdown state assuming that other system has failed and the most reactive rod of the working system is also stuck.

4.3 Mechanism Design

Stationary hexagonal duct of absorber rod is like any other fuel sub-assembly externally, whereas mobile outer sheath of absorber pins is cylindrical. In each control bundle, there are 31 pins (to be determined later) each having B_4C pellets in clad tubes. Pins are sealed having sodium as bonding material (if applicable). Duct, outer sheath and clad are all made of HT9.

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

4.4 Thermal-Hydraulic Design

Sodium flow in absorber bundle is such that

- Maximum cladding mid-wall temperature shall not exceed 650°C (TBD) under normal operating conditions when the rods are in withdrawn position

- The sodium hot spot temperature which is in between B_4C pellet and cladding shall not exceed the boiling point during the fall of one absorber rod into the core when the reactor is operating at full power under new equilibrium configuration.

Since the operating experience in sodium vapor is minimal, it is recommended that the drive mechanism be sealed from the sodium vapor by metallic bellows.

The control assembly hydraulic test and the scram dynamics test provided hydraulic data emphasizing the flow split between the pin bundle and bypass flow, pressure drops and flow induced vibrations and the scram characteristics of the control rod driveline.

4.5 Bowing

The flux and temperature profiles expected in the KALIMER produce differential axial expansion on opposite faces of the fuel-assembly ducts, which may result in control rod assembly duct bowing and requires a radial core-restraint system capable of maintaining safe reactivity control during operation while also providing sufficient clearances for fuel handling during shutdown.

4.6 Core Restraint and Interface Requirements

4.6.1 Absorber Rod

The absorber rod bundle is immerged in the sodium coolant during service life. The interfacing with the coolant should be considered as followings.

1) Coolant flow during normal operation shall be such that the absorber rod cladding will remain in sodium coolant.

2) Sodium coolant chemistry shall be controlled in order to minimize the cladding wastage or corrosion as described in section 8.2.1.

3) Bulk coolant temperature shall be less than 530°C (TBD) to maintain the integrity of cladding.

4.6.2 Control Rod Assembly Duct

The interfacing systems shall compose the core restraint containing the core support structure, driver fuel, primary coolant system (PCS), fuel handling system (FHS).

According to the requirements to allow clearance between control rod assembly duct and driver fuel assembly ducts to accommodate the swelling, and to constrain the core to resist bowing (due to swelling and thermal gradients), it is necessary to provide a core restraint system. Such a system fulfills the following functions:

1) Provide a calculable and reproducible structure response of the core within the limits imposed by reactivity insertion considerations during both long-term irradiation and transient conditions.

2) Maintain the tops of the core assemblies in a position such that handling heads can be remotely located and grappled by the grapple finger of IVTM.

3) Provide clearance for control rod assembly duct insertion and removal, with minimal vertical friction, during shutdown refueling conditions.

4) Debris in the coolant shall be minimized

Design requirements of the outer duct imposed on and by the duct wall are as follows:

1) The hexagonal outer duct and related components must be dimensionally compatible to accommodate any dimensional changes due to irradiation.

2) The hexagonal outer duct shall have provision for attaching and locking to the nosepiece, and shall have adequate support for absorber bundle or inner duct.

3) The thickness of outer duct wall shall be determined to keep its structural integrity due to internal duct pressure and thermal stress due to temperature gradients.

4.7 Design Requirements Imposed on and by Primary Coolant System

1) The coolant flow and temperature during normal operation shall be such that the control rod cladding will remain adequately cooled down below 650°C (TBD). The design mass flow rate will be provided by T/H analysis.

2) The primary coolant system shall provide a vibration-free environment that ensures that control rod assemblies are not internally damaged and that they do not damage the duct wall.

3) Coolant chemistry shall be controlled to minimize cladding corrosion.

4) Debris in the coolant shall be minimized.

5) The control rod assembly duct and core sub system shall be able to withstand the axial load caused by the hydraulic drag load of PCS.

