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Development of In-Reactor Fuel Behavior Observation System

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A great effort has been made to develop an optical apparatus for direct observation of transient fuel behavior in a water environment in actual in-reactor experiments. There are many difficulties to be overcome, such as high radiation fluence, limited space, shock pressure generation, fission products release.

Through the extensive irradiation tests of various kinds of glasses, optical fibers and film and ex-reactor simulation tests, an in-reactor fuel behavior observation system was designed and fabricated for NSRR (Nuclear Safety Research Reactor) experiments. The system consists of a test capsule and connected upper containments. As an image guide is installed inside the containment a periscope with non-browning lenses whose lower part is covered by a stainless steel pipe with anti-shock window made of quartz in the test capsule, and the top of the periscope is connected with a high speed camera. A high intense lamp is immersed directly into water in the capsule as a light source. The motion pictures taken by the system in the NSRR experiments could record clearly Čerenkov glow, states of red hot fuel rod, coolant boiling, cladding melting and cracking, bubble formation, and so on which we had never seen before.

KEYWORDS: transient fuel behavior, water environment, NSRR reactor, in-reactor experiment, non-browning lens, periscope, motion picture, fuel failure, film boiling, light transmission, optical apparatus, in core instruments

I. INTRODUCTION

An in-reactor experimental research on fuel behavior under reactivity initiated accident (RIA) conditions is being conducted in the Nuclear Safety Research Reactor (NSRR) at Tokai Research Establishment, Japan Atomic Energy Research Institute. The threshold energy deposition for fuel failure has been determined for unirradiated light water reactor fuel under RIA conditions through the experiments and the effects of many parameters on fuel behavior have been also investigated⁽¹⁾.

In these experiments, transient fuel behavior is evaluated by the records of thermocouples attached to fuel centerline and cladding surface and immersed in water, pressure transducers attached at a fuel rod and a capsule, so on, and the post-irradiation examination results. However, these informations are not enough to understand transient fuel behavior inside a capsule in detail. Then, a great effort has been made to develop an optical apparatus for the observation of fuel behavior in a water environment during actual

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in-reactor experiments.

The transparent meltdown facility was developed for the TREAT experiments⁽²⁾. The facility consists of two components, the capsule to contain the fuel element under test, and an outer leakproof shell to contain the capsule and provide an inert gas cover. There are transparent windows in the front walls of both components, then, a mirror inside the capsule makes it possible to view the sample. The high speed camera is set outside the reactor and takes pictures through the associated mirrors. The TREAT is a large graphite-moderated air-cooled reactor, and special fuel elements are available with large slots, thus making it possible to provide a large core viewing slot for photography. Most of the motion pictures were taken of samples in an inert gas atmosphere, and a few in a water environment, however, which could not provide clear views of the phenomena occurred on the surface of a fuel rod.

On the other hand, the NSRR is a small TRIGA type reactor and only available space for the system is a central experimental dry cavity of about 20 cm in diameter. Furthermore, main interest in taking motion pictures exists in direct observation of transient behavior of a test fuel rod in a water environment, because the primary objective of the NSRR experiments is to investigate fuel behavior under accident conditions of a light water reactor. Then, original design efforts were directed toward the development of a system by which clear view of the transient fuel behavior in a water environment could be obtained, and which could be installed in the experimental cavity of the NSRR and furthermore did not have any transparent window open on the atmosphere to meet severe Japanese safety regulation.

II. NSRR REACTOR AND COURSE OF DEVELOPMENT OF SYSTEM

1. NSRR Reactor

The NSRR facility and its capability have been reported previously⁽³⁾. Briefly, the NSRR is a modified TRIGA-ACPR (Annular Core Pulse Reactor) whose salient feature is the large pulsing power capability which enables to energize test fuel installed in the experimental cavity by nuclear fission over the melting temperature of UO_2. The core structure is mounted on the bottom of a 9 m deep open-top water pool as shown in **Fig. 1**, and the core size is 62 cm in equivalent diameter and 38 cm in height. The diameter of the dry irradiation space located in the centre of the core is about 20 cm and the total length of the vertical loading tube from the top of the core to its open mouth is 870 cm. The maximum pulsing with $3.41\%\Delta k$ brings peak reactor power of 21,000 MW and core energy release of 117 MW·s with minimum reactor period of 1.13 ms.

Most of the experiments have been performed by utilizing a stainless steel capsule of 12 cm in inner diameter with effective length of 80 cm filled with stagnant water at ambient pressure and temperature as shown in **Fig. 2.** A standard test fuel rod is a Zircaloy-4 clad UO_2 pelletized rod of 10.72 mm in outer diameter, and it is installed in the centre of the capsule at single rod test. The energy deposition in a test fuel rod given by a single pulse is controlled by the amount of the reactivity to be inserted and the enrichment of the fuel. Various kinds of instruments also shown in Fig. 2 are attached in accordance with specified test.

