Mechanical Structure Design Features of the KALIMER-600 Sodium-cooled Fast Reactor

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ABSTRACT

The mechanical structure design features of KALIMER-600 of a sodium-cooled fast reactor (SFR) are described. The reactor is a pool type with a 2-loop system for a 600MWe electrical capacity. The conceptual design has been completed last year. The core outlet temperature of KALIMER-600 is 545^{o}C, and the core inlet temperature is 390^{o}C. Most internal structures and components are exposed to a high temperature environment, and the operating pressure is low at an atmospheric level. The mechanical governing loads of the reactor design are the thermal and seismic loads. The structural design targets are to maintain enough structural integrity for a seismic load of SSE 0.3g and the thermal transient loads from the high temperature environments, and also attaining its economical competitiveness when compared with other reactor types.

INTRODUCTION

Korea Atomic Energy Research Institute [KAERI] has developed the sodium-cooled fast reactor KALIMER-600[1], and its conceptual design was finished recently. Some design features are based on the KALIMER-150, which is also a pool type 2-loop system, and a 150MWe electrical capacity[2]. The NSSS has three heat transport systems of a PHTS (Primary Heat Transport System), an IHTS (Intermediate Heat Transport System) and a SGS (Steam Generation System). PHTS includes two mechanical pumps, 4 IHXs in the reactor pool and has a large amount of sodium in the pool. The pool type reactor eliminates the possibility of a primary coolant loss by a primary pipe break and also provides a large thermal damping of the system which yields a slower transient load during an accident. IHTS of two piping loops has two electromagnetic pumps circulating secondary sodium coolant and two steam generators.

The safety systems of KALIMER-600 are based on a passive design concept and thus KALIMER-600 does not require any active components for design base accidents. KALIMER-600 also has several safety features such as the use of metal fuels, a Self-Actuated Shutdown System (SASS) in the core, and a Passive Decay heat Removal Circuit (PDRC) system. The reactor building and the fuel storage building are seismically isolated. Table 1 summarizes the key design parameters of KALIMER-600. In this paper, the mechanical and structural design features are described and several related R&D activities such as the under-sodium visualization for a reactor internal, a high temperature LBB study, and the development of a high temperature structure integrity evaluation guideline are introduced.

Table 1. KALIMER-600 Key Design Parameters

OVERALL		**PHTS**	
Net plant Power, MWe	600	Reactor Core I/O Temp., ^{o}C	390.0 /545.0
Core Power, MWt	1523.4	Total PHTS Flow Rate, kg/s	7731.3
Gross Plant Efficiency, %	41.9	Primary Pump Type	Centrifugal
Net Plant Efficiency, %	39.4	Number of Primary Pumps	2
Reactor Type	Pool Type		
Number of IHTS Loops	2	**IHTS**	
Safety Decay Heat Removal	Passive	IHX I/O temp., ^{o}C	320.7/526.0
Seismic Design	Seismic Isolation	IHTS Total Flow Rate, kg/s	5800.7
		IHTS Pump Type	Electromagnetic
CORE		Total Number of IHXs	4
Core Configuration	Radially Homogeneous		
		SGS	
Core Height, mm	940	Steam Flow Rate, kg/s	663.25
Maximum Core Diameter, mm	5209	Steam Temperature, ^{o}C	503.1
Metal Alloy Fuel Form	U-TRU-10%Zr	Steam Pressure, MPa	16.5
Cycle Length (EFPM)	18	Number of SGs	2

MECHANICAL STRUCTURE DESIGN

The main features of the mechanical and structural design in KALIMER-600 are the seismically isolated reactor building, the reduced total pipe length of the IHTS, the simplified reactor support, and the compact reactor internal structures. The overall configuration of the KALIMER-600 reactor building is shown in Fig. 1 and the internal configuration of the reactor vessel is in Fig. 2. A total of 164 seismic isolators (ϕ1.2m) are installed between the ground and the lower basemat in the KALIMER-600 reactor building (W49m x D36m x H54m).