5. Design Limits and Strength Requirements

Control rod system for liquid metal reactors must be designed for operation in high neutron fluxes and at operating temperatures of cladding up to 650°C (TBD). At these conditions, control rods must be conformed to following requirements:

- to provide the free moving in directional tubes and the reliability of the insertion in the core at an emergency;
- to keep the mechanical strength;
- to keep the requirement level of the efficiency during the operating life.

Using absorbing and constructional materials must:

- to be compatible to one another in the whole operating temperature region and emergency conditions;
- to have the minimal irradiation destruction and swelling under neutron fluxes.

Control element lifetimes in LMRs (Liquid Metal Reactors) are potentially restricted by several phenomena such as gas pressure, boron carbide swelling, reactivity worth depletion, and duct swelling. For evaluating larger pin designs, thermal performance must also be considered with regard to boron carbide melting, temperature gradients, and heat flux through the cladding. Another major performance parameter to be taken into account is scram behavior of the absorber assembly.

Helium gas is produced in boron carbide during irradiation by the $^{10}B(n,\alpha)^{7}Li$ neutron absorption reaction. Some of the gases are released from the boron carbide pellets and (in the case of sealed pins) causes gas pressure to build up in the control pin plena. For the KALIMER, end-of-life condition prevail if gas pressure reaches a level that produces cladding hoop stresses in excess of 90% (TBD) of the yield strength, or causes a total permanent strain of 0.3% (TBD) (including an allowance of 0.1% (TBD) for transient operation).

Swelling of the boron carbide pellets under irradiation can potentially limit control element lifetime. Should swelling close the annular gap between the pellets and the cladding, the latter could suffer permanent deformation and possibly even rupture. Adequate clearance must be provided to preclude gap closure during operation. At the same time the temperature and eccentricity effects resulting from utilization of large clearances must be considered.

Depletion of reactivity worth in a control element can eventually limit lifetime. For the KALIMER, a 10% (TBD) reduction in worth for a control rod or 20% (TBD) reduction in worth for a fixed shim rod is defined as an end-of-life condition. These values are quite arbitrary and presently are not limiting.

Thermal and flux gradients across control rod duct tubes cause these components to bow during irradiation service. Differential bowing between inner and outer duct tubes can eventually cause three-point contact to be made between these components during axial travel of the control rod. This situation again constitutes and end-of-life condition for the KALIMER control elements. An important aspect of this lifetime-limited phenomenon is the fact that bowing-dependent interference can be reduced by shortening the inner duct. One method for accomplishing this is by employing vented control pins, thereby eliminating the need for gas plena that are required in sealed pins.

Thermal conditions in control pins increase in severity with increasing pin diameter. Central temperature in large-diameter pellets could conceivably exceed the melting temperature of boron carbide, particularly if material enriched in ^{10}B content is used, since heating is a strong function of ^{10}B content. The large temperature gradients in large-diameter pellets may also produce thermal stresses which exceed the material strength, resulting in radial cracking of the boron carbide pellets. This may not degrade performance, but it requires assessment. A third parameter related to thermal performance is heat flux through the control pin cladding. This parameter must be held below the level required to cause film-boiling of the sodium coolant.

The pin bundle moves vertically within the hexagonal outer duct to permit reactivity control of the reactor. The pin bundle has HT9 (which is not determined yet) wear pads at the upper and lower ends that contact the duct tube. A potential wear problem exists with this design because the wear pads can be forced against the duct tube walls by torque from the control rod drive mechanism during rod withdrawal.

This behavior was observed during the FFTF Control Rod System Environmental Life Test. The maximum wear depth in the duct tube was 0.254mm, and the maximum material buildup on the wear pads 2.1mm. These components actually were subjected to over four times the total travel for one year of operation of FFTF control elements, and even with the observed wear effects, no deterioration in scram times was noted in multiple scram tests. Nonetheless, it would be desirable to eliminate this potential foe galling. Changing the hexagonal duct tubes to round duct tubes would accomplish this. With round ducts, there are no contact points to react to inter-component toque, and scram reliability is improved. Core physics calculations indicate that the reduction in reactivity worth in going from a hexagonal to round absorber assembly configuration would be less than 5 percent.