2. Course of Development of System

The design concept was concentrated on the development of a system for the observa-

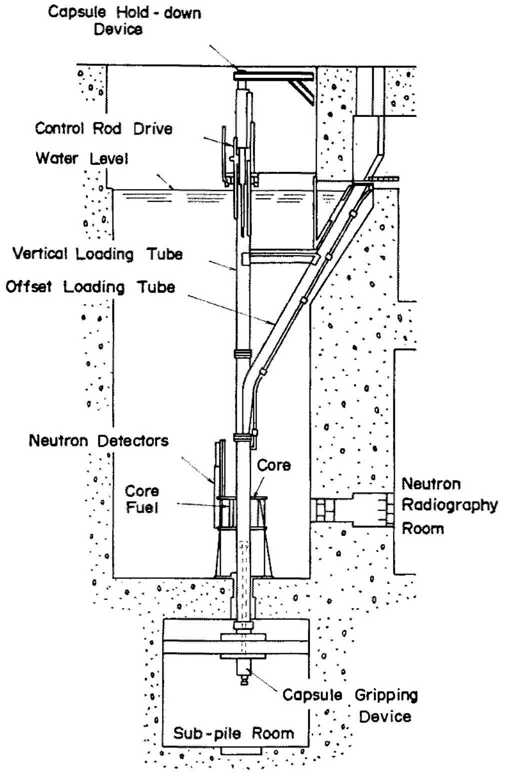


Fig. 1 General arrangement of NSRR

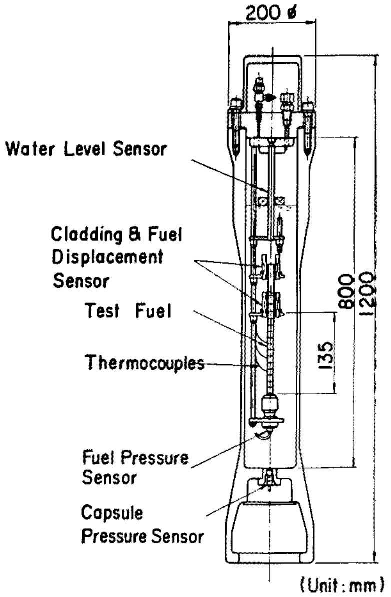


Fig. 2 Atmospheric pressure capsule for NSRR experiment

tion of transient fuel behavior by an optical method. That is, periscope or optical fiber should be used as the image or light guide, and transient behavior should be recorded by a high speed camera. However, there are many difficulties to be overcome for development of an optical system. These are, (1) high neutron and γ-ray fluences which possibly make glass colored, film sensitized and structures radioactive, (2) limited space in the cavity which forces to fabricate a very compact system, (3) shock pressure produced by violent interaction between molten fuel and water from which an optical apparatus should be protected, and so on.

Therefore, irradiation tests of various kinds of glasses, binding agents and films were required to obtain basic data of loss of light transmission or sensitization related to exposed radiation dose in actual reactor conditions, and how to guide light inside a capsule, how to install and handle a high speed camera in the experimental cavity were also unavoidably essential problems.

The part of the periscope installed at the test section should be protected by the stainless steel tube and pressure proof transparent window from shock pressure and hot fuel fragments in the case of fuel failure. Then, it was necessary to make pressure proof test and feasibility test against the attack of hot fuel fragments for proposed transparent window materials. The individual in-reactor tests such as irradiation, feasibility for these materials and ex-reactor simulation tests have been performed extensively, then, the final design of an in-reactor fuel behavior observation system was made based on these test results.

III. IN-REACTOR IRRADIATION TESTS

1. Experimental Methods

Neutron flux, γ-ray dose rate and their spatial distributions were measured in the experimental cavity and the vertical loading tube of the NSRR in parallel with various irradiation tests in order to get the relationships between exposed dose and radiation effects on the proposed materials and also to obtain the basic data for shielding design of the system. The experiment was made in the steady state reactor operation ranging from zero power to 50 kW with and without a capsule in the experimental cavity. Neutron flux was measured by Au foils with and without Cd cover, and γ-ray dose rate by various kinds of thermoluminescent dosimeters (TLDs)$^{(4)}$. The films once taken pictures outside the reactor were irradiated in the cavity changing locations accordant to the measurement of radiation dose to inquire of the sensitization of film by radiation exposure.

The irradiation tests of glasses and optical fibers were also performed to examine the availability in the high radiation field. The positions to set these samples in the experimental cavity were selected in accordance with real use. That is, glass samples, whose specifications are summarized in **Table 1,** were fixed in a small Al bucket and set at the midplane of the reactor core. Optical fibers with three different lengths as also described in Table 1 were accommodated in a vinyl hose and inserted in the cavity to set their tips at the bottom of the core expecting fibers being used as a light guide.

Table 1 Specification of irradiation samples

Sample	Sort	Size
Glass		
Normal	BK7, SF2, SK5, PYREX	25 mmϕ × 5 mm$t$
Non-browning	BK7, SF2, SK4	22 mmϕ × 12 mm$t$
Combined non-browning	BK7+SF2, SK4+SF2	(22 mmϕ × 12 mm$t$) × 2
Fiber		
Normal		Length: 40 cm
Non-browning	Core: F2, L37, L39 Clad: BK7	Dia. of fiber: 40 μm Dia. of clad: 3 mm Length: 0.5, 1, 3 m
Film	Kodak Tri-X pan	

These irradiation tests were performed with single pulses in the NSRR. After the irradiation the transmissibility of light was measured by a spectrophotometer for glasses and optical fibers to compare with that obtained before irradiation.