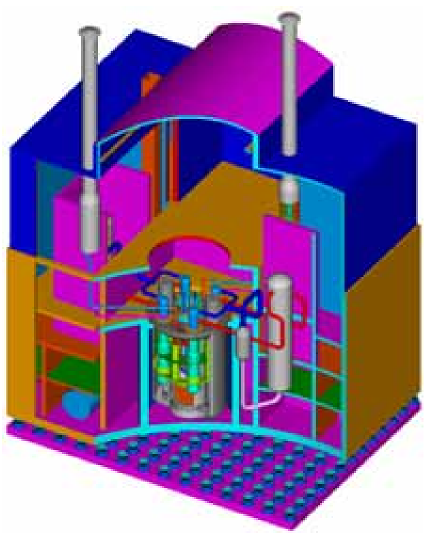

Fig. 1 KALIMER-600 Reactor Building

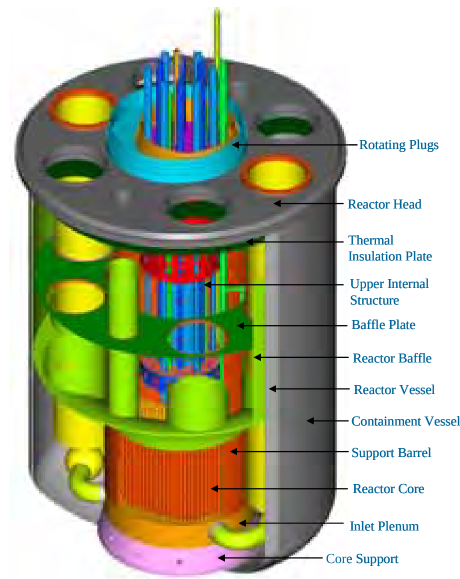

Fig. 2 Reactor Internal Configuration

Fig. 3 shows a schematic arrangement of the isolators on the lower basemat. The seismic gap between the isolated reactor building and the non-isolated wall is about 1.2m, which will allow for no contact even when subjected to a beyond design basis earthquake with a peak ground acceleration of 1.0g. The high damping rubber bearings made of natural rubber have been selected to isolate the reactor building and the fuel handling building. The installation concept of seismic isolators is shown in Fig. 4. The rubber compound of the bearings contains a high amount of filler materials such as carbon black, and this filler material achieves a non-linear behavior which increases the natural rubber's stiffness properties, tear and abrasion resistance, and damping effect. Most of the isolators are placed below the shear walls of the reactor building.

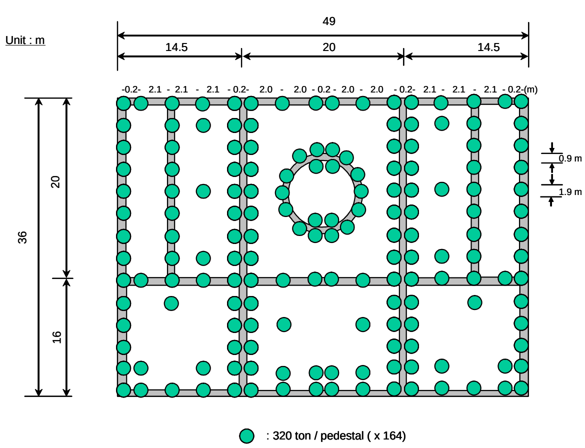

Fig. 3 Schematic Arrangement of the Isolators

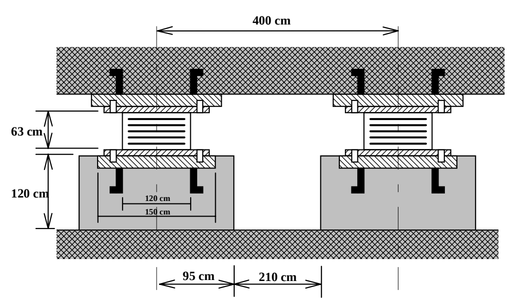

Fig. 4 Installation Concept of the Isolators

The reactor vessel is the boundary of the primary heat transport system and performs support and container functions during all the temperature, pressure, and load variations which occur during an operating lifetime. The reactor vessel has no penetration and no attachments other than those for supporting the core support structure to the bottom head. The reactor vessel, which is made of a type 316 stainless steel, has overall dimensions of 18m in height, 11.41m in outer diameter, and 0.05m in thickness. The structure dimensions and materials are listed in Table 2 and the total reactor weight is about 2,800 tons. The reactor vessel is attached to the reactor head and supports the reactor internal structures, the reactor core, and the primary sodium coolant. The 4-IHXs and 2-PHTS pumps are installed through holes in the baffle plate and the reactor baffle. The space inside the reactor vessel is thermally divided into two regions; that is the hot pool region and the cold pool region. The support barrel, the baffle plate and the reactor baffle form the boundary of these two regions. The reactor vessel for KALIMER-600 directly contacts the cold sodium of 390°C. So, the reactor vessel can maintain its structural integrity for a 60 years design lifetime.