The lifetime of the absorber element may be determined by one of the following criteria:

- Loss of boron 10 which reduces the effectiveness of the control rod to an unacceptable level;

- Helium gas pressure limit;

- Swelling of the B_4C pellets leading to pellet-cladding mechanical interaction (PCMI);

- Excessive clad embrittlement due either to radiation damage or to pellet cladding chemical interaction (PCCI);

- Excessively high pellet temperature. The swelling rate of boron carbide is essentially independent of exposure temperature up to a temperature ~1500°C (TBD), above which the swelling increases rapidly with temperature. Pellet melting at ~2450°C (TBD) is also be avoid;

- Maximum wear depth limit.

Control rod system for LMRs must be designed for operation in high neutron fluxes and at operating temperatures of cladding up to 650°C (TBD). At these conditions, control rods must be conformed to following requirements:

- to provide the free moving in directional tubes and the reliability of the insertion in the core at an emergency;

- to keep the mechanical strength;

- to keep the requirement level of the efficiency during the operating life.

Using absorbing and constructional materials must:

- to be compatible to one another in the whole operating temperature region and emergency conditions;

- to have the minimal irradiation destruction and swelling under neutron fluxes.

5.1 Assembly Duct

The design limit and strength requirements are expected to be more severe than any intrinsic capability of the fuel assembly ducts. The followings are some general guidelines with the control rod assembly ducts.

1) The duct and related components must be dimensionally compatible to accommodate the design limits of the duct dilation.

2) The maximum interference caused by bundle-duct interaction should be considered. In the case of high fast flux, the bundle configuration of control rod will be expanded and could be restricted by the inner duct. The factors contributing to the bundle-duct interaction are the followings: the irradiation induced swelling of the cladding and duct; the thermal expansion differences between the bundle and duct; the creep strain of the cladding; elastic deformation of the cladding; the corrosion amount of the cladding outer surface and duct inner surface.

3) Duct thinning shall be accomplished without an undue loss of structural strength, so that nuclear characteristics and economics would be improved.

6. Seismic Requirements

The control rod assembly ducts shall be designed as seismic category I. The assembly ducts shall be designed to permit continued operation through OBE seismic events. The control rod assembly ducts shall be seismically qualified to a Design Basis Earthquake(DBE) of 0.22 g (TBD) horizontal ground acceleration. The assembly and components shall maintain their structural integrity during and after DBE. The seismic qualification of the control rod assembly ducts shall be limited to verifying structure soundness only, i.e., stress encountered during a DBE shall be less than 70% of the yield limit.

The control absorber units' seismic qualification should be limited to verifying structural soundness only. The CA (control assembly) unit need not remain functional during or after a DBE. However, the occurrence of a DBE must not cause removal of an absorber from the core, unless so commanded by RRS. Further, the occurrence of a DBE must not result in the control absorber units inhibiting the operation of the shutoff units.

7. Structural Requirements

7.1 Absorber Rod

Ferritic martensitic steel has been chosen as the reference cladding material for the KALIMER control rod because of its low-swelling characteristics. The structural design requirements for the absorber rod are determined by cladding integrity aspects. These requirements are explicitly embedded within the operational and reliability requirements. Appropriate limits to cladding cumulative damage fraction (CDF) and cladding strain provide the structural evaluation criteria to assure satisfaction of the high level reliability and performance requirements defined in the prior sections.

7.2 Control Rod Assembly Duct

The structural design requirements for control rod assembly ducts are explicitly embedded within the operational and reliability requirements. The structural material characteristics are determined by the Nuclear Systems Materials Handbook and the Alloy Properties Databook. Appropriate limits to duct dilation and bowing, and restraint contact forces provide the structural evaluation criteria to assure satisfaction of the high level reliability and performance requirements defined in the prior sections.