Besides these irradiation tests, real fuel failure tests were made to check the usefulness of quartz as a transparent window of the periscope guide tube by utilizing the capsule shown in Fig. 2. A 10 mm thick quartz of 30 mm in diameter fixed to the supporting frame by bolts was set at 25 mm apart from the surface of a fuel rod inside the capsule. Two tests were performed, one was the pressure proof test of a quartz in which a waterlogged fuel rod was subjected to an energy deposition of 232 cal/g·UO_2 to produce an enough high shock pressure pulse, and the other was the feasibility test against the attack of hot fuel fragments to a quartz in which a 20% enriched fuel rod was subjected to an energy deposition of 518 cal/g·UO_2 to eject molten fuel fragments outside the rod. In the latter test, the cladding was previously scratched locally to address the ejected fuel fragments toward the quartz.

2. Experimental Results

(1) Neutron Flux and γ-ray Dose Rate in Central Cavity

The measurements of neutron flux and γ-ray dose rate were made to obtain their axial distributions in the experimental cavity as well as their figures at the midplane of the core related to reactor power. The experiments were performed in the conditions with and without a capsule filled with water in the experimental cavity. A number of experiments were made, and the results were basically obtained as neutron flux and γ-ray dose rate per unit reactor power as a parameter of measured positions[(4)]. **Figure** 3 shows axial distributions of thermal neutron fluence and γ-ray dose in the central cavity of the NSRR with and without experimental capsule at a pulse operation with core energy release of 100 MW·s estimated by the measured data. The thermal neutron fluence and γ-ray dose at the midplane of the core in the experimental cavity were estimated to be 4.1×10^{14} n/cm^2, 4.5×10^6 R, respectively, at the maximum pulsing operation with core energy release of 117 MW·s. Those values decrease by an order for each 0.8~1 m apart from the midplane of the core in the central cavity. Furthermore, the thermal neutron fluence and γ-ray dose with the capsule in the experimental cavity become about one tenth and a half to two thirds of those without capsule, respectively, as also shown in Fig. 3. The attenuation of γ-ray above the capsule due to its installation is not so large.

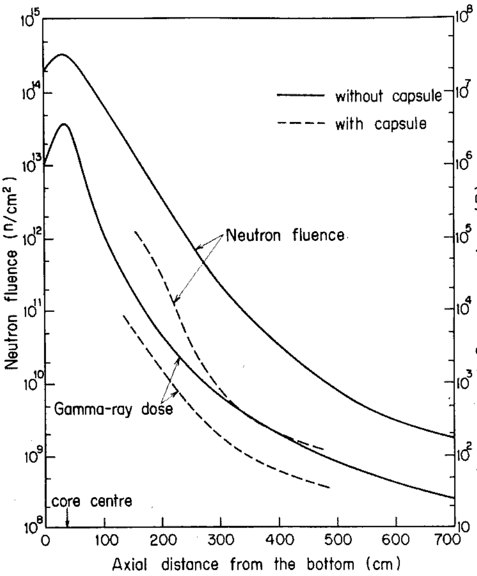


Fig. 3 Axial distributions of neutron fluence and γ-ray dose in central cavity of NSRR with and without installation of capsule at pulse operation with core energy release of 100 MW·s

(2) Radiation Effect of Glasses

The normal glasses, non-browning glasses and pairs of non-browning glasses combined with binding agents as described in Table 1 were irradiated in the experimental cavity of the NSRR to measure the loss of visible light transmission by irradiation.

The irradiation was made by single pulse operation with core energy release of 62 MW·s, therefore, the estimated exposure dose is 2.4×10^6 R. The measured spectral transmissions before and after irradiation are shown for various normal glasses in **Fig. 4.** The light transmissions after irradiation were measured 4 and 78 days after irradiation. The light transmission of normal BK7 glass after irradiation decreases to the range of nearly zero to 70% with the change of wave length from 400 to 700 mμ although it is more than 90% for the whole visible wave length before irradiation. The SF2 and

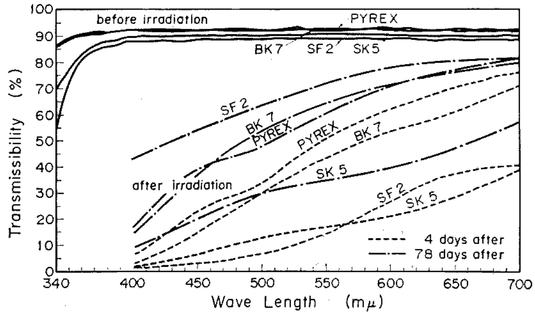


Fig. 4 Spectral transmissions of normal glasses before and after irradiation

SK5 glasses have only 40% in the transmissibility at maximum after irradiation, while the pyrex has larger transmissibility by 5 to 10% than BK7 has. It is interesting that the recovery of the transmissibility is rather high for normal glasses as also shown in Fig. 4, even though the glasses were kept in the room temperature. However, as far as normal glass is used, the transmissibility of light decreases considerably by a single pulse irradiation in the NSRR, and enormous loss of visible light transmission is estimated for a periscope with normal glasses by irradiation because more than several lenses are needed to compose a system. Furthermore, it should be kept in mind that transient fuel behavior to be observed continues even after pulse power burst, while the lens loses light transmission during power burst.