Table 2. Dimensions and Materials of Reactor's Structural Components

Components	Diameter (m)	Height (m)	Weight(tons)	Materials
Reactor Vessel	11.41	18	275	SS 316
Containment Vessel	11.76	18.35	137	2.25Cr-1Mo
Reactor Baffle	11.26	6.45	110	SS 316
Support Barrel	5.81	11.5	65	SS 316
Inlet Plenum	5.91	1.4	72	SS 316
Core Support Structure	5.9 ~ 6.2	0.85	25	SS 316
Upper Internal Structure	3.1	10.2	23	SS 316
Reactor Head	11.76	0.5	239	SS 316
IHX	2.4	7.9	30	Mod.9Cr-1Mo
Primary Sodium Pump	2.4	17	110	-
Steam Generator	4.1	20.6	190	Mod.9Cr-1Mo

The reactor internal structures of the KALIMER-600 are composed of the core support structure, the inlet plenum, the support barrel, the reactor baffle and the reactor baffle plate. The reactor internal structures have 3-main functions of providing a core support, a primary coolant flow path, and a component support. The baffle structure with an annulus shape can accommodate a large thermal difference between the hot pool and the cold pool regions. The core support structure is a simple detached skirt type. This structure supports the core assemblies and the fixed internal structures. This provides for a very simple core support design, fabrication and ISI (In Service Inspection). The core support structure will be forged, thus the number of weld parts are minimized. Inside the core support structure, a core catcher is located between the lower grid plate and the reactor vessel bottom head. The proposed conceptual design of the core catcher was assumed that the core catcher will support a whole molten core and maintain it in a subcritical condition.

The principal functions of the upper internals structure (UIS) are a lateral support for the control rod drivelines(CRDLs), a protection of the drivelines from a sodium flow induced vibration, and a support for the above core instrumentation drywells. It primarily consists of three vertical cylinders, which are joined by a welding to an intermediate horizontal plate. The UIS is made of Type 316 SS. The upper cylinder of 5.0m long has an outer diameter of 310cm and a wall thickness of 2.5cm. The intermediate cylinder of 4.5m long has an outer diameter of 150cm and a wall thickness of 5cm. Another lower skirt cylinder of 62cm long, which is enclosed by two horizontal plates (upper plate thickness 7.5cm, lower plate thickness is 2.5cm), is connected to the lower part of the intermediate cylinder, and it has the same dimensions as the upper cylinder. The UIS is attached to a rotatable plug installed on the reactor closure of the reactor head and cantilevered downward into the reactor hot pool. The total length of the UIS is 10.2m with porosity and the bottom end of the shroud tube will be located 5.0cm above the top of the core assemblies during a power operation.

The reactor head of the KALIMER-600 is the top closures of both the reactor vessel and the containment vessel. It provides a mechanical support for all the PHTS components including the IHX, primary pump, rotatable plugs, reactor internals and the primary sodium, etc. The reactor head, of which the diameter is 1176cm and the thickness is 50cm. It is designed to operate at a low temperature of less than 150°C. The low temperature is attained by an inclusion of 5 horizontal layers of stainless steel insulation and shield plates in the design, the top one of which is installed 45cm below the bottom of the reactor head. The insulation and shield plates are 3cm thick and are spaced at 2.5cm.

The reactor support structure is the extended part of the reactor head by 30cm in the radial direction and it rests on the HAA(Head Access Area) floor and a self-lubricating bearing is installed between the outer part of the reactor head (the reactor support ring) and the HAA floor to allow for radial direction reactor thermal movements by a sliding motion. The reactor support ring is anchored to the HAA floor to restrain a vertical movement by a bolting and a lateral seismic restraint is provided by a close fit of the support ring bolts within the radial slotted holes in the support ring.

