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Proposed Concept of a Tube-Type Passive Water-Cooled Reactor Without Emergency Core Cooling System

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비상노심냉각계통을 제거한 압력관형 피동 수냉각로

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Abstract

This paper presents a concept of a pressure tube-type water-cooled reactor without the emergency core cooling system. It adopts an innovative fuel channel design using metallic fuel matrix to improve heat transfer from fuel to moderator at loss of coolant cooling. The heat produced in the fuel is cooled by the coolant system during normal operation, but by the passive moderator system at loss of coolant cooling including the loss-of-coolant accident(LOCA). Simple analysis shows that the fuel channel temperature can be maintained within the permissible range for both normal operation and a complete LOCA.

요 약

본 논문은 비상노심냉각계통을 필요로 하지 않는 압력관형 피동 수냉각로 개념을 제시한다. 여기서는 사고시 핵연료에서 생성되는 열을 감속재로 효과적으로 전달시키기 위해 금속 핵연료 매트릭스를 사용하는 핵연료 채널을 채택한다. 정상 운전시에는 보통의 냉각재가 핵연료를 냉각시키지만, 냉각재상실사고를 포함하여 정상적인 냉각계통의 작동이 이루어지지 않을 경우에는 피동 감속재냉각계통에 의해 핵연료가 냉각된다. 유한요소 코드를 이용한 해석 결과, 정상 상태 및 사고시 핵연료 온도를 허용 한도 이내로 유지할 수 있는 것으로 나타났다.

1. Introduction

The development of advanced reactors is expected to make great contribution to the revival of nuclear power through resolving the challenges of increasingly demanding safety requirements, economic competitiveness, and public acceptance. Advanced reactors are being developed for all principal reactor types: light water reactors (LWRs), heavy water reactors (HWRs), gas-cooled reactors (GCRs) and liquid metal reactors (LMRs), among which the LWR concept is being the most actively studied primarily due to its much greater operating experience compared with other types[1 – 3].

Severe accidents can be prevented in water-cooled reactors as long as the reactor is properly tripped and the decay heat is adequately removed. Since reliable reactor trip is relatively easily achievable, main attention is given to reliable decay heat removal during normal shutdown and accident conditions. The safety concept in view of the emergency core cooling system (ECCS) against loss-of-coolant accidents (LOCAs) is evolving as illustrated in Fig. 1[4]. Most passive LWRs are designed with a primary safety objective to minimize the possibility of severe core damage by adopting the passive ECCS. While the loop-type passive water-cooled reactor is considered as a promising candidate for the next-generation reactor, it usually requires proper actuation of an automatic depressurization system (ADS), the reliability of which is a matter of great concern now. Therefore, it is natural to consider the feasibility of a loop-type water-cooled reactor not requiring the ECCS.

The pressure tube concept adopted in most HWR designs has been considered as being excellent from the viewpoint of decay heat removal in case of LOCAs owing to the separation of the low-pressure moderator from the high-pressure coolant. The moderator around fuel channels can be used as an emergency heat sink during a LOCA. This fact was theoretically confirmed by Hejzlar et al. [5] at Massachusetts Institute of Technology (MIT). They investigated various alternatives for passive decay heat removal from the core to the ultimate heat sink, and concluded that the system of solid matrix pressure tubes dispersed in a low pressure calandria was the most promising one. The thermal switch concept - switching of the cooling mode from coolant cooling in normal operation to moderator cooling in accident conditions - was shown to be practically applicable. The MIT group seem to concentrate their efforts on the development of a pressure tube light-water reactor (PTLWR) using graphite matrix[6]. Atomic Energy of Canada Limited (AECL) also started the program for the development of an advanced CANDU which incorporates various passive safety concepts into the present CANDU design[7, 8].

The Center for Advanced Reactor Research (CARR) is studing an innovative tube-type reactor concept not requiring the ECCS, while investigating advanced LWR concepts and related technology as the major work. The concept of an ECCS-free Inherently Safe and Simple Tube Reactor (ISSTER) was already introduced at several international meetings[9, 10]. This paper describes the basic concepts, expected advantages, and the developmental strategy of the ISSTER.