As the second stage, a few kinds of non-browning glasses were irradiated in the NSRR owing to hopeless results in the irradiation tests of normal glasses. The measured spectral transmissions are shown for three different non-browning glasses in **Fig. 5.** The BK7 glass has very good radiation resistance and keeps transmissibility of 90% for nearly whole visible range even after irradiation. While non-browning SK4 and SF2 glasses become to have rather low light transmissions by irradiation in the lower wave length than 500 mμ although they have lower light transmissions even before irradiation than the BK7 has.

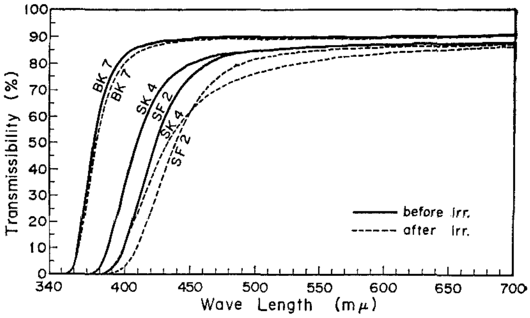


Fig. 5 Spectral transmissions of non-browning glasses before and after irradiation

In order to examine radiation damage and reduction of transmission in binding agents, pairs of non-browning glasses combined with binding agents were also irradiated, and measured spectral transmission is shown in **Fig. 6** with those of normal and non-browning BK7 glasses[(5)]. Small reduction of transmission by irradiation is observed in the range between 400 and 500 mμ. However, it coincides with that of non-browning SF2 glass and radiation damage of binding agents was not observed. Then, it is verified that binding agents are not influenced from pulsing irradiation in the NSRR.

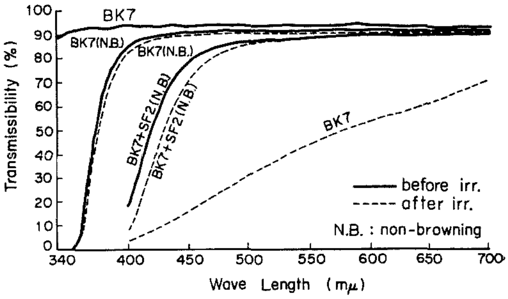


Fig. 6 Spectral transmissions of normal, non-browning and combined non-browning glasses before and after irradiation

(3) Radiation Effect of Optical Fibers

The optical fibers in which non-browning glasses are used as materials for core and clad were also irradiated, and spectral transmissions of them before and after irradiation are shown in **Fig. 7** compared

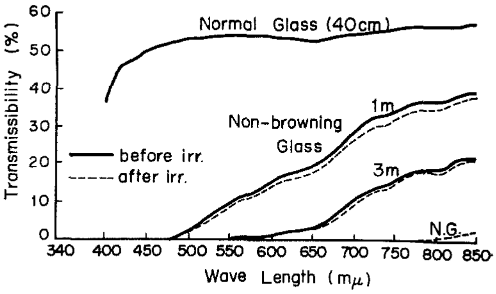
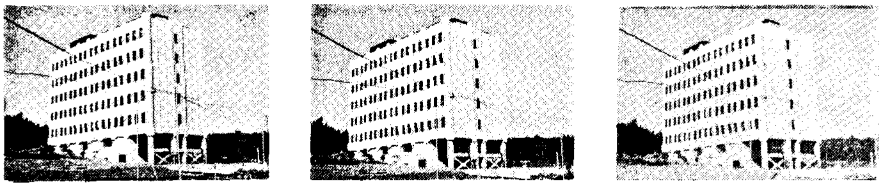


Fig. 7 Spectral transmissions of optical fibers made of normal and non-browning glasses before and after irradiation

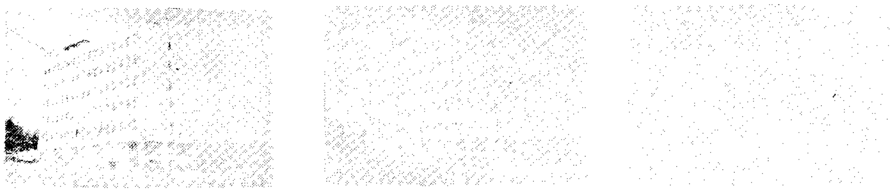
with those of the fiber made of normal glass. The loss of light transmission by irradiation is not so significant for the former, although the transmissibility for the latter decreases to nearly zero by irradiation. However, the fiber made of non-browning glass has very low light transmission in the visible range even before irradiation, so it is not of use as an image guide as well as a light guide in a reactor environment.

(4) Sensitization of Film by Radiation

The Kodak Tri-X pan black and white films which were once taken pictures outside a radiation field were inserted into the cavity of the NSRR and exposed to γ-ray and neutron concurrently in the measurement of neutron flux and γ-ray dose rate. The film irradiation tests were also made by pulse power burst. **Photograph 1** shows pictures after radiation exposure related with exposed γ-ray dose. The neutron fluence is not indicated in the photograph because film is insensitive to neutron. It can be pointed out from the results that the sensitization of film is not so significant when exposed γ-ray dose is less than 1～2 R. The γ-ray dose becomes about 300 R even at 3 m above the core in the cavity by single pulse operation with core energy release of 100 MW·s as shown in Fig. 3. Therefore, it is required to provide enough shielding to reduce γ-ray dose by order two or three in order to protect the film from sensitization.