The IHTS piping system of KALIMER-600 connects IHX, steam generator and secondary EMP. The piping material is Mod.9Cr-1Mo, which has a low thermal expansion and a high ultimate strength. The shortening of the IHTS piping is a key issue in the SFR design to reduce the construction and maintenance costs. The piping layout is simplified through several layout design studies to obtain the minimum total pipe length. The hot leg in the IHTS piping is 60cm in inner diameter and 0.95cm in thickness, while the cold leg is 82cm in inner diameter and 1.25cm in thickness. The total length of the IHTS piping a loop has been reduced to 102.6m. Rigid supports, constant spring hangers and snubbers are to be used for the pipe supports.

The service limits of the stresses, accumulated inelastic strains, and creep-fatigue damages for the reactor structures satisfy the ASME design criteria. Currently, the ASME code provides design data for 40 years and it is necessary to acquire the corresponding design data for 60 years or to extrapolate the 40 years data to the 60 years data. This is one of the challenging issues for 60 years design.

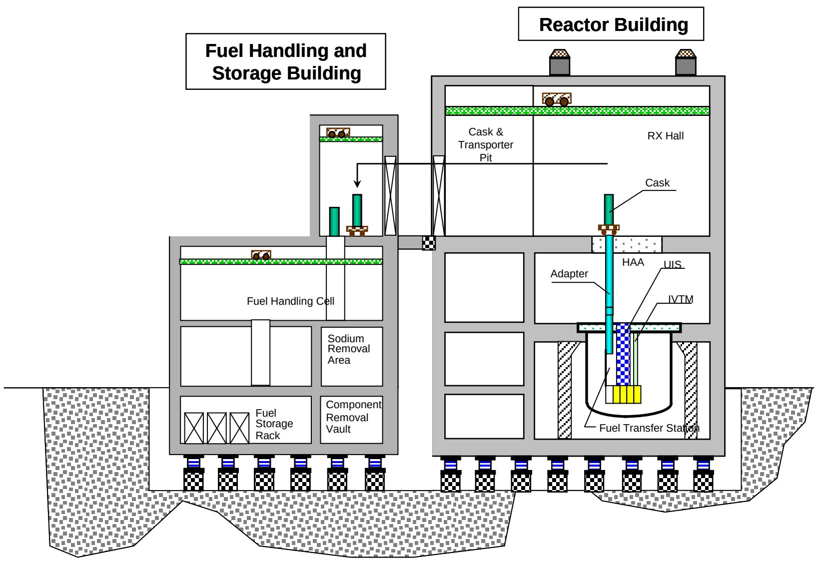

Fig. 5 Arrangement of the Reactor Refueling System (RRS)

The Reactor Refueling System (RRS) provides the means of transporting, storing and handling the reactor core assemblies including the fuels, control rods, and the shields. The system consists of the facilities and equipments needed to accomplish the normal scheduled refueling operations and all the other functions for a handling of the core assemblies. Fig. 5 depicts the arrangement of the RRS. The system consists primarily of the In-Vessel Transfer Machine (IVTM), the double rotating plug drives, and the fuel transfer port which are all located inside the reactor. New control and shield assemblies are transported into the fuel handling and storage building, unloaded from their shipping containers, inspected and temporarily stored. New fuel assemblies are received and stored in the Fuel Handling Cell (FHC).

CONTAINMENT DESIGN

The KALIMER-600 design contains features which provide a defense-in-depth for a full spectrum of severe accidents including a Hypothetical Core Disruptive Accident (HCDA) and a core melt. The containment shown in Fig. 6 provides a low leakage, and a pressure-retaining boundary which completely surrounds the primary system boundary. It includes a lower containment vessel designed to contain reactor vessel leaks and an upper containment structure which will mitigate severe events, such as an HCDA, which are postulated to cause an explosion of radio-nuclides through the reactor head into the region above the reactor.

The lower portion of the containment which is made of 2.25Cr-1Mo has overall dimensions of 18.25m in height, 11.76m in outer diameter, and 0.025m in thickness. It has no penetrations and is designed to remain essentially leak tight. The annulus between the reactor and the containment vessel is sized to retain the primary sodium such that the reactor core and the inlet of the IHX will remain covered in the event of a reactor vessel leak. The 15cm annulus gap is filled with argon gas and maintained at a higher pressure than the reactor cover gas. During normal operations, all the sodium and cover gas service lines are closed and all the other penetrations into the reactor closure are seal-welded, which means that the containment system operates in a totally sealed manner. Its length and diameter also limit the volume between the containment vessel and reactor vessel. With this volume limitation, a sodium leakage from the reactor vessel will not sufficiently lower the sodium level to prevent a continuance of a flow into the IHXs and retention of the core cooling circuit. The annulus volume between the reactor vessel and the containment vessel is 102.4m^3. The bottom head of the containment vessel is torispherical with a contour like the bottom head of the reactor vessel.