2. Basic Design Features

The primary design objective of the ISSTER is to eliminate the ECCS by accomplishing passive decay heat removal through moderator cooling. It is achieved by adopting the reactor with configuration similar to the present CANDU reactors but with

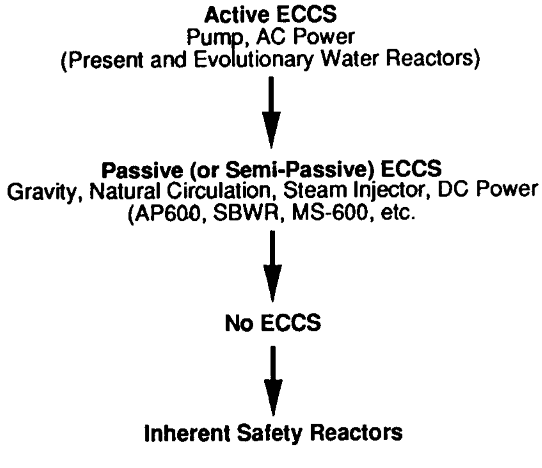

Fig. 1. Evolution of the Safety Conceptin View of the ECCS A gainst the LOCA

innovative fuel channels and a passive moderator cooling system (PMCS).

2.1. Metallic Matrix Fuel

The reactor core is composed of a large number of tube-type fuel channels dispersed in the moderator pool within a large low-pressure reactor vessel (calandria) as in the present CANDU. Each fuel channel consists of a calandria tube, a pressure tube, and a fuel matrix. There are several design options for the fuel matrix, but the metallic fuel matrix with dispersed coolant holes is adopted as the basic design (Fig. 2). During normal operation, the fission heat generated in fuel elements is transferred to the coolant via conduction through the matrix and used to generate steam in steam generators as in the present pressurized heavy water reactors.

The Uranium-Zirconium alloy fuel matrix has the following advantages:

(a) Metallic fuel gives a large negative reactivity feedback effect against power excursion;

(b) Larger fuel-to-moderator ratio allows the use of natural uranium and improves moderator reactivity feedback.

(c) The temperature distribution within the fuel matrix is rather plain during normal operation so that temperature redistribution due to the stored energy brings little problem at the initial stage of a LOCA.

Though the metallic fuel has been reported to work well in some liquid metal reactors[11], the available information is very limited, especially for the behavior of the irradiated metallic fuel of a large dimension. Therefore much more experimental and theoretical investigation is required to complete the feasibility evaluation and to finalize the design details of the fuel channel.

2.2. Passive Moderator Cooling

The decay heat transferred passively from fuel to moderator should also be passively removed. Figure 3 shows a typical example of the ISSTER nuclear steam supply system (NSSS) including the passive moderator cooling system (PMCS) suggested by the present authors. The moderator is cooled through forced circulation during normal operation but

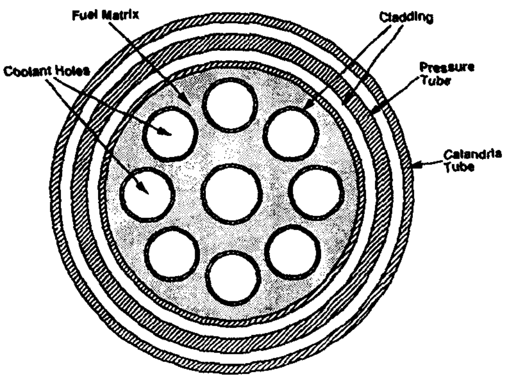

Fig. 2. Matrix-Type Fuel Channel Design

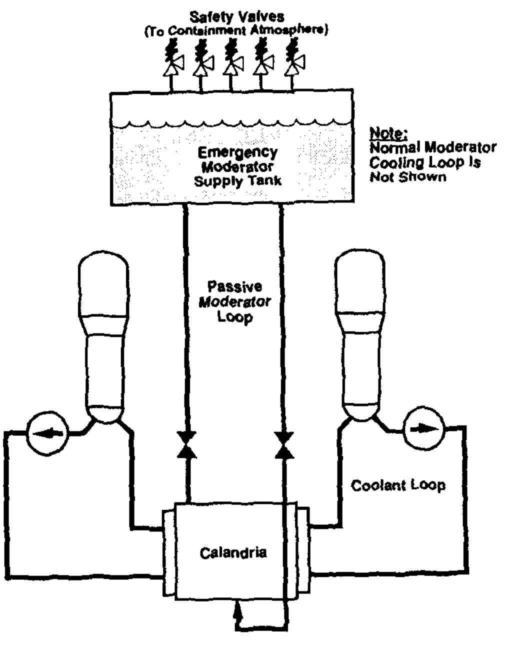

Fig. 3. Schematic of the ISSTER NSSS (Example)