No exposure 0.26 R 1.4 R



3.8 R 12 R 49 R

Photo. 1 Sensitization of film by radiation exposure with various γ-ray doses

(5) Soundness of Quartz against Shock Pressure and Attack of Hot Fuel Fragments

The first test was performed to confirm shock pressure proof of quartz glasses with various thickness, which were placed surrounding a waterlogged test fuel rod in the capsule. The thicknesses of the quartz glasses are 3, 7 and 10 mm. The fuel rod was subjected to an energy deposition of 232 cal/g·UO_2 with minimum reactor period of 2.42 ms and failed producing a pressure pulse of 6 MPa with full width at half maximum (FWHM) of 0.4 ms. However, any quartz glass did not fail, nor crack, and was completely sound. Besides, hydraulic pressure test for a 10 mm thick quartz glass was made, and it was confirmed to stand against a static pressure of at least 34.5 MPa.

The second test was performed to inquire of the extent of damage of quartz glass by the attack of hot fuel fragments. Quartz glasses were placed in the capsule surrounding a test fuel rod on which an artificial scratch was made locally to address the ejected fuel fragments toward a quartz glass. The rod was subjected to a 1.28 ms period transient with core energy release of 96 MW·s which resulted in an energy deposition of 518 cal/g·

UO_2, and broken into fine fragments resulting in the pressure generation of 1.5 MPa. A quartz glass was attacked by molten fuel as intended, however, it was not broken as shown in **Photo. 2.** The surface of the quartz glass once melted, but, even the cracking of the quartz glass due to thermal stress was not generated. Also did not occur the coloring of the quartz which brought loss of visible light transmission.

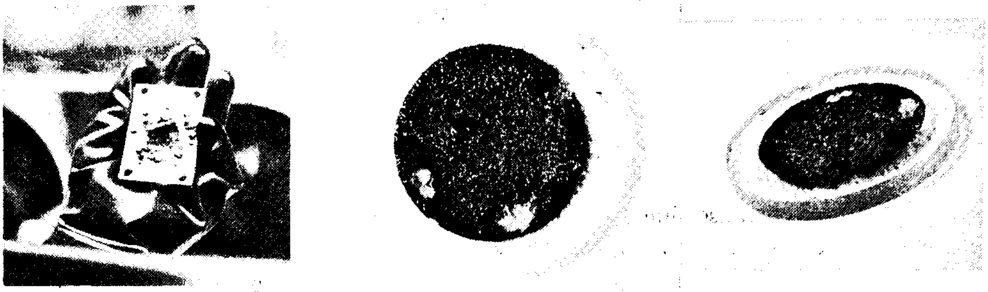

(a) With holder (b) After dismantling

Photo. 2 Quartz glass attacked by molten fuel

It was concluded from these results that a quartz glass was applicable to the transparent window of the guide tube which also constituted pressure boundary.

IV. EX-REACTOR SIMULATION TESTS

1. Experimental Methods

As described above, optical fiber is hardly available to a light guide or an image guide in reactor condition. On the other hand, periscope has possibility to be used in reactor condition as an image guide, if non-browning lenses were used. As a light source, it was considered to use a small sized high intensity lamp which could be contained in the capsule.

The ex-reactor simulation tests were carried out in the condition described below. That is, a periscope and a lamp which have outer diameters of 21 and 45 mm, respectively, were immersed directly into water in the same sized capsule as used in the in-reactor experiments as shown in **Fig. 8.** The top of the periscope was connected with a high speed camera. The Zr rod with outer diameter of 10 mm heated up to 1,000°C was used as the simulant of a heated fuel rod, and dropped into water guided by a pipe.

The transient behavior on the surface of the rod was recorded by the high speed camera at rate of 500 to 3,000 frames per second (fps) for a few seconds. Besides,