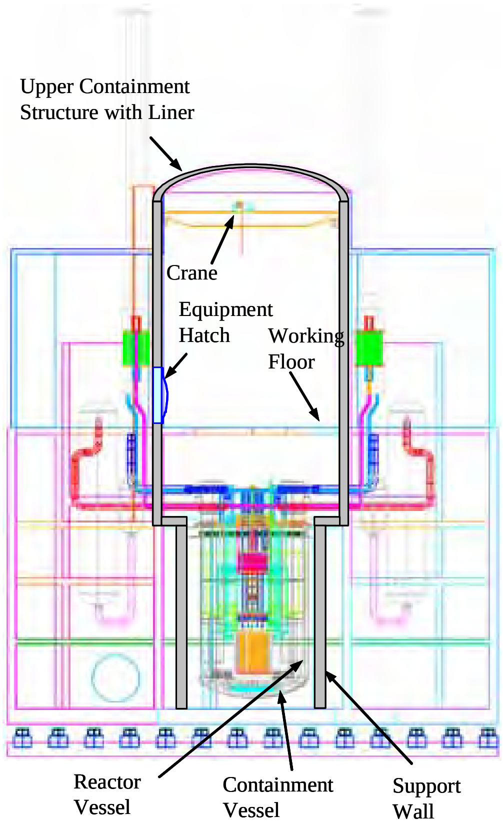

Fig. 6 Schematic Drawing of the Containment Concept

While the containment vessel provides a leak tight boundary, the thick concrete support wall surrounding the containment vessel protects the reactor structures against external loadings including both natural phenomena and nonnatural hazards. Thus the structural integrity of the containment can be achieved. The concrete support wall maintains its low temperature by the adoption of a passive reactor cavity cooling system, which operates passively between the containment vessel and the surrounding support wall.

The upper containment structure is composed of a thick concrete rectangular structure with a dome, and a metal liner is attached inside the containment structure. The metal liner is designed to limit a leakage to less than 1% of its volume per day at a design pressure and temperature. The thick concrete rectangular structure with a dome structure provides a solid barrier to protect the interior structures against all kinds of external loadings.

All the piping and instrument penetrations through this containment boundary are located above the reactor primary system boundary and the wall above the operating sodium level. The containment penetrations are similar to those used in LWR containments, including the main loop IHTS piping penetrations which are provided with bellow seals for wall penetrations.

R&D ACTIVITIES

There are several R&D items to implement in the KALIMER-600 mechanical structure design.

- ❑ ISI technology development for the reactor internals
- ❑ High temperature leak before break approach
- ❑ Development of structural integrity assessment technology for elevated temperature structures

Under Sodium Visualization Technique

The in-service inspection (ISI) and maintenance methods of the reactor system have been designed based on the safety goals and high plant availability. Section XI, Division 3, of the ASME Boiler and Pressure Vessel Code[3] specifies the general type and an extent of the ISI required for Class 1, 2 and 3 systems of a liquid metal cooled plant. Major structures of the reactor system are designed for a low-maintenance operation for the life of the plant. For the equipment or components which directly affect its safety and availability, the system has provided features that allow for a removal and in-place maintenance.

The waveguide sensor visualization technology has been developed to inspect the reactor internals using some specific waveguides in the hot sodium, as shown in Fig. 7. The waveguide sensor consists of a long strip plate, a wedge and ultrasonic sensors. The sensor can be applicable for the under-sodium visualization, ranging and dimensional gauging. The sensors are installed in the rotating plug on the reactor head. A visualization imaging can be achieved by a scanning of the waveguide sensor assembly above the core top plane by a rotation of the rotating plug. Visualization image of the reactor core provides the distortion information for a fuel assembly due to a neutron-induced swelling. The position of the core structures and components can be determined directly through ultrasonic under-sodium visualization before a refueling operation.

To validate the visualization techniques for an underwater condition, a waveguide specimen was fabricated. The C-scan visualization experiment for a similar shape of the reactor core was performed. The visualization image is clearly identified as shown in Fig. 8.