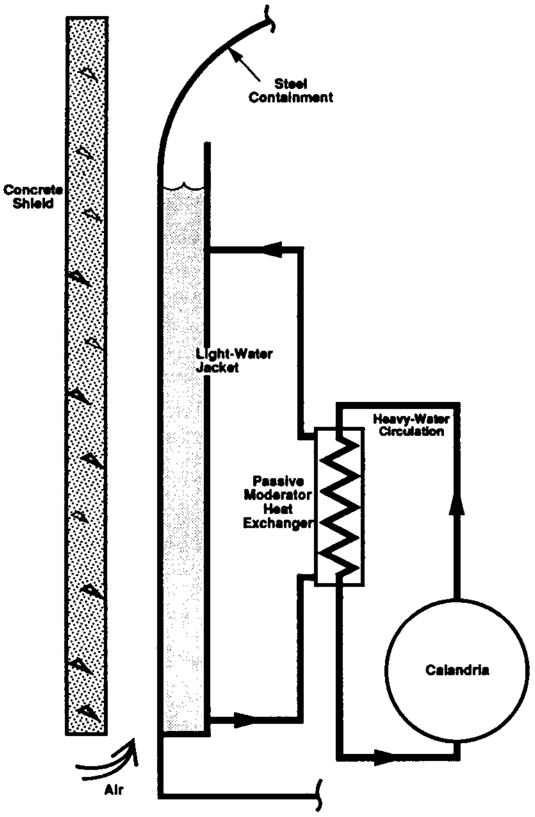

Fig. 4. Passive Moderator Cooling System by Spinks et al.

through natural circulation and passive containment cooling at loss of normal moderator cooling. Figure 4 illustrates a PMCS being investigated by Spinks et al. [7, 8]. Passive moderator cooling is considered to be achievable in several ways.

2.3. Direct Contact Thermal Switch Concept

The gap between the pressure tube and the calandria tube in each fuel channel is provided to detect fuel channel failure and to minimize undesirable loss of fission heat from coolant to moderator during normal operation. In case of a LOCA, however, this gap acts as a barrier against heat transfer from fuel to moderator since radiation heat transfer will prevail in that gap. Actually there exist two gaps in series (between the fuel matrix and the pressure tube; between the pressure tube and the calandria tube) in case of a complete LOCA, which will result in the fuel matrix surface temperature much higher than the moderator temperature.

An engineered thermal switch is a device to increase the heat transfer in the gap under accident conditions compared with normal operation. Tang et al. [6] categorized the thermal switch concepts into three types (i. e., material, dimensional, and fluid-path) and evaluated their performance.

A direct contact thermal switch concept is under investigation in this work. It is expected to change the heat transfer mechanism from radiative heat transfer to conductive heat transfer by mechanically eliminating the gap between the pressure tube to the calandria tube. The thermal switch concept is divided into three parts: the channel geometry, the flexible joint, and the driving mechanism.

To effectively transfer heat by contacting the calandria tube to the pressure tube, the contacting area must be maximized. Since conventional cylindrical tubes have the minimum contacting area when they are contacted, their shape should be changed by adjusting their curvature as shown in Fig. 5. To allow movement of the calandria tube, a flexible joint (bellows) is provided between the calandria tube and the shield wall. The movement of the calandria tube is derived from the thermal expansion of a bar longitudinally lying on the pressure tube outside surface.

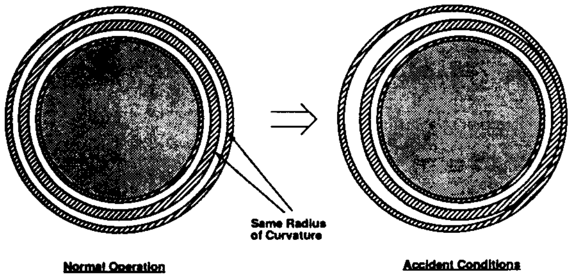

Fig. 5. Fuel Channel Geometry to Maximize the Contacting Area

2.4. Other Considerations

Several options may be possible for the reactor coolant design. For moderator/coolant materials, D_2O/D_2O or D_2O/H_2O options are considered to be the most promising from the viewpoint of reactor physics characteristics. Reactor orientation, refueling strategy, arrangement of NSSS equipment require further investigation. Passive containment concept can be selected in connection with the PMCS design.