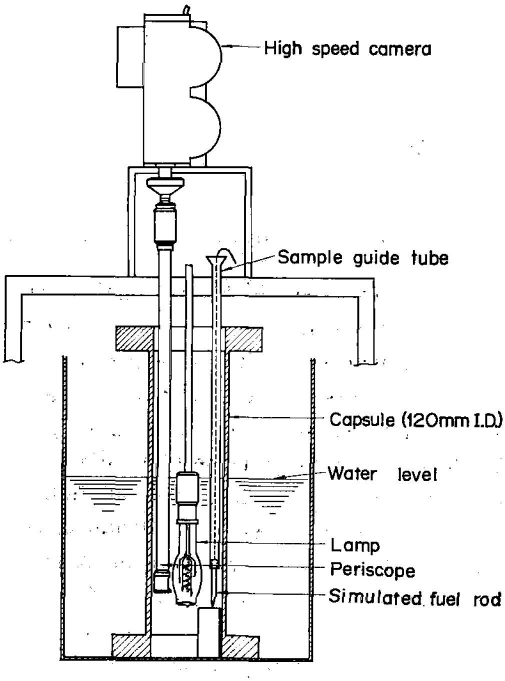
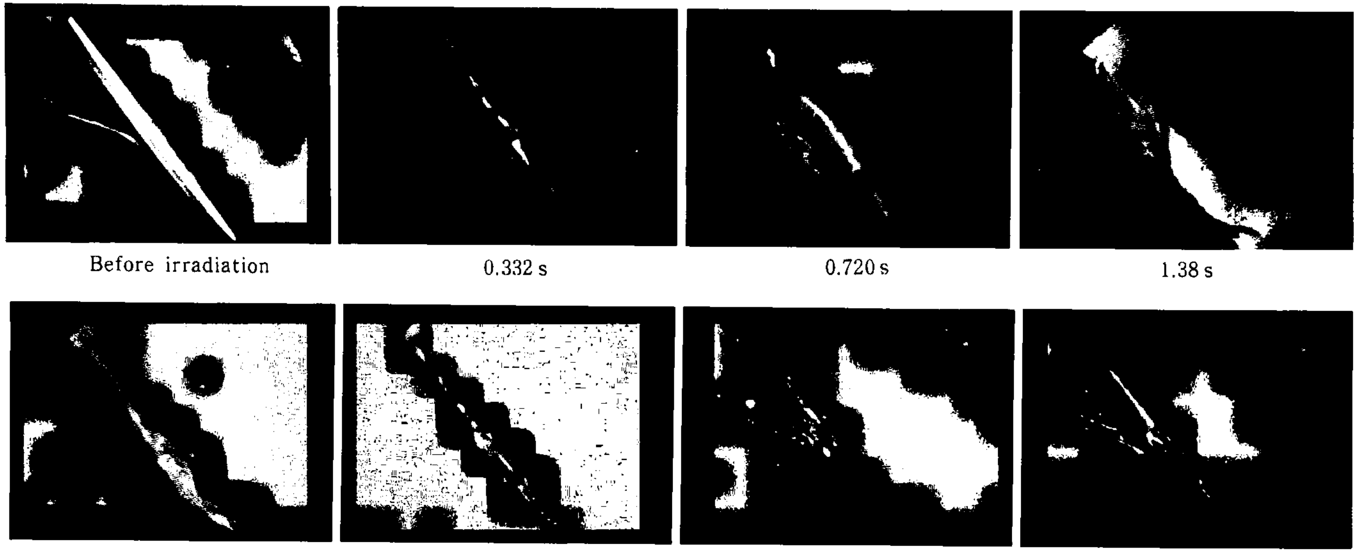


Fig. 8 Schematic view of ex-reactor experimental apparatus

0 s 0.02 s 0.08 s 0.38 s 1.61 s

Photo. 3 Pictures printed from motion film taken at 2,000 fps in ex-reactor experiment showing transient behavior on surface of heated rod