Leak Before Break

The high temperature Leak Before Break (LBB) approach has been applied to the reactor vessel and the IHTS piping of KALIMER-600. The main purpose of the LBB application to the reactor vessel of KALIMER-600 is to verify the absence of a risk related with a core support function and to demonstrate the defense in depth safety argument. ITHS piping serves as the main piping of the KALIMER-600 since it is a pool type reactor and a Double Ended Guillotine Break (DEGB) needs to be considered as a design basis event otherwise a designer demonstrates the possibility of a DEGB as being extremely low quantitatively. One way of demonstrating the possibility of a DEGB being extremely low quantitatively, is to apply LBB approach and it has been applied to the IHTS piping of KALIMER-600 in the early stage by assuming the piping material as SS 316 rather than Mod.9Cr-1Mo. The LBB procedures for the Mod.9Cr-1Mo piping have been under development especially for creep and creep-fatigue crack growth evaluation methodologies. With a successful application of the LBB to the IHTS piping, the fire extinguishing facilities and the massive protective concrete structures against large a sodium fire could be greatly decreased to enhance the economical efficiency of KALIMER-600.

Design Evaluation Guideline

A preliminary guideline for the High Temperature Structure Integrity Assessment Procedure has been presented in two parts[4]. Part I deals with the design and evaluation of the LMR high temperature structure based mainly upon ASME B&PV Code, Section III, Subsection NH while adopting the features of the French RCC-MR and/or Japanese BDS/DDS for certain items where these codes have an excellence to improve this guideline. Part II covers a high temperature structural integrity assessment of which the contents are the evaluation procedures of a creep-fatigue crack initiation and growth in a high temperature condition, the high temperature LBB evaluation procedure, and the inelastic evaluations of the welded joints in SFR structures. The methodologies for a proper inelastic analysis of SFR structures in high temperature are explained, and the guidelines for the inelastic analysis options using ANSYS, ABAQUS, and a developed NONSTA code are included. This guidelines need to be continuously revised to improve this applicability to the design and analysis of the SFR structures.

CONCLUSIONS

The design features of KALIMER-600 have been described and several related R&D activities have been introduced. It has the compact reactor internal structures and small vessel compared to other pool type reactors, and the simplified IHTS piping layout. The reactor and fuel storage buildings are seismically isolated. The mechanical design has enough structural integrity for a seismic load of SSE 0.3g and high temperature thermal loads, and also an economical competitiveness when compared with other reactor types.

Acknowledgement

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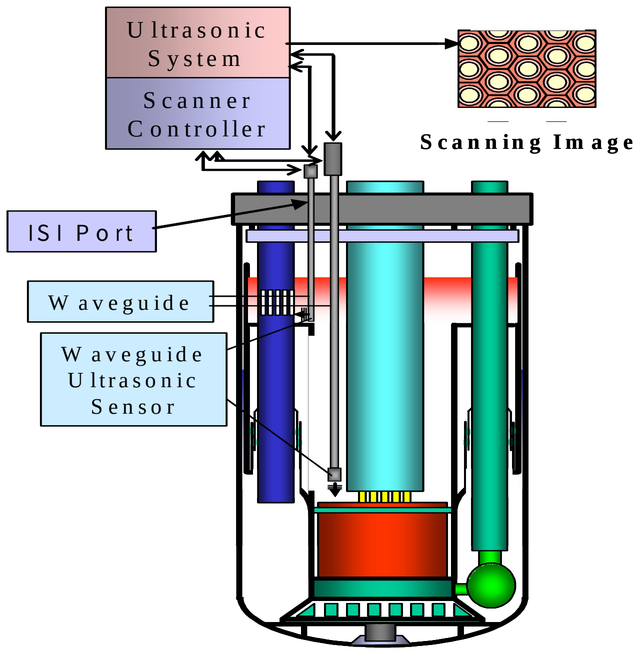
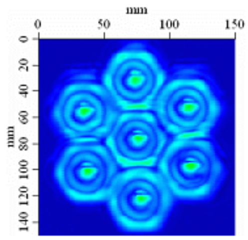


Fig. 7 Visual Inspection Concept Using the Ultrasonic Waveguide Sensor



(a) Mock-up (b) C-scan result

Fig. 8 Visualization Images of the Reactor Core Mock-Up