Dilation of the hexagonal duct is an important factor during the operational lifetime of control assemblies in the core. It is caused by the irradiation-enhanced creep, void swelling and thermal gradient of the hexagonal duct material. Excessive duct dilation should be minimized to accommodate removal from the core and storage where the grid size of the storage basket is limited. Therefore, it is important to determine the hexagonal duct dilation behavior to guide the design and in-core management of the fuel assemblies in the ways that excessive duct deformation can be avoided.

In the double hexagonal duct, the dilation causes the duct contacts between inner and outer ducts. It prevents the absorber assembly to move in the outer duct. Changing the hexagonal duct tubes to round duct tubes would accommodate this problem. With round ducts, there are no contact points to react to inter-component toque, and scram reliability is improved.

8. Environmental Requirements

The effects of environmental factors can cause substantial changes in the response and failure properties utilized by the Code. In extreme circumstances the environmental effects may change the material properties to the extent that the premises upon which the design process is based may be rendered invalid. A normally ductile material may exhibit characteristics that are associated with brittle materials. Clearly, the effects of the environment must be considered in the design process.

There are at least three different types of environmental effects:

1) loss of structural material by erosion or corrosion

2) introduction of failure modes not explicitly addressed by Code design rules(such as stress corrosion), and

3) modification of mechanical and physical properties (such as a loss in fatigue strength or a loss in creep rupture strength).

8.1 Environmental Effects

8.1.1 Irradiation

Changes in material properties may occur due to environmental effects. In particular, fast neutron irradiation above a certain level ($E>0.1$ MeV) may result in significant increase in the brittle fracture transition temperature and deterioration in the resistance to fracture at temperatures above the transition range. Therefore, nozzles or other structural discontinuities in ferritic vessels should preferably not be placed in regions of high fast neutron flux.

Since the LMR is operated in the high exposure irradiation environment, reactor core shall have a concept of shielding end cap and HT9 solid end cap, and so on by the above criterion.

8.1.2 Corrosion

Material subject to thinning by corrosion, erosion, mechanical abrasion, or other environmental effects shall have provision made for these effects during the design or specified life of the component by a suitable increase in or addition to the thickness of the base metal over that determined by the design formulas. Material added or included for these purposes need not be of the same thickness for all areas of the component if different rates of attack are expected for various areas.

8.1.3 Mechanical Design Criteria

Forces resulting from the flow of coolant or mechanical wear during any mode of normal operation or event shall not interfere with the free motion of the control rods, nor cause deformations (including fuel geometry disruption) that could prevent sufficient reactivity control or core cooling.

The reduction of the yield strength due to environmental effects can significantly reduce the Code's design margin for failure modes. The effect of the service environment on the 0.2% offset yield strength should be limited to a 10% reduction of the original value at all service temperatures. The loss in yield strength should be evaluated over the entire temperature range of service. Since gross plastic deformation and plastic ratcheting involve the entire cross-section, the reduction in yield strength due to the service environment should be determined on a cross-section-averaged basis.

- Enhancement of the yield strength due to the effect of the service environment would reduce the design margin in the Code elastic creep-fatigue evaluation procedure.

- The design limits and procedures should be reviewed to assure that the intended design margins remain intact when the environment produces a 10% change in the yield strength.

8.2 Control Rod and Control Rod Assembly

8.2.1 Environmental and Dynamic Effects Design Bases

Control rod systems and components important to safety shall be designed to accommodate the effects of and to be compatible with the environmental conditions associated with normal operation, maintenance, testing, and postulated accidents, including loss-of-coolant accidents.

8.2.2 Control Rod in Core

The control assemblies that will be surrounded by the primary cooling system sodium shall have sufficient corrosion resistance during its resistance time. Their environmental conditions shall be as follows:

- Medium: sodium

- Coolant flow velocity: TBD.

- Pressure: TBD.

- Temperature: up to 530°C (Bulk) (TBD)

- Max. fast neutron fluence: $< 4.0 \times 10^{23}$ n/cm^2 (TBD)

9. Reliability and Safety

9.1 Absorber Rod

For the analysis of reliability and safety for the KALIMER absorber rod, different concepts shall be used between the DBEs (design basis events) and the BDBEs (beyond design basis events).