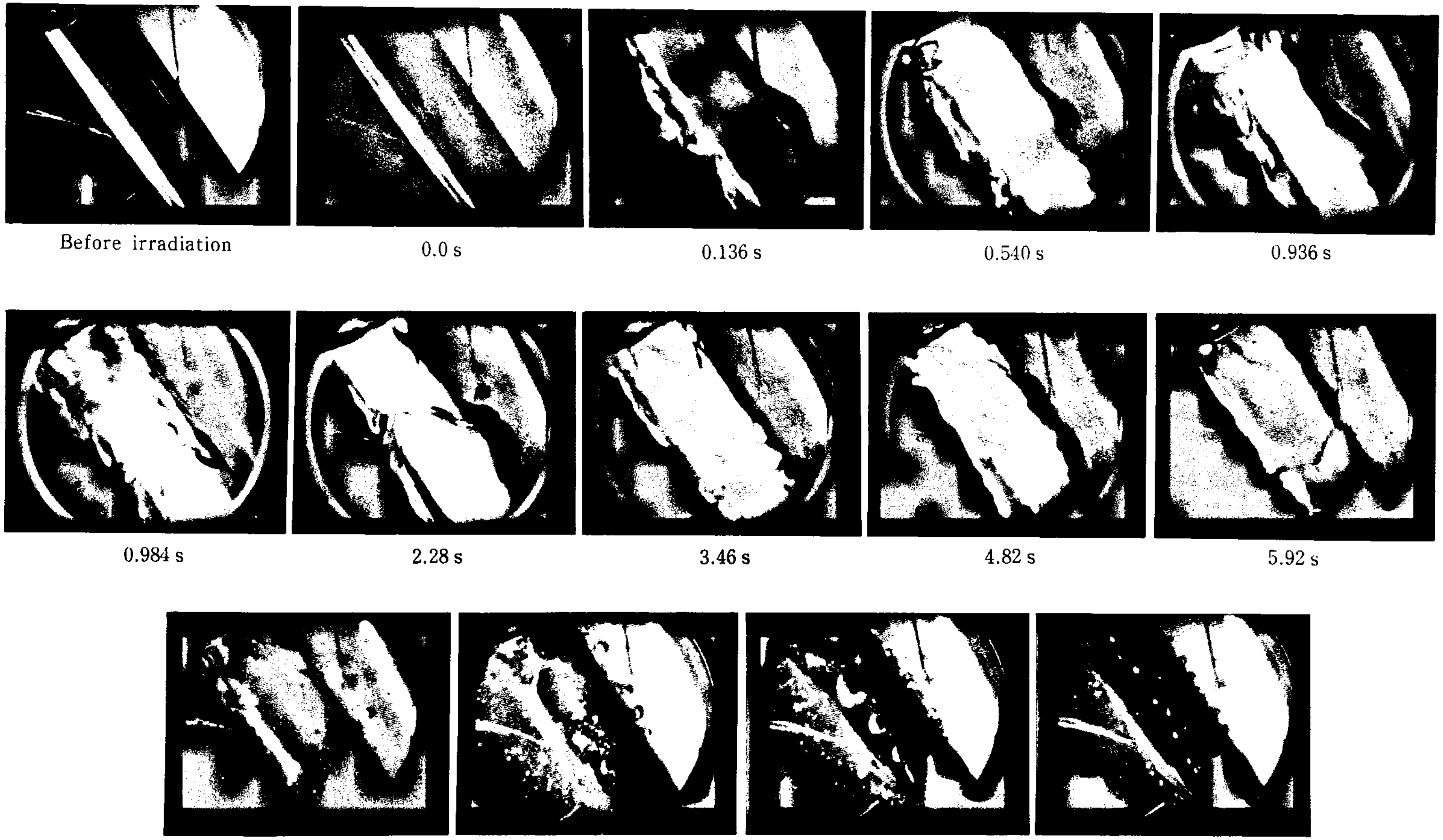


Before irradiation 0.332 s 0.720 s 1.38 s

2.45 s 3.35 s 4.79 s 8.12 s

The fuel rod was subjected to ~270 cal/g·UO_2. (Test No. 600-3)

Photo. 4 Pictures printed from motion film taken at 250 fps in in-reactor experiment showing, red hot state, film boiling, cladding melting and deformation, quenching, bubble formation



Before irradiation 0.0 s 0.136 s 0.540 s 0.936 s

0.984 s 2.28 s 3.46 s 4.82 s 5.92 s

7.12 s 8.65 s 9.70 s 14.7 s

The fuel rod was subjected to ~300 cal/g·UO$_2$. (Test No. 600-4)

Photo. 5 Pictures printed from motion film taken at 250 fps in in-reactor experiment showing Čerenkov glow, red hot state, film boiling, crack, cladding deformation, quenching, bubble formation many pictures were taken for the unheated rod varying the intensity of the light and shutter speed by the camera connected to the top of the periscope instead of the high speed camera.

2. Experimental Results

Ex-reactor simulation tests were carried out in the arrangement described above. After possibility for use of a periscope and a lamp in a water environment was examined, the transient behavior on the surface of a heated rod was successfully recorded both in black and white and in color photographically by the high speed camera through the periscope. The periscope, 1 m in length, in which non-browning lenses are used has transmissibility of about 60% in the whole visible range, and a lamp with 3 kW gives enough light to take pictures at 2,000 fps. Typical pictures printed from the film taken by the high speed camera at 2,000 fps are shown in **Photo. 3.** The motion of a heated rod with a conic cap and transient behavior on the surface of the rod can be observed clearly. Also observed are the motion of water, boiling scheme and so on.

V. DESIGN AND FABRICATION OF IN-REACTOR FUEL BEHAVIOR OBSERVATION SYSTEM

Through the extensive irradiation tests and ex-reactor simulation tests described above, an in-reactor fuel behavior observation system was designed as shown in **Fig. 9** and fabricated$^{(6)}$ to meet the requirements mentioned in Sec. II-2.

Both a periscope and a waterproof treated lamp are accommodated directly inside a capsule, and the top of the periscope is connected with a high speed camera installed also inside the central cavity. Non-browning BK7 glass was specifically chosen as the lens materials for the periscope based on the irradiation test results. The periscope, 2.6 m in length and 30 mm in outer diameter, is composed of a prism, 2 mirrors and 22 lenses. The prism is set at the bottom of the periscope and used to turn the image of an object at right angles. The light path in the periscope is turned two times at right angles by the mirrors at the middle of the path to protect the film from the radiation streamed through the periscope. The visible light transmission of the periscope becomes about 30% in the whole visible range because each non-browning lens, which is 3 mm thick and 14 mm in diameter, has light transmission of about 95%. The portion of the periscope which is in the standard NSRR water capsule is covered by a tube with anti-shock window made of quartz to be protected from shock pressure produced by