3. Fuel Channel Temperature Distribution

A finite element code package, CONCORD-F (Conduction Convection Radiation Analysis Using FEM), has beed developed and applied to calculate the steady-state temperature distribution in fuel channels of complex geometry.

Tables 1 and 2 summarize the calculated temperature distribution within the fuel matrix for normal operation and for a complete LOCA, respectively. Calculations were performed based on the following simplifying assumptions:

(a) Power distribution is uniform over the fuel area;

(b) The thermal conductivity of the metallic fuel is 30 W/m-K;

(c) Axial heat conduction within a fuel channel is negligible;

(d) Coolant temperature is 300°C during normal operation;

(e) Overall heat transfer coefficient from fuel to coolant is uniform as 2000 W/m2-K during normal operation; and

(f) Decay heat is removed by the moderator only.

The linear channel power in Table 1 means the power in normal operation per unit length of a channel. In the present calculation, the diameter of the fuel matrix is assumed to be 0.068 m.

Though the present analysis is based on several simplifying assumptions, it indicates some important characteristics of the fuel channels. The temperature variation within the fuel matrix is small for both normal operation and the complete LOCA. Then the major concerns in heat transfer aspects would be (a) how to achieve a high heat transfer coefficient between the metallic fuel and the Zircaloy cladding for normal operation, and (b) how to improve the heat transfer through the gap between the calandria tube and the pressure tube for accident conditions. If the heat transfer through the gap between the metallic fuel matrix and the zircaloy tube is comparable to the gap conductance of LWR or HWR fuel rods, the allowable linear channel power can be considerably increased. More detailed analysis of the fuel channel thermal behavior is being performed.

Table 1. Calculated Matrix Temperature (°C) for Normal Operation

Linear Channel Power	Minimum Temperature	Maximum Temperature
400 kW/m	637	728
500 kW/m	721	895
600 kW/m	805	942

Table 2. Temperature Increase (°C) in the Matrix Assuming a Linear Channel Power of 400 kW/m

Decay Power Level	6%	4%	2%	1%
Temperature Increase *	100	67	33	17

* The temperature increase means the difference between the maximum temperature within the matrix and the matrix surface temperature.

4. Advantages and Future Work

4.1. Expected Advantages

Though there is much work to be done even in conceptual design aspects, it has been confirmed through preliminary calculations that passive decay heat removal can be achieved by the moderator system without the ECCS. The present concept is expected to have several advantages over existing water-cooled reactors in operation or under development as follows:

(a) The safety of the reactor can be remarkably improved against LOCA since no active ECCS is required to cool the core;
(b) Selection of the loop-type NSSS maximizes the use of proven technology and existing design of NSSS components;
(c) Design verification test is expected to be remarkably simple because subjects to be tested are the heat removal from a single channel and passive moderator cooling;
(d) Elimination of the ECCS would make the plant design that is easy to understand, analyze and operate; and
(e) Change of reactor power is easily achievable.

4.2. Developmental Status

Presently research efforts are forcused on the following areas:

(a) investigation of PMCS options,
(b) comparative assessment of various fuel material options including U-Zr, UC, and UN,
(c) geometrical optimization of the fuel matrix with assessment of the allowable peak linear power,
(d) feasibility of other types of the fuel matrix design,
(e) investigation of thermal switch concepts, and
(f) assessment of reactor physics aspects.

The overall objective is to deduce a reliable conclusion on the engineering feasibility of the present concept.

4.3. Research Areas

The ISSTER concept suggests us several research topics in thermal-hydraulics(T/H), reactor physics, and material engineering. Gap design and passive moderator cooling are the important subjects in the T/H area. Low pressure boiling and natural circulation would be the typical phenomena for the passive moderator cooling system. It is also necessary to assess the various options (for coolant materials, fuel matrix composition, fuel channel configuration, fuel channel arrangement in the calandria, etc.) from the viewpoint of reactor physics. Achievement of negative reactivity feedback and efficient fuel reloading would be of important consideration. Practical applicability of the ISSTER concept heavily depends on the material consideration. Extensive investigation would be required for selection of fuel channel material, determination of material properties, development of manufacturing process, etc.

5. Conclusion

The concept of the ISSTER has been briefly introduced in this paper. An ECCS-free loop-type water-cooled reactor is considered to be feasible with maximizing the use of existing technology. Easy verification test, simple accident analysis, easy operation and accident management would be additional advantages. However, it should be clearly stated that the present concept is just an infant and is open to many creative ideas.

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