In the conditions of steady state and the DBEs, the conservative analysis method shall be applied. The followings are the requirements on the evaluation of rod temperatures, reliability and integrity for the absorber rods:

1) It is required by the safety criteria for the KALIMER designs to maintain absorber rod integrity not only during normal operation but also during anticipated transients.

2) The cladding strains should be calculated using conservative equations for thermal creep and tensile properties, and considering the worst cases, such as hot channel rod temperatures, peak helium gas release, and cladding thickness considering conservative wastage allowance.

3) The rod cladding stresses should be calculated by the considerations of the worst case helium gas release and reduction of cladding thickness due to chemical attack.

In the case of the BDBEs conditions, best engineering estimates (nominal analyses) shall be used to evaluate the events, such as ATWS (anticipated transient without scram). It also shall be shown by the analyses that rod integrity is fully maintained during the BDBEs without exceeding rod damage limits, and with having sufficient safety margins. The requirements on the evaluation of reliability and safety for the rod during BDBEs are as follows:

1) The initial conditions of the BDBEs analyses should be used by the worst case of steady state conditions, such as end-of-life condition, hot spot temperatures and the worst case of helium gas release.

2) In the case of temperature conditions, 2 sigma (TBD) value should be used to accommodate the uncertainties instead of nominal values.

9.2 Control Rod Assembly Duct

The control rod assembly duct shall be designed to maintain the integrity of the control assembly with minimum release of radioactive material. Radioactivity releases from the control rod assembly will be minimized by design and operation to ensure that resultant radiation doses are as low as reasonably achievable, and that individual dose limits are not exceeded.

Although all major problems are currently being addressed, much research remains to be performed in order to establish the safety and reliability of the specific control rod. The data base to support the control rod assembly duct system to be used in the KALIMER design needs to be developed. The data are needed to support the establishment of the control rod design limits and the rod damage limits for licensing, and for the validation of the analytical tools for licensing evaluations.

10. Standard and Codes

Nuclear safety-related control rod system shall be designed, fabricated, erected, and tested to quality standards commensurate with the importance of the nuclear safety functions to be performed. Where generally recognized codes and standards are used, they shall be identified and evaluated to determine their applicability, adequacy, and sufficiency and shall be supplemented or modified as necessary to assure a quality product in keeping with the required nuclear safety functions.

Control system is classified as safety-grade. The nuclear industry standard, ANSI/ANS-54.1-1989 was written to establish general design criteria (GDC) for large-loop and pool type LMRs as well as small modular reactors. The standard was developed with the emphasis placed on retaining the GDC wherever the criterion is applicable to the LMR design. Thus the design standard proposed by ANSI/ANS-54.1-1989, "General Safety Design Criteria for a Liquid Metal Nuclear Power Plant" may be specific guidance of the components design of KALIMER. These Design criteria supplement the required design criteria contained in 10 CFR Part 50, Appendix A.

Any components in the Reactor Coolant Pressure Boundary (RCPB) in the KALIMER shall be designed and constructed to be applicable sections of the American Society of Mechanical Engineers(ASME) Boiler and Pressure Vessel Code and Code Case.

The design of mechanical system and components includes specifying and complying with the analytical methods used for all components and components supports covered by the American Society of Mechanical Engineers, Boiler and Pressure Vessel Code Class 1, 2 and 3.

In the ASME code, Class 1 components and component supports are categorized as low-temperature components or elevated-temperature components, and are described by components operating conditions and design loading conditions, design stress and pressure limit, analytical and empirical methods for design of pumps and valves and design and installation criteria for pressure-relieving device and component and piping supports.

11. Quality Assurance Programs

In this chapter, the applicant should provide a description of the QA program to be established and executed during the design of the control system for LMR. The QA program must be established at the earliest practical time consistent with the schedule for accomplishing the activity.