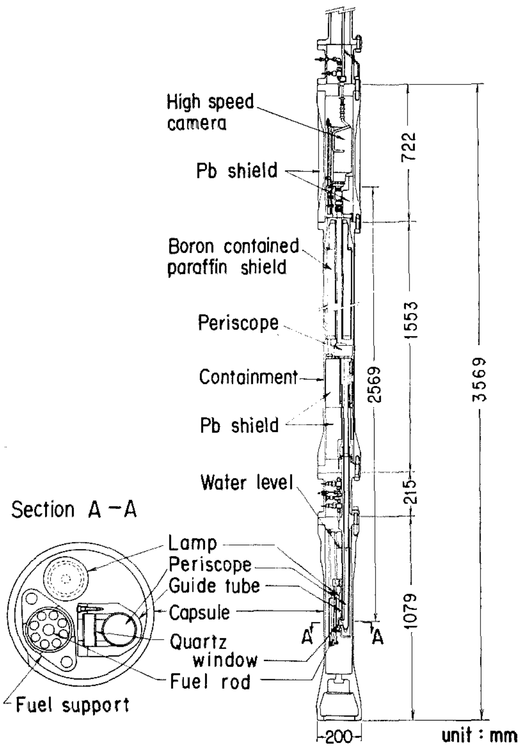


Fig. 9 Schematic configuration of in-reactor fuel behavior observation system

molten fuel and water interaction and the attack of hot fuel fragments. A small sized high speed camera which can be installed inside the cavity is set at 2.6 m apart from the midplane of the core. The upper portion of the periscope and the high speed camera are also covered by a containment to prevent the release of fission products to the cavity in the case of failure of the anti-shock quartz window. The high speed camera and film are protected from neutron and γ-ray radiation by shielding structures of Pb and B contained paraffin not only installed inside the containment but also attached outside it. The system connected to the specially designed shield plug in the top end is installed in the experimental cavity through the vertical loading tube. The operation of the high speed camera is made remotely.

VI. RESULTS OF ACTUAL USE OF SYSTEM

Two actual in-reactor experiments photographing transient fuel behavior have been performed so far since the completion of the system. These test numbers in the NSRR experiment series are 600-3 and 600-4.

1. Test No. 600-3

As visual field through the periscope is 30 mm, a special test fuel rod was fabricated for the experiment. The rod consists of four 10% enriched UO_2 pellets of 10 mm in height put between natural UO_2 pellets and Al_2O_3 pellets clad by Zircaloy-4 tube as shown in **Fig. 10.** The outer diameter of the cladding is 10.72 mm. Five bare thermocouples of Pt/Pt·13%Rh were spot-welded on the cladding surface and a sheathed chromel-alumel thermocouple was immersed in water as indicated also in Fig. 10 to measure temperatures of cladding surface and water.

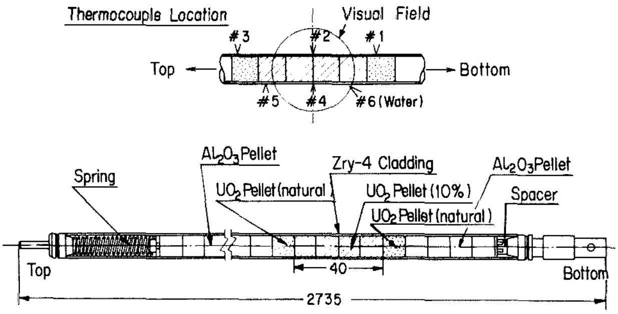


Fig. 10 Test fuel rod for fuel behavior observation test

The conditions of having taken a film by the 16 mm high speed camera are as follows:

Film: Fuji Color Reversal RT500 (100 ft), Frame speed: 250 fps
Recording duration: 1 s before pulsing to 15 s after, Lighting: 3 kW lamp

The irradiation test was made by pulsing power with reactor period of 1.48 ms to provide energy deposition of about 270 cal/g·UO_2 in the fuel.

The film recorded clearly a red hot fuel rod, occurrence of film boiling, cladding melting and deformation, quenching, bubble formation and so on, as shown in **Photo. 4.** The reason why the rod is oblique in the picture attributes to the fact that the high speed camera cannot be adjusted at the proper angle due to the limited space.

2. Test No. 600-4

The second test was made in the same condition as the former test except following. The UO_2 pellets contained in the test fuel rod consist of three 10% enriched pellets put between 5% enriched pellets, and the fuel rod was subjected to a 1.25 ms period transient which resulted in an energy deposition of about 300 cal/g·UO_2. The neutron moderator made of paraffin block surrounded the capsule in a half circle to get uniform azimuthal distribution of power density in the fuel rod because the tilt of power density in the azimuthal direction in the rod was large in the former test. Furthermore, the Al-plate for light reflector was accommodated inside the capsule in the test.

The recording conditions are same as those of Test No. 600-3.

Photograph 5 shows typical pictures printed from the film which indicate red hot state of the rod, violent film boiling, cracking initiation, bubble formation *etc.*

The detailed description of these test results related to the records of thermocouples and the post-irradiation examination results will be presented in the separate paper.

VII. DISCUSSIONS AND CONCLUSIONS

The system in which a periscope with non-browning lenses is directly installed in the test section was developed for photographing transient fuel behavior in a water environment in the actual in-reactor experiments. The transient fuel behavior was successfully recorded in color by a high speed camera in the recent NSRR experiments. The motion pictures taken by the system could provide a clear Čerenkov glow, states of red hot fuel rod, coolant boiling, cladding melting and cracking, bubble formation and so on, which we had never seen. The direct observation of these phenomena suggests that a new model should be developed for describing fuel failure mechanism as well as hydrodynamic behavior.

There is one minor problem in the use of the system. That is the momentary darkening just after the power burst. It might be caused by momentary loss of light transmission of non-browning lens in the periscope due to an instantaneous exposure of extremely high radiation. The continuous research on the matter is necessary.

On the other hand, the techniques described here for photographing transient fuel behavior in a water environment of atmospheric pressure can be extended for photographing samples in a high temperature and high pressure condition by accommodating a pressure-proof lamp house and some cooling function for a periscope.

The success of the development of an optical apparatus for observation of transient fuel behavior contributes to understand fuel behavior during accident conditions in detail, and to verify and develop computing codes which describe fuel behavior in the transient state, furthermore, these results are surely useful for the research on reactor safety.

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