11.1 Quality Assurance During Design

11.1.1 Organization

The PSAR (Preliminary Safety Analysis Report) should describe clearly the authority and duties of persons and organizations performing quality assurance (QA) functions of assuring that the QA Program is established and executed or of verifying that an activity has been correctly performed.

The PSAR should describe those measures which assure that persons and organization performing QA functions have sufficient authority and organizational freedom to

1) identify quality problems,

2) initiate, recommend, or provide solutions, and

3) verify implementation of solutions.

The PSAR should describe the measures which assure that persons and organizations assigned the responsibility for checking, auditing inspecting, or otherwise verifying that an activity has been corrected performed report to a management level such that this required authority and organizational freedom, including sufficient independence from the pressures of production, are provided. Irrespective of the organizational structure, the PSAR should describe how the individual or individuals with primary responsibility for assuring effective implementation of the QA Program at any location where activities subject to the control of the QA Program are being performed will have direct access to such levels of management as may be necessary to carry out this responsibility.

The PSAR should describe the extent to which the applicant will delegate to other contractors the work of establishing and executing the QA Program or any part thereof. A clear delineation of those QA functions which are implemented within the applicant's QA organization(s) and those which are delegated to other organizations should be provided in the PSAR. The PSAR should described the method by which the applicant will retain responsibility for and maintain control over those portions of the QA Program delegated QA functions are properly carried out. The PSAR should identify major work interfaces for activities affecting quality and describe how clear and effective lines of communication exist between the applicant and his principal contractors to assure necessary coordination and control of the QA Program.

11.1.2 Quality Assurance Program

The QA Program in the PSAR should cover each of the criteria in Appendix B to 10 CFR Part 50 in sufficient detail to permit a determination as to whether and how all of the requirements of Appendix B will be satisfied.

The PSAR should identify the safety related structures, systems, and components to be controlled by the QA program. The PSAR should describe the measures which assure that the QA Program is being established at the earliest practicable time consistent with the schedule for accomplishing activities affecting quality for the project . that is, the PSAR should describe how the QA Program is being established in advance of the activity to be controlled and how it will be implemented as the activity proceeds. Those activities affecting quality initiated prior to the submittal of the PSAR, such as establishing information required to be included in the PSAR, design and procurement, and safety-related site preparation activities should be identified in the PSAR. The PSAR should describe how these activities are controlled by a QA Program which complies with Appendix B to 10 CFR Part 50.

11.1.3 Design Control

The PSAR should describe the design control measures which assure that

1) applicable regulatory requirements and design bases for safety- related structures, systems, and components are correctly translated into specifications, drawings, procedures, and instructions,

2) appropriate quality standards are specified in design documents,

3) and deviations from such standards are controlled.

The PSAR should describe the design control measure to such aspects of design as reactor physics; stress, thermal, hydraulic, and accident analysis; materials compatibility; and accessibility for maintenance, in-service inspection, and repair and should describe measures for delineation of acceptance criteria for inspects and tests.

The PSAR should describe measures which assure verification or checking of design adequacy, such as design reviews, use of alternative calculation methods, or performance of a qualification testing program under the most adverse design conditions. The PSAR should identify the positions or organizations responsible for design verification or checking and should describe measures which assure that the verifying or checking process is performed by individuals or groups other than those who performed the original design, but who may be from the same organization.

The PSAR should describe measures for identifying and controlling design interfaces, both internal and external and for coordination between participating design organizations. The PSAR should describe measures in effect between participating design organizations for review, approval, release, distribution, collection, and storage of documents involving design interfaces and changes thereto. The PSAR should describe how these measures will assure that these design documents are controlled in a timely manner to prevent inadvertent use of superseded design information.

11.1.4 Procurement Document Control

The PSAR should describe measures assure that documents, and changes thereto, for procurement of material, equipment, and services, whether purchased by the applicant or by his contractors or subcontractors, correctly include or reference the following as necessary to achieve required quality:

1) Applicable regulatory, code, and design requirements.

2) Quality assurance program requirements.

3) Requirements for supplier documents such as instructions, procedures, drawings, specifications, inspection and test records, and supplier QA records to be prepared, submitted, or made available for purchaser review or approval.

4) Requirements for the retention, control, and maintenance of supplier QA records.

5) Provision for purchaser's right of access to suppliers' facilities, and work documents for inspection and audit.

6) Provision for supplier reporting and disposition of non-conformances from procurement requirements.

11.1.5 Instructions, Procedures, and Drawings

The PSAR should describe measure that assure that activities affecting quality such as design, procurement, manufacturing, construction and installation, testing, inspection, and auditing are prescribed by appropriately documented instructions, procedures, or drawings and that these activities will be conducted in accordance with the documented instructions and procedures.

The PSAR should describe the system whereby the documented instructions and procedures will include appropriate quantitative (such as dimensions, tolerances, and operating limits) and qualitative (such as workmanship samples and weld radiographic acceptance standards) acceptance criteria for determining that prescribed activities been satisfactorily accomplished.

12. Other Requirements

Other requirements for control rod assembly duct design will be considered with additional items that are not defined by the above requirements. The additional requirements can contain several items such as the research activities, database of operational experiences, further safety features and the modified design concept.

12. 1 Maintainability Requirements

The shutdown and control assembly shall be designed for a minimum of routine maintenance and a minimum person-Sievert exposure.

1) No routine maintenance or periodic replacement shall be required for components submerged in the pool, which includes electrical cables, bearings, guides, transducers, etc.

2) For out-of-reactor components, periodic maintenance, i.e., inspection of bearings, seals and moving parts, etc should not be required at intervals shorter than 10 years (TBD).

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Abstract (About 300 Words)

This document establishes the design guidelines which are needs for designing the control rod assembly duct of the KALIMER as design requirements. It describes control rod assembly duct of the KALIMER and its requirements that includes functional requirements, performance requirements, interfacing systems, design limits and strength requirements, seismic requirements, structural requirements, environmental requirements, reliability and safety requirements, standard and codes, QA programs, and other requirements. The control rod system consists of three parts, which are drive mechanism, driveline, and absorber bundle. This report deals with the absorber bundle and its outer duct only because the others are beyond the scope of fuel system design. The guidelines for design requirements intend to be used for an improved design of the control rod assembly duct of the KALIMER.

Subject Keywords (About 10 Words) Control rod, design requirement, design criteria, design limits, absorber bundle, inner duct, outer duct, absorber, boron carbide, B_4C, KALIMER.

서 지 정 보 양 식

수행기관 보고서 번호	위탁기관 보고서 번호	표준 보고서 번호	INIS 주제코드
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제목/부제 :	KALIMER 제어봉 덕트에 대한 설계요건
연구책임자 및 부서명 (AR, TR일 경우 주저	황 완, 금속핵연료 설계개발
연구자 및 부서명	강희영, 남 철, 김종오, 김영진 금속핵연료 설계개발

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초록(300단어 내외)

본 문서는 KALIMER 제어봉 덕트의 설계길잡이로써 설계하는데 필요한 설계요건을 확립한다. KALIMER 제어계통은 구동장치, 구동선로 및 제어집합체로 구성되지만 제어집합체를 제외한 부분은 핵연료설계의 범위가 아니므로 본 문서에서는 다루지 않았다. 이 문서는 KALIMER 제어집합체는 흡수재가 배열된 내부 덕트와 이를 감싸고 있는 외부 덕트로 되어 있으므로 흡수재의 기능 및 성능요건과 내부 및 외부 덕트의 설계한계 및 강도요건을 기술하였고 그외 인접계통요건, 지진시요건,구조적요건, 환경적요건, 신뢰도 안전요건, 표준요건, QA요건 및 기타요건 들을 기술한다. 본 지침서는 KALIMER의 제어봉 집합체 덕트의 향상된 설계에 사용되도록 작성되었다.

주제명 키워드 (10단어 내외): 제어봉, 설계요건, 설계기준, 설계한계, 흡수체다발, 내부덕트, 외부덕트, 흡수체, B_4C, KALIMER